SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - I
High Voltage Engineering – SEE1402

UNIT – I OVER VOLTAGES IN ELECTRICAL POWER SYSTEMS

1.1 NATURAL CAUSES OF OVER VOLTAGES

1.1.1 Introduction

Examination of over voltages on the power system includes a study of their magnitudes, shapes, durations, and frequency of occurrence. The study should be performed at all points along the transmission network to which the surges may travel

1.1.2 Types of Overvoltage

- The voltage stresses on transmission network insulation are found to have a variety of origins.
- In normal operation AC (or DC) voltages do not stress the insulation severely.
- Over voltage stressing a power system can be classified into two main types:

External overvoltage

Generated by atmospheric disturbances of these disturbances, lightning is the most common and the most severe. Internal over voltages: generated by changes in the operating conditions of the network.

Internal over voltages

Lightning Over voltages

Lightning is produced in an attempt by nature to maintain dynamic balance between the positively charged ionosphere and the negatively charged earth.

Over fair-weather areas there is a downward transfer of positive charges through the global air-earth current. This is then counteracted by thunderstorms, during which positive charges are transferred upward in the form of lightning. During thunderstorms, positive and negative charges are separated by the movements of air currents forming ice crystals in the upper layer of a cloud and rain in the lower part.

The cloud becomes negatively charged and has a larger layer of positive charge at its top. As the separation of charge proceeds in the cloud, the potential difference between the centers of charges _increases and the vertical electric field along the cloud also increases. The total potential difference between the two main charge centers may vary from l00 to 1000 MV. Only a part of the total charge-several hundred coulombs is released to earth by lightning; the rest is consumed in inter cloud discharges. The height of the thundercloud dipole above earth may reach5 km in tropical regions.

Figure: 1.1 Overvoltage due to arcing ground

The Lightning Discharge

The channel to earth is first established by a stepped discharge called a leader stroke. The leader is initiated by a breakdown between polarized water droplets at the cloud base caused by the high electric field, or a discharge between the negative charge mass in the lower cloud and the positive charge pocket below it. (Figure 1.2) As the downward leader approaches the earth, an upward leader begins to proceed from earth before the former reaches earth. The upward leader joins the downward one at a point referred to as the striking point. This is the start of the return stroke, which progresses upward like a travelling wave on a transmission line

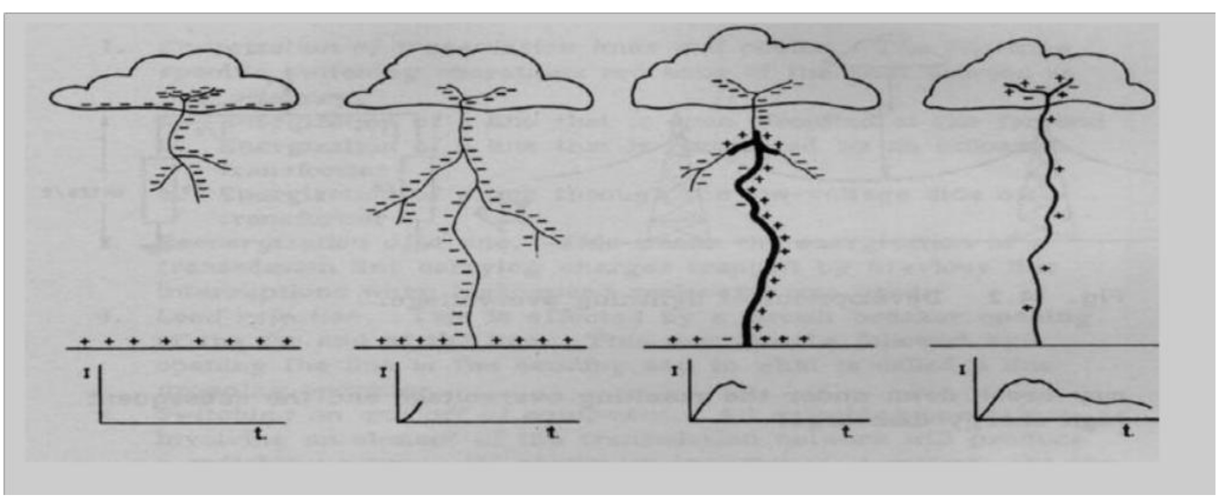


Figure:1.2 Developmental Stages Of A Lighting Flash And The Corresponding Current Surge

1.2 LIGHTNING PHENOMENON

At the earthling point a heavy impulse current reaching the order of tens of kilo amperes occurs, which is responsible for the known damage of lightning. The velocity of progression of the return stoke is very high and may reach half the speed of light. The corresponding current heats its path to temperatures up to 20,000°C, causing the explosive air expansion that is heard as thunder. The current pulse rises to its crest in a few microseconds and decays over a period of tens or hundreds of microseconds.

1.2.1 Facts about Lightning

- A strike can average 100 million volts of electricity
- Current of up to 100,000 amperes
- Can generate 54,000
- Lightning strikes somewhere on the Earth every second
- Kills hundreds of people every year.
- Use The Five Second Rule Light travels at about 186,291 miles/second
- Sound travels at only 1,088 feet/second
- You will see the flash of lightning almostimmediately5280/1088= 4.9
- About 5 seconds for sound to travel 1 mile1 miles (statute) is equal to 1,609.34 meters.1 Feet are equal to 0.30 meters.

1.2.2 Lightning Voltage Surges

The most severe lightning stroke is that which strikes a phase conductor on the transmission line. The lightning stroke injects its current into a termination impedance Z, which in this case is half the line surge impedance Zo since the current will flow in both directions as shown In Figure1.3. Therefore, the voltage surge magnitude at the striking points = (½) IZo The lightning current magnitude is rarely less than 10 kA. For typical overhead line surge impedance Zo of 300Ω, the lightning surge voltage will Probably have a magnitude in excess of 1500 kV.

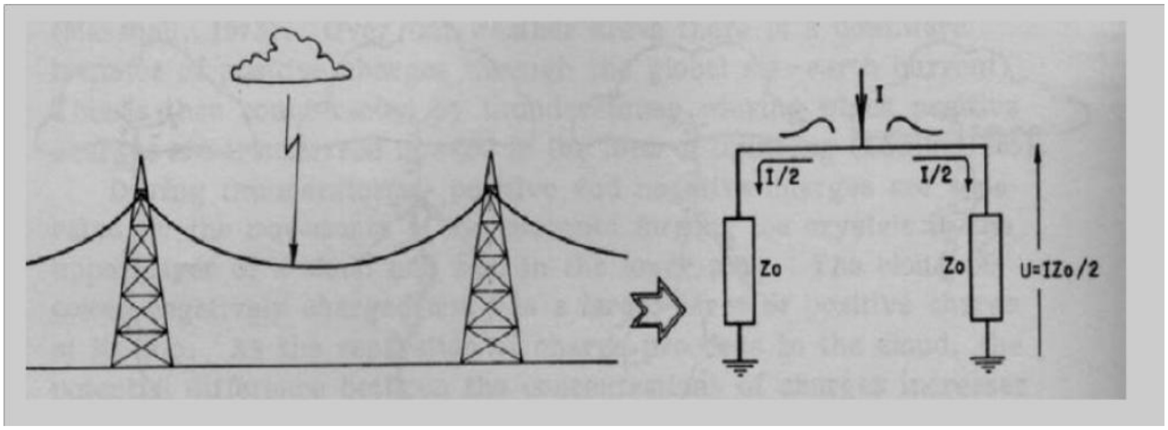


Figure: 1.3 Developmental lighting over voltage

1.3 EFFECT OF LIGHTNING

The impedance of the lightning channel itself is much larger than 1/2Zo (it is believed to range from l00to 3000 Ω).

- Lightning voltage surge will have the same shape characteristics.
- In practice the shapes and magnitudes of lightning surge waves get modified by their
- Reflections at points of discontinuity as they travel along transmission lines.
- Lightning strokes represent true danger to life, structures, power systems, and
- Communication networks.
- Lightning is always a major source of damage to power systems where equipment
- Insulation may break down, under the resulting overvoltage and the subsequent high-
- Energy discharge.

Lightning has been a source of wonder to mankind for thousands of years. Scotland points out that any real scientific search for the first time was made into the phenomenon of lightning by Franklin in18th century. Before going into the various theories explaining the charge formation in a thunder cloud and the mechanism of lightning, it is desirable to review some of the accepted facts concerning the thunder.

1.3.1 Cloud and the Associated Phenomenon.

- The height of the cloud base above the surrounding ground level may vary from 160 to 9,500m. The charged centers which are responsible for lightning are in the range of 300 to 1500 m.

- The maximum charge on a cloud is of the order of 10 coulombs which is built up exponentially
- over a period of perhaps many seconds or even minutes. The maximum potential of a cloud lies approximately within the range of 10 MV to 100 MV.
- The energy in a lightning stroke may be of the order of 250 kWhr.

1.3.2 Raindrops:

Raindrops elongate and become unstable under an electric field, the limiting diameter being0.3 cm in a field of 100 kV/cm. A free falling raindrop attains a constant velocity with respect to the air depending upon its size. This velocity is 800 cms/sec. for drops of the size
0.25 cm dia. and is zero for spray. This means that in case the air currents are moving upwards with a velocity greater than 800 cm/sec, no rain drop can fall. Falling raindrops greater than 0.5 cm in dia become unstable and break up into smaller drops. When a drop is broken up by air currents, the water particles become positively charged and the air negatively charged. When ice crystal strikes with air currents, the ice crystal is negatively charged and the air positively charged.

Wilson's Theory of Charge Separation Wilson's theory is based on the assumption that a large number of ions are present in the atmosphere. Many of these ions attach themselves to small dust particles and water particles. It also assumes that an electric field exists in the earth's atmosphere during fair weather which is directed downwards towards the earth (Figure.1.4 (a)). The intensity of the field is approximately 1 volt/cm at the surface of the earth and decreases gradually with height so that at 9,500 m it is only about 0.02 V/cm. A relatively large raindrop (0.1 cm radius) falling in this field becomes polarized, the upper side acquires a negative.

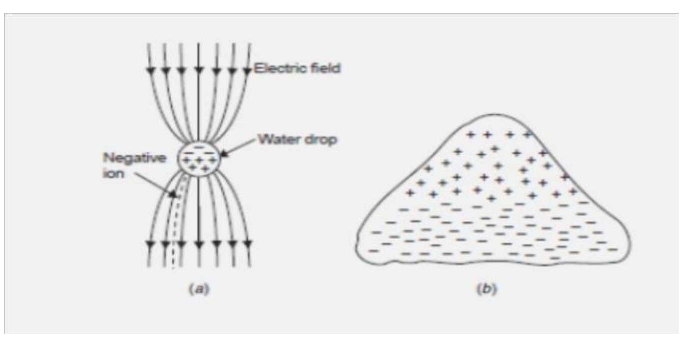


Figure:1.4 (a) Capture of negative ions by large falling drop;
(b) Charge separation in a thunder cloud according to Wilson's theory

1.3.3 Wilson's Theory of Charge Separation

Wilson's theory is based on the assumption that a large number of ions are present in the atmosphere. Many of these ions attach themselves to small dust particles and water particles. It also assumes that an electric field exists in the earth's atmosphere during fair weather which is directed downwards towards the earth (Figure.1.4 (a)). The intensity of the field is approximately 1 volt/cm at the surface of the earth and decreases gradually with height so that at 9,500 m it is only about 0.02 V/cm. A relatively large raindrop (0.1 cm radius) falling in this field becomes polarized, the upper side acquires a negative charge and the lower side a positive charge. Subsequently, the lower part of the drop attracts –ve charges from the atmosphere which are available in abundance in the atmosphere leaving a preponderance of positive charges in the air.

The upwards motion of air currents tends to carry up the top of the cloud, the +ve air and smaller drops that the wind can blow against gravity. Meanwhile the falling heavier raindrops which are negatively charged settle on the base of the cloud. It is to be noted that the selective action of capturing –ve charges from the atmosphere by the lower surface of the drop is possible. No such selective action occurs at the upper surface. Thus in the original system, both the positive and negative charges which were mixed up, producing essentially a neutral space charge, are now separated.

Thus according to Wilson's theory since larger negatively charged drops settle on the base of the cloud and smaller positively charged drops settle on the upper positions of the cloud, the lower base of the cloud is negatively charged and the upper region is positively charged (Figure.1.4 (b)). **Simpson's and Scarse Theory** Simpson's theory is based on the temperature variations in the various regions of the cloud. When water droplets are broken due to air currents, water droplets acquire positive charges whereas the air is negatively charged. Also when ice crystals strike with air, the air is positively charged and the crystals negatively charged. The theory is explained with the help of Fig. 1.5.

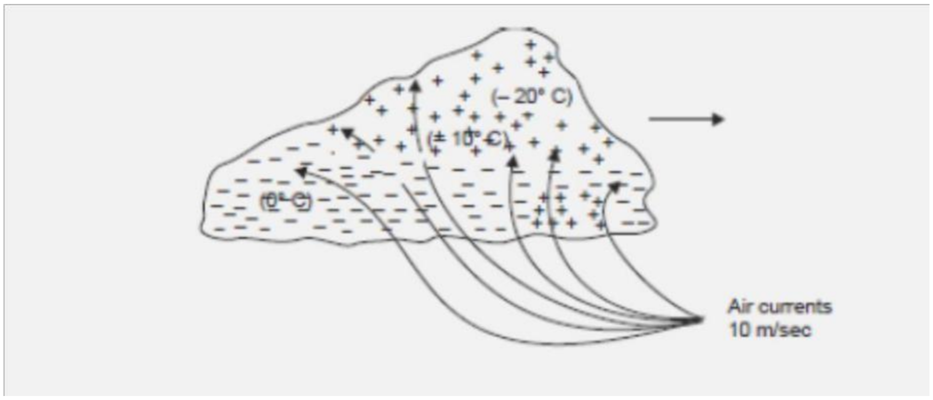


Figure:1.5 Charge generation and separation in a thunder

Cloud according to Simpson‘s theory Let the cloud move in the direction from left to right as shown by the arrow. The air currents are also shown in the diagram. If the velocity of the air currents is about 10 m/sec in the base of the cloud, these air currents when collide with the water particles in the base of the cloud, the water drops are broken and carried upwards unless they combine together and fall down in a pocket as shown by a pocket of positive charges. With the collision of water particles we know the air is negatively charged and the water particles positively charged. These negative charges in the air are immediately absorbed by the cloud particles which are carried away upwards with the air currents. The air currents go still higher in the cloud where the moisture freezes into ice crystals.

The air currents when collide with ice crystals the air is positively charged and it goes in the upper region of cloud whereas the negatively charged ice crystals drift gently down in the lower region of the cloud. This is how the charge is separated in a thundercloud. Once the charge separation is complete, the conditions are now set for a lightning stroke.

1.4 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 STP 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. The mechanism of lightning discharge is best explained with the help of Fig. 1.6. After a gradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets ionized. At this a streamer (Fig. 1.6(a)) 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 (Fig.1.6(b)). 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 (Fig.1.6(c)).Once the stepped leader has made contact with the earth it is believed that a power return stroke(Fig. 1.6(c)) 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. It is here where the –ve charge of the cloud is being neutralized by the positive induced charge on the earth (Fig. 1.6 (d)).

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 ionized path. This streamers known as dart leader (Fig.1.6 (e)). 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 whereas the 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. 1.2.3 Line Design Based On Lightning The severity of switching surges for voltage 400 kV and above is much more than that due to lightning voltages. All the same it is desired to protect the transmission lines against direct lightning strokes. The object of good line design is to reduce the number of outages caused by lightning. To achieve this following actions are required. (I) The incidence of stroke on to power conductor should be minimized. (ii) The effect of those strokes which are incident on the system should be minimized. To achieve (i) we know that lightning normally falls on tall objects; thus tall towers are more vulnerable to lightning than the smaller towers. In order to keep smaller tower height for a particular ground clearance, the span lengths will decrease which requires more number of towers and hence the associated accessories like insulators etc. The cost will go up very high. Therefore, a compromise has to be made so that adequate clearance is provided, at the same time keeping longer span and hence lesser number of towers.

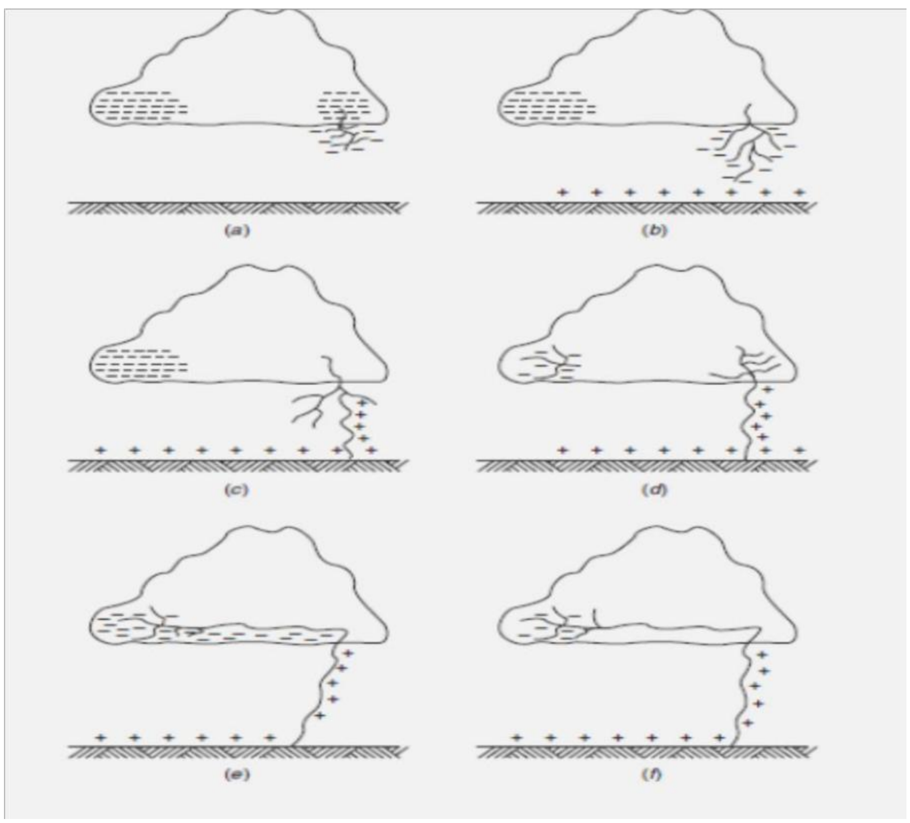


Figure:1.6 Lightning mechanism

With a particular number of towers the chances of incidence of lightning on power conductor scan be minimized by placing a ground wire at the top of the tower structure. . The tower presents a discontinuity to the travelling waves; therefore they suffer reflections and refraction. The system is, then, equivalent to a line bifurcated at the tower point. We know that the voltage and current transmitted into the tower will depend upon the surge impedance of the tower and the ground impedance (tower footing resistance) of the tower. If it is low, the wave reflected back up the tower will largely remove the potential existing due to the incident wave. In this way the chance of flashover is eliminated. If, on the other hand, the incident wave encounters high ground impedance, positive reflection will take place and the potential on thetop of the tower structure will be raised rather than lowered. It is, therefore, desired that for good line design high surge impedances in the ground wire circuits, the tower structures and the tower footing should be avoided.

1.5 OVER VOLTAGES DUE TO SWITCHINGSURGES

The increase in transmission voltages needed to fulfill the required increase in transmitted powers, switching surges have become the governing factor in the design of insulation for EHV and UHV systems. In the meantime, lightning over voltages come as a secondary factor in these networks. There are two fundamental reasons for this shift in relative importance from lightning to switching surges as higher transmission voltages are called for:

- Over voltages produced on transmission lines by lightning strokes are only slightly dependent on the power system voltages. As a result, their magnitudes relative to the system peak voltage decrease as the latter is increased.
- External insulation has its lowest breakdown strength under surges whose fronts fall in the range 50-500 micro sec., which is typical for switching surges.
- According to the International Electro-technical Commission (IEC) recommendations, all equipment designed for operating voltages above 300 kV should be tested under switching impulses (i.e., laboratory-simulated switching surges).

1.5.1 Temporary over voltages

The purpose of this Guide is to provide information on transient and temporary over voltages and currents in end-user AC power systems. With this information in hand, equipment designers and users can more accurately evaluate their operating environment to determine the need for surge protective devices (SPDs) or other mitigation schemes. The Guide characterizes electrical transmission and distribution systems in which surges occur, based upon certain theoretical considerations as well as on the data that have been recorded in interior locations with particular emphasis on industrial environments. There are no specific mathematical models that simulate all surge environments; the complexities of the real world need to be simplified to produce a manageable set of standard surge tests. To this end, a scheme to classify the surge environment is presented.

This classification provides a practical basis for the selection of surge-voltage and surge-current waveforms and amplitudes that can be applied to evaluate the capability of equipment to withstand surges when connected to power circuits. The fundamental approach to electromagnetic compatibility (EMC) in the arena of surges is the requirement that equipment immunity and characteristics of the surge environment characteristics should be properly coordinated. By definition, the duration of the surges considered in this Guide do not exceed a one-half period of the normal mains waveform. They can be periodic or random events and might appear in any combination of line, neutral, or grounding conductors. They include those surges with amplitudes, durations, or rates of change sufficient to cause equipment damage or operational upset (see Figure1.7). Surge protective devices acting primarily on the voltage are often applied to divert damaging surges, but the upset can require other remedies.

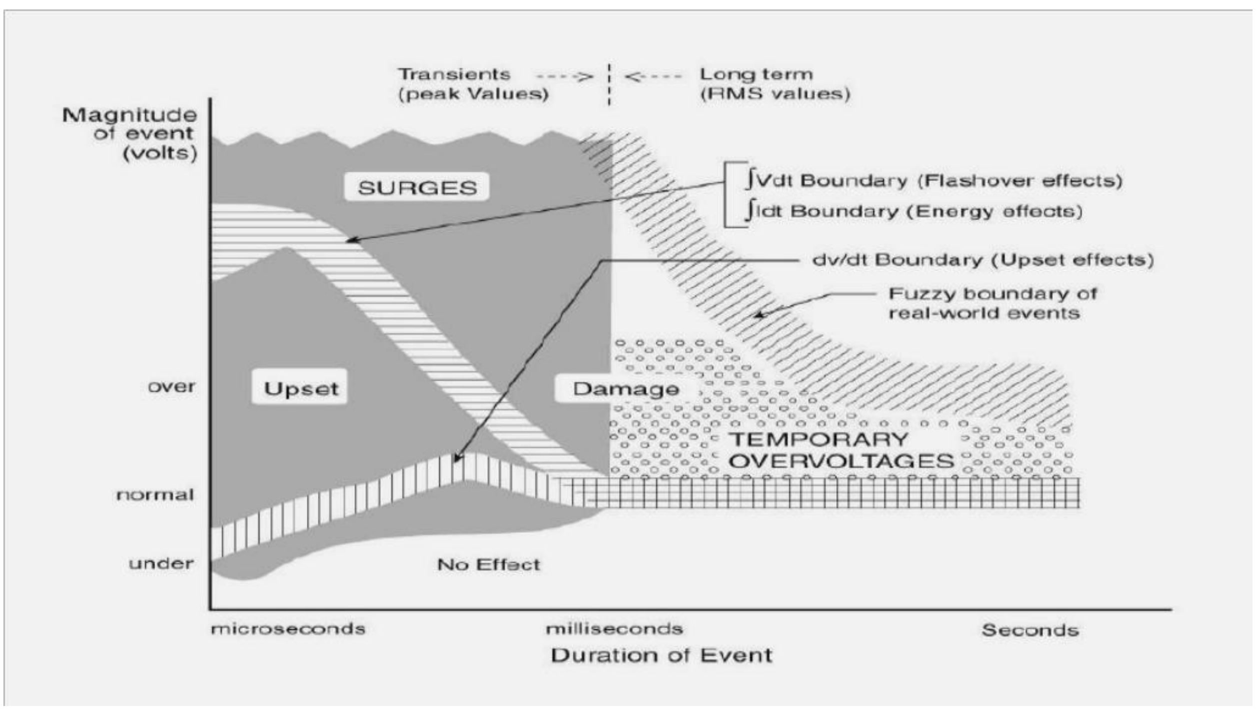


Figure: 1.7 Simplified relationships among voltage, duration, rate of change, and effect on equipment.

Temporary over voltages represent a threat to equipment as well as to any surge protective devices that may have been provided for the mitigation of surges. The scope of this Guide includes temporary over voltages only as a threat to the survival of SPDs, and therefore includes considerations on the selection of suitable SPDs. No equipment performance requirements are specified in this Guide. What is recommended is a rational, deliberate approach to recognizing the variables that need to be considered simultaneously, using the information presented here to define a set of representative situations. For specific applications, the designer has to take into consideration not only the rates of occurrence and the waveforms described in this Guide, but also the specific power system environment and the characteristics of the equipment in need of protection. As an example, the following considerations are necessary to reach the goal of practical surge immunity:

- Desired protection
- Hardware integrity
- Process immunity
- Specific equipment sensitivities
- The power environment
- Surge characteristics
- Electrical system
- Performance of surge protective devices
- Protection
- Lifetime
- The test environment
- Cost effectiveness

Answers may not exist that address all of the questions raised by the considerations listed above. In particular, those related to specific equipment sensitivities, both in terms of component failure and especially in terms of processing errors, might not be available to the designer. The goal of the reader may be simply selecting the most appropriate device from among the various surge protective devices available and meet the requirements of the equipment that they must protect. Subsets of the considerations in this section might then apply, and the goal of the reader may then be the testing of various surge protective devices under identical test conditions. The following can guide the reader in identifying parameters, seeking further facts, or quantifying a test plan.

1.5.2 Desired Level of Protection

The desired level of protection can vary greatly depending upon the application. For example, in applications not involving online performance, protection may only be needed to reduce hardware failures by a certain percentage. In other cases, such as data processing or critical medical or manufacturing processes, any interruption or upset of a process might be unacceptable. Hence, the designer should quantify the desired goal with regard to the separate questions of hardware failure and process interruption or upset.

1.5.3 Equipment Sensitivities

Specific equipment sensitivities should be defined in concert with the above-mentioned goals. The sensitivities (immunity) will be different for hardware failure or process upset. Such definitions might include: maximum amplitude and duration of the surge remnant that can be tolerated, wave-form or energy sensitivity, et cetera.

1.5.4 Power Environment

The applicable test waveforms recommended in this Guide should be quantified on the basis of the location categories and exposure levels as explained in the corresponding clauses of the Guide. The magnitude of the voltage, including any anticipated variation, should be quantified. Successful application of surge protective devices requires taking into consideration occasional abnormal occurrences. It is essential that an appropriate selection of the SPD limiting voltage is based on actual characteristics of the mains voltage.

1.5.5 Performance of Surge Protective Devices

Evaluation of a surge protective device should verify a long life in the presence of both the surge and electrical system environments described above. At the same time, its remnant and voltage levels should provide a margin below the immunity levels of the equipment in order to achieve the desired protection. It is essential to consider all of these parameters simultaneously. For example, the use of a protective device rated very close to the nominal system voltage might provide attractive remnant figures, but can be unacceptable when a broad range of occasional abnormal deviations in the amplitude of the mains waveform are considered. Lifetime or overall performance of the SPDs should not be sacrificed for the sake of a low remnant.

1.5.6 Test Environment

The surge test environment should be carefully engineered with regard to the preceding considerations and any other parameters that are important to the user. A typical description of the test-environment includes definitions of simultaneous voltages and currents, along with proper demonstrations of short-circuit.

It is important to recognize that the specification of an open-circuit voltage without simultaneous short-circuit current capability is meaningless. Cost Effectiveness The cost of surge protection can be small, compared to overall system cost and benefits in performance. Therefore, added quality and performance in surge protection may be chosen as a conservative engineering approach to compensate for unknown variables in the other parameters. This approach can provide excellent performance in the best interests of the user, while not significantly affecting overall system cost.

Definitions

The definitions given here have been developed by several standards-writing organizations and have been harmonized.

Back Flashover (Lightning):

A flashover of insulation resulting from a lightning strike to part of a network or electrical installation that is normally at ground potential. Blind Spot: A limited range within the total domain of application of a device, generally at values less than the maximum rating. Operation of the equipment or the protective device itself might fail in that limited range despite the device's demonstration of satisfactory performance at maximum ratings.

Clamping Voltage:

Deprecated term. See measured limiting voltage.

Combination Surge (Wave): A surge delivered by an instrument which has the inherent capability of applying a 1.2/50 us voltage wave across an open circuit, and delivering an 8/20 us current wave into a short circuit. The exact wave that is delivered is determined by the instantaneous impedance to which the combination surge is applied.

Combined Multi-Port Spd: A surge protective device integrated in a single package as the means of providing surge protection at two or more ports of a piece of equipment connected to different systems (such as a power system and a communications system).

Coordination Of Spds (Cascade):

The selection of characteristics for two or more SPDs to be connected across the same conductors of a system but separated by some decoupling impedance such that, given the parameters of the impedance and of the impinging surge, this selection will ensure that the energy deposited in each of the SPDs is commensurate with its rating.

Direct Strike:

A strike impacting the structure of interest or the soil (or objects) within a few meters from the structure of interest. Energy Deposition: The time integral of the power dissipated in a clamping-type surge protective device during a current surge of a specified waveform. Failure Mode: The process and consequences of device failure.

Leakage Current:

Any current, including capacitive coupled currents, that can be conveyed from accessible parts of a product to ground or to other accessible parts of the product.

Lightning Protection System (LPS):

The complete system used to protect a space against the effects of lightning. It consists of both external and internal lightning protection systems.

Lightning Flash To Earth:

An electrical discharge of atmospheric origin between cloud and earth consisting of one or more strikes.

Lightning Strike: A single electrical discharge in a lightning flash to earth.

Mains:

The AC power source available at the point of use in a facility. It consists of the set of electrical conductors (referred to by terms including service entrance, feeder, or branch circuit) for delivering power to connected loads at the utilization voltage level.

Maximum continuous operating voltage (MCOV):

The maximum designated root- mean-square (rms) value of power-frequency voltage that may be applied continuously between the terminals of the arrester.

Measured limiting voltage:

The maximum magnitude of voltage that appears across the terminals of the SPD during the application of an impulse of specified wave shape and amplitude.

Nearby strike:

A strike occurring in the vicinity of the structure of interest.

Nominal System Voltage:

A nominal value assigned to designate a system of a given voltage class.

Nominal Arrestor voltage:

The voltage across the arrestor measured at a specified pulsed DC current, IN(dc), of specific duration. IN(dc) is specified by the arrestor manufacturer.

One-Port SPD:

An SPD having provisions (terminals, leads, plug) for connection to the AC power circuit but no provisions (terminals, leads, receptacles) for supplying current to the AC power loads.

Open-circuit voltage (OCV):

The voltage available from the test set up (surge generator, coupling circuit, back filter, connecting leads) at the terminals where the SPD under test will be connected.

Point of strike:

The point where a lightning strike contacts the earth, a structure, or an LPS.

Pulse life:

The number of surges of specified voltage, current amplitudes, and wave shapes that may be applied to a device without causing degradation beyond specified limits. The pulse life applies to a device connected to an AC line of specified characteristics and for pulses sufficiently spaced in time to preclude the effects of cumulative heating.

Response time (arrestor):

The time between the point at which the wave exceeds the limiting voltage level and the peak of the voltage overshoot. For the purpose of this definition, limiting voltage is defined with a 8/20 Its current waveform of the same peak Current amplitude as the waveform used for this response time.

Short-Circuit Current (Scc):

The current which the test set up (surge generator, coupling circuit, back filter, connecting leads) can deliver at the terminals where the SPD under test will be connected, with the SPD replaced by bonding the two lead terminals. (Also sometimes abbreviated as SCI).

SPD disconnect or:

A device for disconnecting an SPD from the system in the event of SPD failure. It is to prevent a persistent fault on the system and to give a visible indication of the SPD failure.

Surge Response Voltage:

The voltage profile appearing at the output terminals of a protective device and applied to downstream loads, during and after a specified impinging surge, until normal stable conditions are reached.

Surge Protective device (SPD):

A device that is intended to limit transient over voltages and divert surge currents. It contains at least one nonlinear component—a surge reference equalizer. A surge protective device used for connecting equipment to external systems whereby all conductors connected to the protected load are routed—physically and electrically—through a single enclosure with a shared reference point between the input and output ports of each system.

Swell:

A momentary increase in the power frequency voltage delivered by the mains, outside of the normal tolerances, with a duration of more than one cycle and less than a few seconds.

1.6 Switching Surge Test Voltage Characteristics

Switching surges assume great importance for designing insulation of overhead lines operating at voltages more than 345 kV. It has been observed that the flashover voltage for various geometrical arrangements under unidirectional switching surge voltages decreases with increasing the front duration of the surge and the minimum switching surge corresponds to the range between 100 and 500 μ sec. However, time to half the value has no effect as flashover takes place either at the crest or before the crest of the switching surge. Fig.1.8 gives the relationship between the critical flashover voltage per meter as a function of time to flashover for on a 3 m rod-rod gap and a conductor-plane gap.

It can be seen that the standard impulse voltage (1/50 μ sec) gives highest flashover voltage and switching surge voltage with front time varying between 100 to 500 μ sec has lower flashover voltages compared to power frequency voltage. The flashover voltage not only depends upon the crest time but upon the gap spacing and humidity for the same crest time surges.

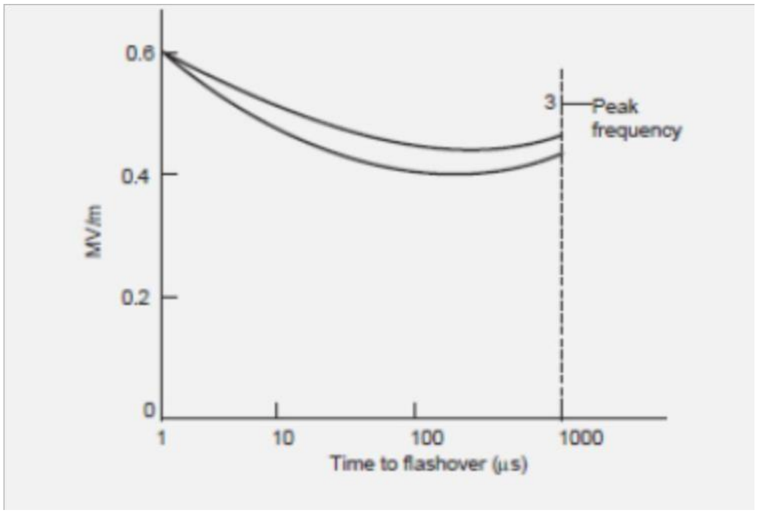


Figure: 1.8 Variation of F.O. V/m as a function of time to flashover

It has been observed that the switching surge voltage per meter gap length decreases drastically with increase in gap length and, therefore, for ultra high voltage system, costly design clearances are required. Therefore, it is important to know the behavior of external insulation with different configuration under positive switching surges as it has been found that for nearly all gap configurations which are of practical interest positive switching impulse is lower than the negative polarity switching impulse.

It has also been observed that if the humidity varies between 3 to 16 gm/m3, the breakdown voltage of positive and gaps increases approximately 1.7% for 1 gm/m3 increase in absolute humidity. For testing purposes the switching surge has been standardized with wave front time 250 μ deceit is known that the shape of the electrode has a decided effect on the flashover voltage of the insulation.

Lot of experimental work has been carried on the switching surge flash over voltage furlong gaps using rod-plane gap and it has been attempted to correlate these voltages with switching surge flash over voltage of other configuration electrodes. Several investigators have shown that if the gap length varies between 2 to 8 m, the 50% positive switching surge flash over for any configurations given by the expression

$$V_{50} = 500\ kd^{0.6}\ \text{kV}$$

where d is the gap length in meters, k is the gap factor which is a function of electrode geometry. Forrod-plane gaps K = 1.0. Thus K represents a proportionality content and is equal to 50% flash overvoltage of any gap geometry to that of a rod-plane gap for the same gap spacing

$$k = \frac{V_{50}}{V_{50}\text{rod} - \text{plane gap}}$$

i.e., The expression for V50 applies to switching impulse of constant crest time. A more general expression which applies to longer times to crest has been proposed as follows :

$$V_{50} = \frac{3450\,K}{1 + \frac{8}{d}}\ \text{kV}$$

here K and d have the same meaning as in the equation above. The gap factor K depends mainly on the gap geometry and hence on the field distribution in the gap. Shown in Fig 1.9

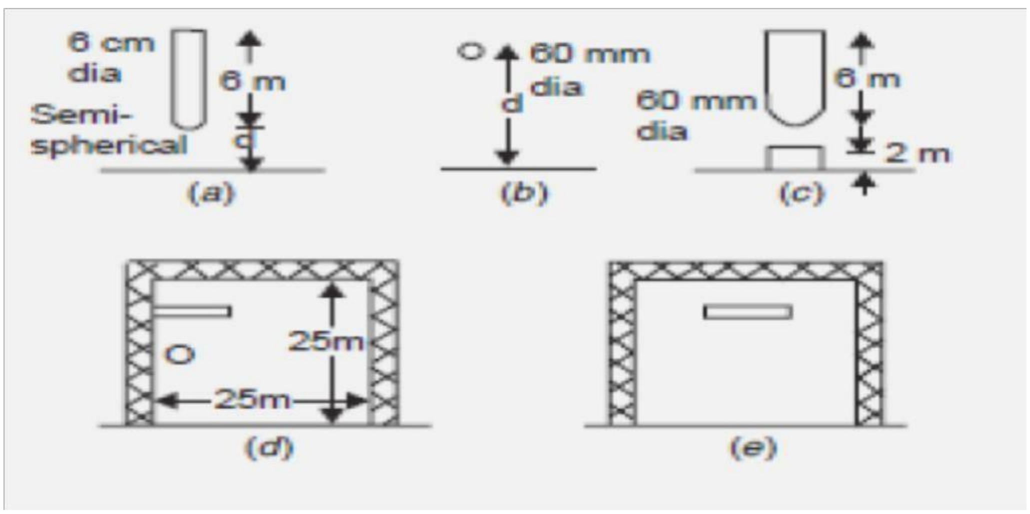


Figure: 1.9 Different gap geometries

1.7 OVERVOLTAGE PROTECTION

The causes of over voltages in the system have been studied extensively in previous sections. Basically, there are two sources: (i) external over voltages due to mainly lightning, and(ii) internal overvoltage mainly due to switching operation. The system can be protected against external over voltages using what are known as shielding methods which do not allow an arc path to form between the line conductors and ground, thereby giving inherent protection in the line design. For protection against internal voltages normally non-shielding methods are used which allow an arc path between the ground structure and the line conductor but means are provided to quench the arc. The use of ground wire is a shielding method whereas the use of spark gaps, and lightning arresters are the non-shielding methods. We will study first the non-shielding methods and then the shielding methods. However, the non shielding methods can also be used for external over voltages.

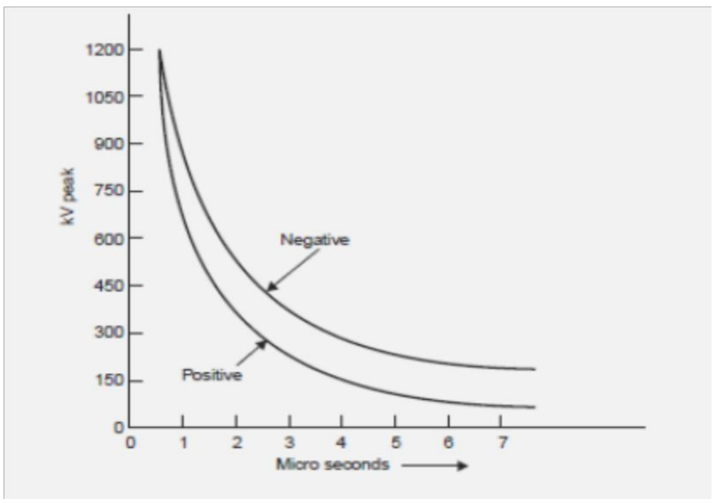


Figure: 1.10 Volt-time curves of gaps for positive and negative polarity

The non-shielding methods are based upon the principle of insulation breakdown as the Overvoltage is incident on the protective device; thereby a part of the energy content in the overvoltage is discharged to the ground through the protective device. The insulation breakdown is not only a function of voltage but it depends upon the time for which it is applied and also it depends upon the shape and size of the electrodes used.

The steeper the shape of the voltage wave, the larger will be the magnitude of voltage required for breakdown; this is because an expenditure of energy is required for the rupture of any dielectric, whether gaseous, liquid or solid, and energy involves time. The energy criterion for various insulations can be compared in terms of a common term known as Impulse Ratio which is defined as the ratio of breakdown voltage due to an impulse of specified shape to the breakdown voltage at power frequency. The impulse ratio for sphere gap is unity because this gap has a fairly uniform field and the breakdown takes place on the field ionization phenomenon mainly whereas for a needle gap it varies between 1.5 to 2.3 depending upon the frequency and gap length. This ratio is higher than unity because of the non-uniform field between the electrodes.

The impulse ratio of a gap of given geometry and dimension is greater with solid than with air dielectric. The insulators should have a high impulse ratio for an economic design whereas the lightning arresters should have a low impulse ratio so that a surge incident on the lightning arrester may be-by passed to the ground instead of passing it on to the apparatus. The volt-time characteristics of gaps having one electrode grounded depend upon the polarity of the voltage wave. From Fig.1.10 it is seen that the volt-time characteristic for positive polarity is lower than the negative polarity, i.e. the breakdown voltage for a negative impulse is greater than for a positive because of the nearness of earthed metal or of current carrying conductors. For post insulators the negative polarity wave has a high breakdown value whereas for suspension insulators the reverse is true.

1.7.1 Horn Gap

The horn gap consists of two horn-shaped rods separated by a small distance. One end of this is connected to be line and the other to the earth as shown in Fig. 1.11, with or without a series resistance. The choke connected between the equipment to be protected and the horn gap serves two purposes: (i) The steepness of the wave incident on the equipment to be protected is reduced. (ii) It reflects the voltage surge back on to the horn.

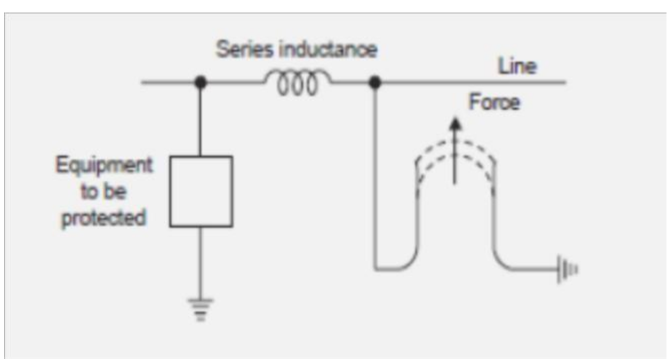


Figure: 1.11 Horn gap connected in the system for protection

Whenever a surge voltage exceeds the breakdown value of the gap a discharge takes place and the energy content in the rest part of the wave is by-passed to the ground. An arc is set up between the gap, which acts like a flexible conductor and rises upwards under the influence of the electro-magnetic forces, thus increasing the length of the arc which eventually blows out. There are two major drawbacks of the horn gap; (*i*) The time of operation of the gap is quite large as compared to the modern protective gear. (*ii*) If used on isolated neutral the horn gap may constitute a vicious kind of arcing ground. For these reasons, the horn gap has almost vanished from important power lines.

1.7.2 Surge Diverters

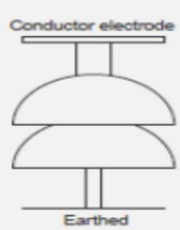
The following are the basic requirements of a surge diverter:

- It should not pass any current at normal or abnormal (normally 5% more than the normal voltage) power frequency voltage.
- It should breakdown as quickly as possible after the abnormal high frequency voltage arrives.
- It should not only protect the equipment for which it is used but should discharge the surge current without damaging itself.
- It should interrupt the power frequency follow current after the surge is discharged to ground.

There are mainly three types of surge diverters: (*i*) Rod gap, (*ii*) Protector tube or expulsion type of lightning arrester, (*iii*) Valve type of lightning arrester.

1.7.3 Rod gap

This type of surge diverter is perhaps the simplest, cheapest and most rugged one. Fig. 1.12 shows one such gap for a breaker bushing.



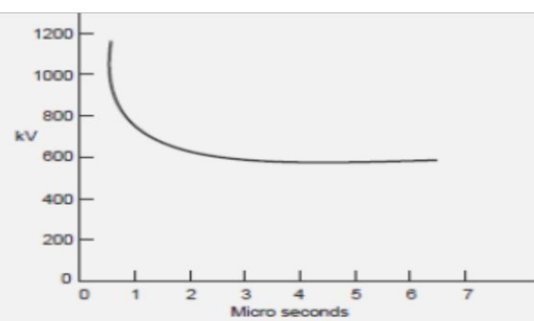


Figure: 1.12 A rod gap

Figure:1.13 Volt-time characteristic of rod gap

This may take the form of arcing ring. Fig. 1.13 shows the breakdown characteristics (volt-time) of a rod gap. For a given gap and wave shape of the voltage, the time for breakdown varies approximately inversely with the applied voltage.

The time to flashover for positive polarity is lower than for negative polarities. Also it is found that the flashover voltage depends to some extent on the length of the lower (grounded) rod. For low values of this length there is a reasonable difference between positive (lower value) and negative flashover voltages. Usually a length of 1.5 to 2.0 times the gap spacing is good enough to reduce this difference to a reasonable amount. The gap setting normally chosen is such that its breakdown voltage is not less than 30% below the voltage withstand level of the equipment to be protected. Even though rod gap is the cheapest form of protection, it suffers from the major disadvantage that it does not satisfy one of the basic requirements of a lightning arrester listed at no. (*iv*) *i.e.,* it does not interrupt the power frequency follow current. This means that every operation of the rod gap results in a *L-G* fault and the breakers must operate to de-energize the circuit to clear the flashover. The rod gap, therefore, is generally used as back up protection.

1.7.4 Expulsion type of lightning arrester

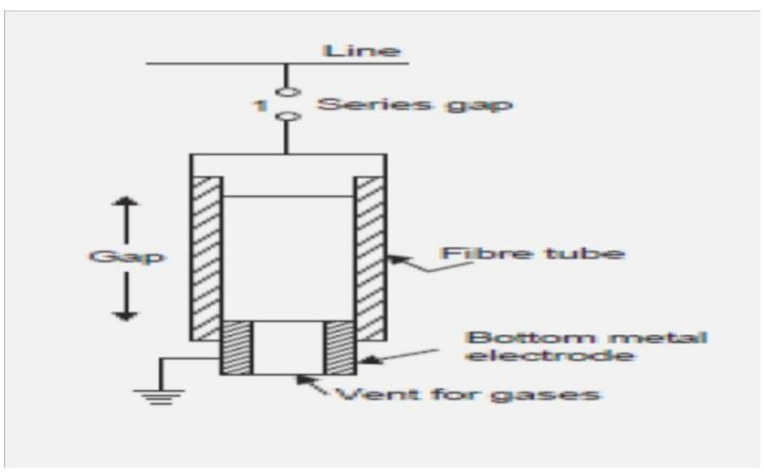


Figure: 1.14 Expulsion type

An improvement of the rod gap is the expulsion tube which consists of (i) a series gap (1) external to the tube which is good enough to withstand normal system voltage, thereby there is no possibility of corona or leakage current across the tube; (ii) a tube which has a fiber lining on the inner side which is a highly gas evolving material; (iii) a spark gap (2) in the tube; and (iv) an open vent at the lower end for the gases to be expelled (Fig. 1.14). It is desired that the breakdown voltage of a tube must be lower than that of the insulation for which it is used.

1.7.5 Surge Protection of Rotating Machine

A rotating machine is less exposed to lightning surge as compared to transformers. Because of the limited space available, the insulation on the windings of rotating machines is kept to a minimum. The main difference between the winding of rotating machine and transformer is that in case of rotating machines the turns are fewer but longer and are deeply buried in the stator slots. Surge impedance of rotating machines in approx. 1000 Ω and since the inductance and capacitance of the windings are large as compared to the overhead lines the velocity of propagation is lower than on the lines. For atypical machine it is 15 to 20 metres/ μ sec. This means that in case of surges with steep fronts, the voltage will be distributed or concentrated at the first few turns. Since the insulation is not immersed in oil, its impulse ratio is approx. unity whereas that of the transformer is more than 2.0.

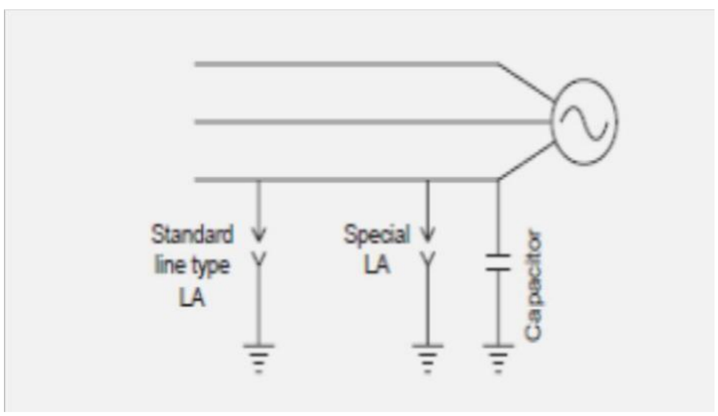
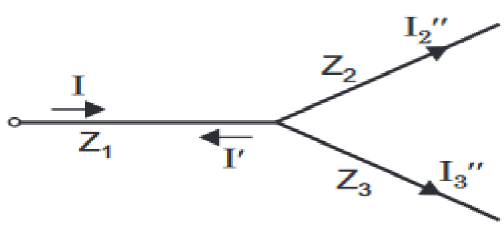


Figure: 1.15 Surge Protection of Rotating Machine

The rotating machine should be protected against major and minor insulations. By major insulation is meant the insulation between winding and the frame and minor insulation means inter-turn insulation. The major insulation is normally determined by the expected line-to-ground voltage across the terminal of the machine whereas the minor insulation is determined by the rate of rise of the voltage. Therefore, in order to protect the rotating machine against surges requires limiting the surge voltage magnitude at the machine terminals and sloping the wave front of the incoming surge. To protect the major insulation a special lightning arrester is connected at the terminal of the machine and to protect the minor insulation a condenser of suitable rating is connected at the terminals of the machine as shown in Fig. 1.15.

1.8 REFLECTION AND REFRACTION OF TRAVELLING WAVES

A voltage wave V is travelling over the line with surge impedance Z_1 as shown BELOW.. When it reaches the junction, it looks a change in impedance and, therefore, suffers reflection and refraction.Let V_2'', I_2'' and V_3'', I_3'' be the voltages and currents in the lines having surge impedances Z_2 and Z_3 respectively. Since Z_2 and Z_3 form a parallel path as far as the surge wave is concerned, $V_2'' = V_3'' = V''$. Therefore, the following relations hold good.



$$V + V' = V''$$

$$I = \frac{V}{Z_1}, I' = -\frac{V'}{Z_1}$$

$$I_2'' = \frac{V''}{Z_2} \quad \text{and} \quad I_3'' = \frac{V''}{Z_3}$$

and $$I + I' = I_2'' + I_3''$$

Substituting in equation (7.13) the values of currents

$$\frac{V}{Z_1} - \frac{V'}{Z_1} = \frac{V''}{Z_2} + \frac{V''}{Z_3}$$

Substituting for $V' = V'' - V$,

$$\frac{V}{Z_1} - \frac{V'' - V}{Z_1} = \frac{V''}{Z_2} + \frac{V''}{Z_3}$$

$$\frac{2V}{Z_1} = V''\left(\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}\right)$$

or $$V'' = \frac{2V/Z_1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3}}$$

Similarly other quantities can be derived.

1.9 INSULATION COORDINATION AND OVERVOLTAGE PROTECTION

Insulation coordination means the correlation of the insulation of the various equipments in a power system to the insulation of the protective devices used for the protection of those equipments against over voltages. In a power system various equipments like trans-formers, circuit breakers, bus supports etc. have different break-down voltages and hence the volt-time characteristics. In order that all the equipments should be properly protected it is de-sired that the insulation of the various protective devices must be properly coordinated. The basic concept of insulation co ordination is illustrated in Fig.1.16. Curve A is the volt-time curve of the protective device and B the volt-time curve of the equipment to be protected. Fig. 1.16 shows the desired positions of the volt-time curves of the protecting device and the equipment to be protected. Thus, any insulation having a withstand volt-age strength in excess of the insulation strength of curve B is protected by the protective device of curve A. The 'volt-time curve' expression will be used very frequently in this chapter. It is, therefore, necessary to understand the meaning of this expression.

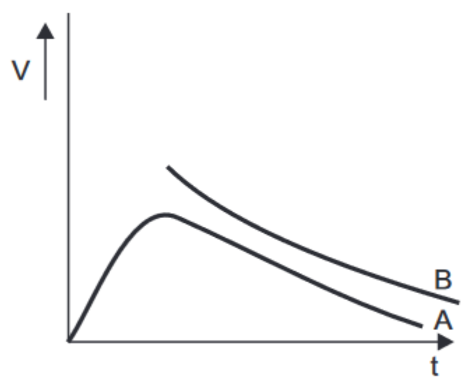


Figure 1.16 Volt-Time curve

Volt-Time Curve

The breakdown voltage for a particular insulation of flashover voltage for a gap is a function of both the magnitude of voltage and the time of application of the voltage. The volt-time curve is a graph showing the relation between the crest flashover voltages and the time to flashover for a series of impulse applications of a given wave shape. For the construction of volt-time curve the following procedure is adopted. Waves of the same shape but of different peak values are applied to the insulation whose volt-time curve is required. If flashover occurs on the front of the wave, the flashover point gives one point on the volt-time curve. The other possibility is that the flashover occurs just at the peak value of the wave; this gives another point on the V-T curve. The third possibility is that the flashover occurs on the tail side of the wave. In this case to find the point on the V-T curve, draw a horizontal line from the peak value of this wave and also draw a vertical line passing through the point where the flash over takes place. The intersection of the horizontal and vertical lines gives the point on the V-T curve. This procedure is nicely shown in Fig.1.17

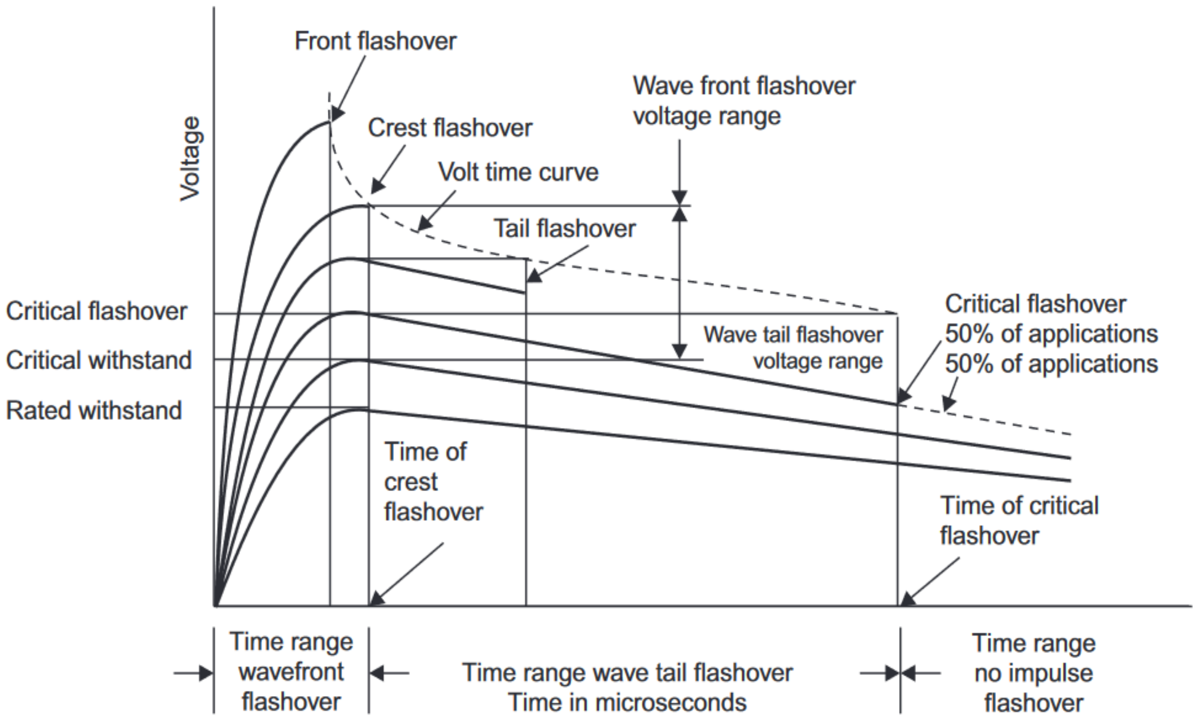


Figure 1.17 Volt-Time curve (construction)

The over voltages against which coordination is required could be caused on the system due to system faults, switching operation or lightning surges. For lower voltages, normally up to about 345 kV, over voltages caused by system faults or switching operations do not cause damage to equipment insulation although they may be detrimental to protective devices. Over voltages caused by lightning are of sufficient magnitude to affect the equipment insulation whereas for voltages above 345 kV it is these switching surges which are more dangerous for the equipments than the lightning surges. The problem of coordinating the insulation of the protective equipment involves not only guarding the equipment insulation but also it is desired that the protecting equipment should not be damaged. To assist in the process of insulation coordination, standard insulation levels have been recommended. These insulation levels are defined as follows. Basic impulse insulation levels (BIL) are reference levels expressed in impulse crest voltage with a standard wave not longer than 1.2/50 μ sec wave. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the basic insulation level. The problem of insulation coordination can be studied under three steps:

1. Selection of a suitable insulation which is a function of reference class voltage (i.e.,1.05× operating voltage of the system). Table 1 gives the BIL for various reference class voltages.

Table 1 Basic impulse insulation levels

Reference class kV	*Standard Basic impulse level kV*	*Reduced insulation levels*
23	150	
34.5	200	
46	250	
69	350	
92	450	
115	550	450
138	650	550
161	750	650
196	900	
230	1050	900
287	1300	1050
345	1550	1300

2. The design of the various equipments such that the breakdown or flashover strength of all insulation in the station equals or exceeds the selected level as in (1).
3. Selection of protective devices that will give the apparatus as good protection as can be justified economically.

The above procedure requires that the apparatus to be protected shall have a withstand test value not less than the kV magnitude given in the second column of Table 1, irrespective of the polarity of the wave positive or negative and irrespective of how the system was grounded. The third column of the table gives the reduced insulation levels which are used for selecting insulation levels of solidly grounded systems and for systems operating above 345 kV where switching surges are of more importance than the lightning surges. At 345 kV, the switching voltage is considered to be 2.7 p.u., i.e.,345 × 2.7 = 931.5 kV which corresponds to the lightning level. At

500 kV, however,2.7 p.u. will mean 2.7 × 500 = 1350 kV switching voltage which exceeds the lightning voltage level. Therefore, the ratio of switching voltage to operating voltage is reduced by using the switching resistances between the C.B. contacts. For 500 kV it is has been possible to obtain this ratio as 2.0 and for 765 kV it is 1.7. With further increase in operating voltages, it is hoped that the ratio could be brought to 1.5.So, for switching voltages the reduced levels in third column are used i.e., for 345 kV, the standard BIL is 1550 kV but if the equipment can withstand even 1425 kV or 1300 kV it will serve the purpose.

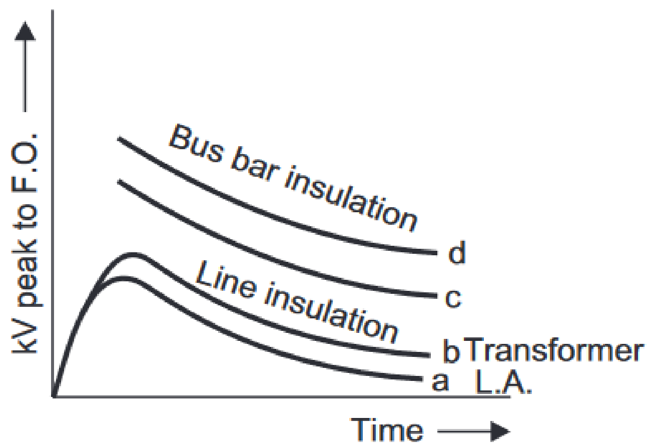


Figure 1.18 Volt-Time Curves

Fig. 1.18 gives the relative position of the volt-time curves of the various equipments in a substation for proper coordination. To illustrate the selection of the BIL of a trans-former to be operated on a 138 kV system assume that the transformer is of large capacity and its star point is solidly grounded. The grounding is such that the line-to-ground voltage of the healthy phase during a ground fault on one of the phases is say 74% of the normal L-L voltage. Allowing for 5% overvoltage during operating conditions, the arrester rms operating voltage will be 1.05 × 0.74 × 138 = 107.2 kV. The nearest standard rating is 109 kV. The characteristic of such a L.A. is shown in Fig. 7.19. From the figure the breakdown value of the arrester is 400 kV. Assuming a 15% margin plus 35 kV between the insulation levels of L.A. and the transformer, the insulation level of transformer should be at least equal to 400 + 0.15 × 400 + 35 = 495 kV. From Fig. 7.19 (or from the table the reduced level of transformer for 138 kV is 550 kV) the insulation level of transformer is 550 kV; therefore a lightning arrester of 109kV rating can be applied.

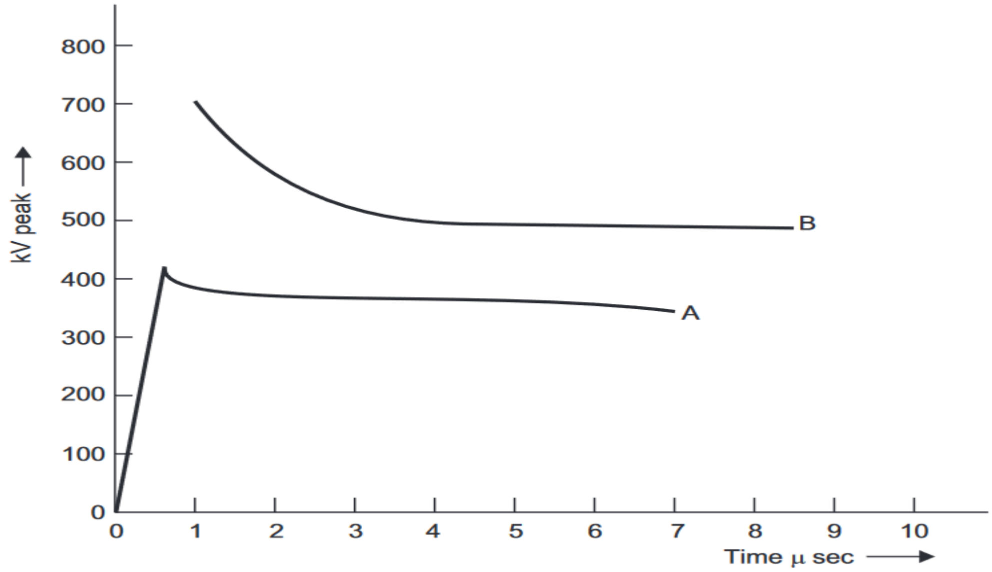


Figure 1.19 Coordination of transformer insulation with lightning arrester

It is to be noted that low voltage lines are not as highly insulated as higher voltage lines so that lightning surges coming into the station would normally be much less than in a higher voltage station because the high voltage surges will flashover the line insulation of low voltage line and not reach the station. The traditional approach to insulation coordination requires the evaluation of the highest over voltages to which equipment may be subjected during operation and selection of standardized value of withstand impulse voltage with suitable safety margin. However, it is realized that over voltages are a random phenomenon and it is uneconomical to design plant with such a high degree of safety that they sustain the infrequent ones. It is also known that insulation designed on this basis does not give100% protection and insulation failure may occur even in well designed plants and, therefore, it is desired to limit the frequency of insulation failures to the most economical value taking into account equipment cost and service continuity. Insulation coordination, therefore, should be based on evaluation and limitation of the risk of failure than on the prior choice of a safety margin.

TEXT / REFERENCE BOOKS

1. M. S. Naidu and V. Kamaraju, ‘High Voltage Engineering’, 5thEdition Tata McGraw Hill Publishing Co. Ltd., New Delhi, 2013.
2. E.Kuffel and M.Abdullah, “High Voltage Engineering” -Per gammon Press, Oxford, 1970.
3. C.L.WADHWA, “High Voltage Engineering” -New Age International (P) Ltd, Publishers, 2007
4. E.Kuffel and W.s. Zaengal, “High Voltage Engineering Fundamentals”,2nd Edition, Butterworth Heinemann, 2000.
5. H.M.Ryam, “High voltage Engineering and testing”, 2nd Edition, 2001, IEEE power and energy series 32.

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - II
High Voltage Engineering – SEE1402

UNIT - II

1. CONDUCTION AND BREAKDOWN IN GASES

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

BACK GROUND MATERIAL
Recollect kinetic theory of gases (Developed by Maxwell)

PV=nRT where numerically R is equal to 8.314 joules/□Kmol.
The fundamental equation for the kinetic theory of gas is derived with the following assumed conditions:

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

1.1 Gases as Insulating Media

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

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

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

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

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

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

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

1.2 Ionization Process

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

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

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

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

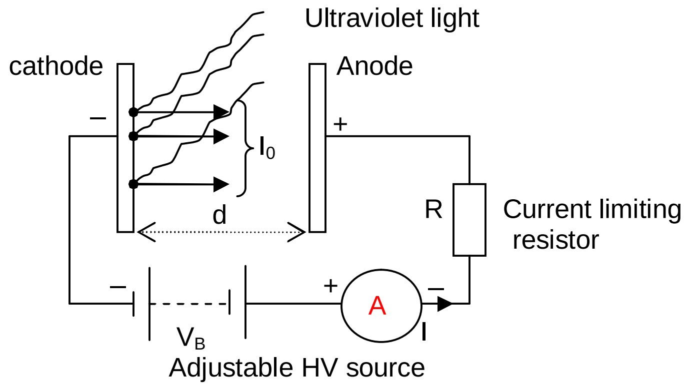


Fig. 1.1 Arrangement for study of a Townsend discharge

1.3 Townsend's Current Growth Equation

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

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

and

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

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

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

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

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

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

1.4 Current Growth Equation in the Presence of Secondary Processes

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

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

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

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

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

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

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

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

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

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

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

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

1.5 Townsend's Criterion for Breakdown

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

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

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

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

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

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

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

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

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

1.5.1 Determination of Townsend's Coefficients α and γ

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

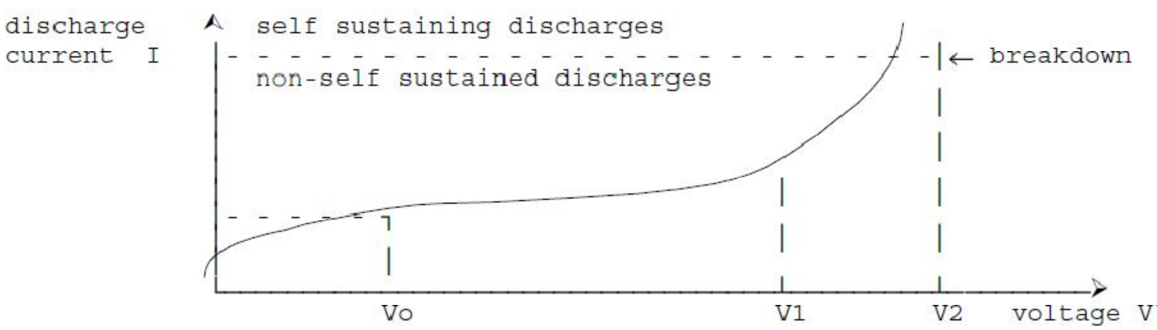


Fig.1.2 Growth of Current in gaseous dielectrics

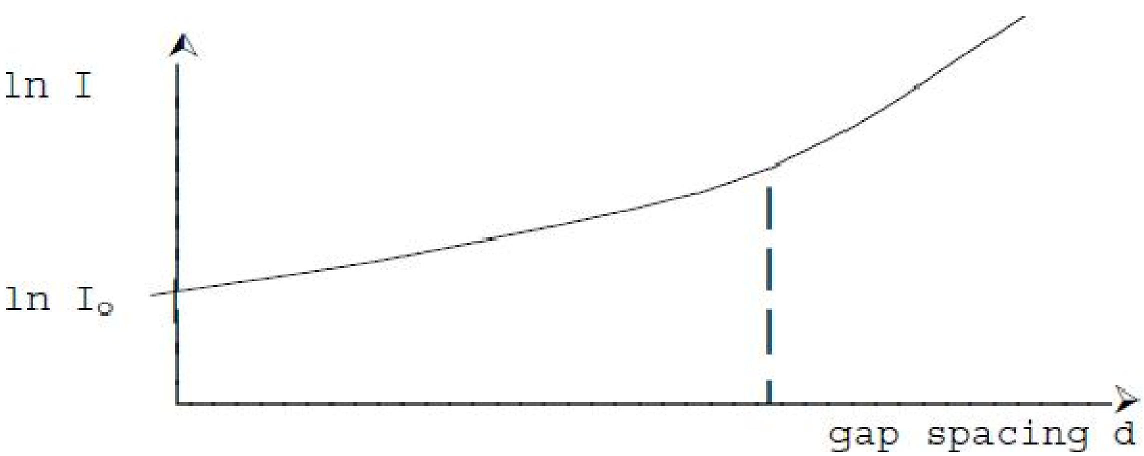


Fig.1.3 Plot of ln I vs. gap spacing d to determine the coeeficients α and γ

1.6 Breakdown in Electronegative Gases

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

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

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

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

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

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

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

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

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

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

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

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

1.7 Paschen's Law

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

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

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

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

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

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

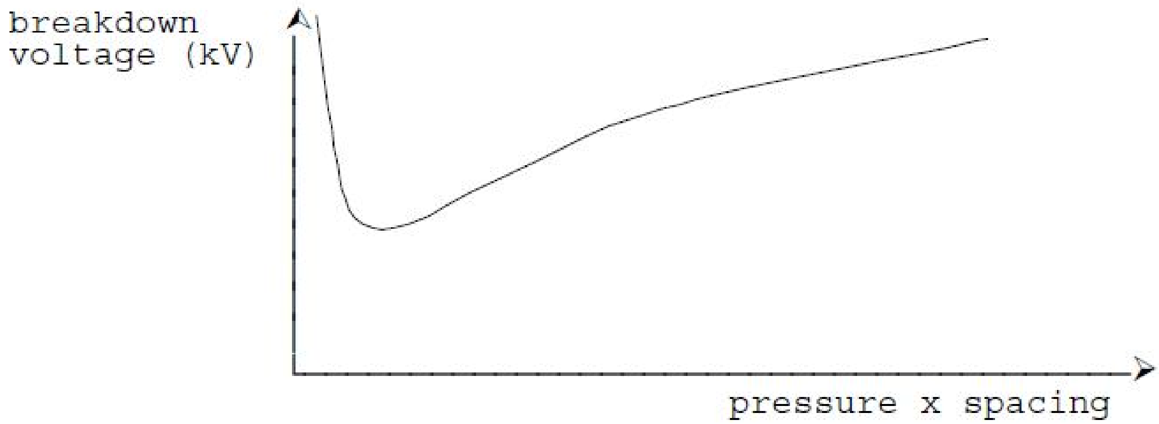


Fig.1.4 Variation of Breakdown voltage vs. pd

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

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

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

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

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

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

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

At 760 torr and 293˚K

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

1.8 Time Lags for Breakdown

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

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

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

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

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

(i) Statistical Time lag t_s

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

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

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

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

then, the average time lag

$$t_s = 1/(ß\, P_1\, P_2)$$

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

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

(ii) Formative time lag(t_f)

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

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

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

(iii) Time lag characteristics

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

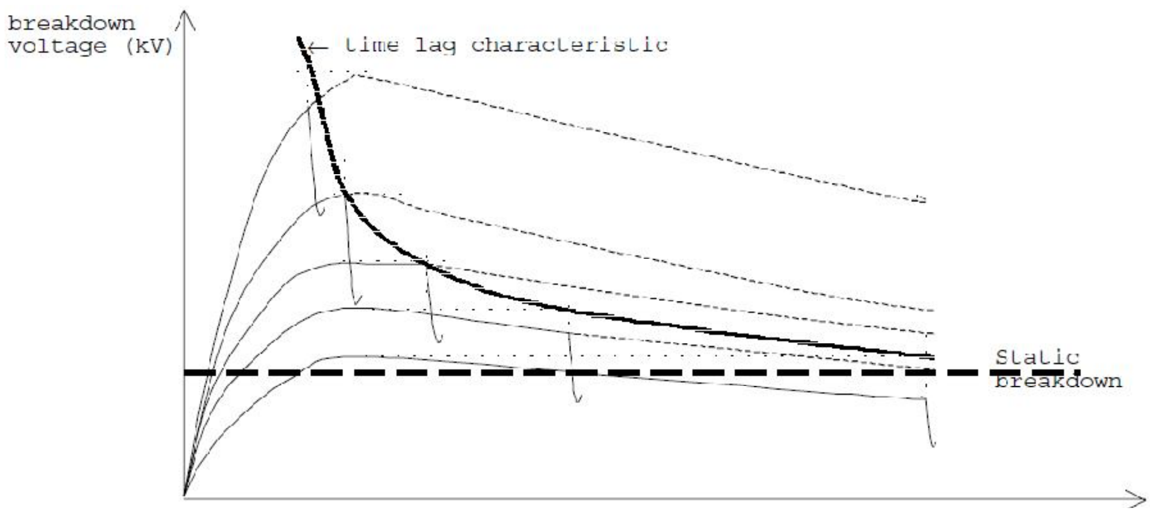


Fig.1.5 Time lag characteristic based on impulse waveform

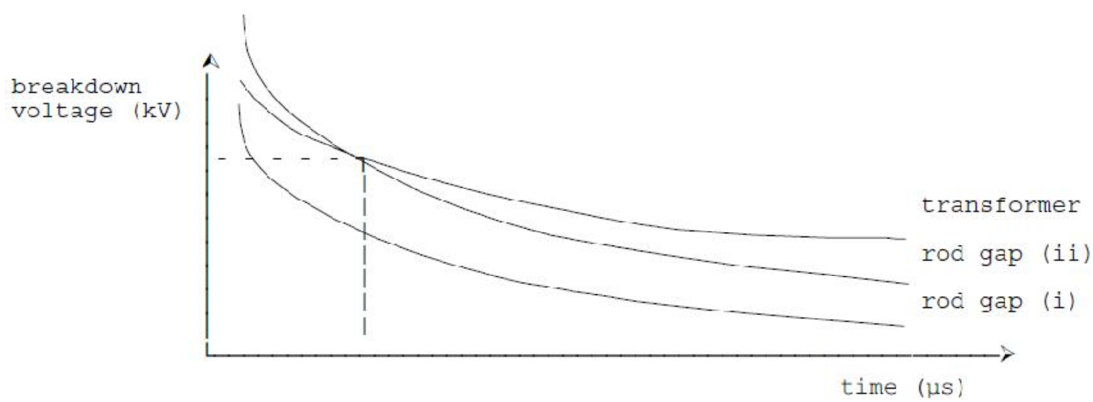


Fig.1.6 Voltage Time characeteristics

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

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

1.9. Limitations of Townsend Theory

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

1.10 Streamer Theory of Breakdown in Gases

According to the Townsend theory;

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

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

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

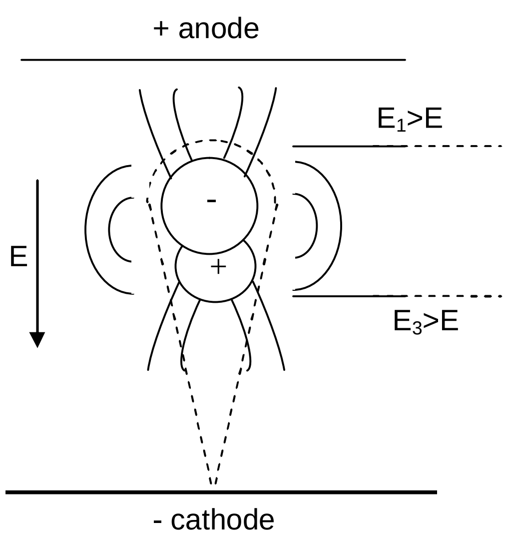


Fig.1.7 Effect of space charge produced by an avalanche on the applied electric field

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

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

$E_r = 5.27 \times 10^{-7} \frac{\alpha e^{\alpha x}}{\sqrt{x/p}} \frac{V}{cm}$ where α is the Townsend's first ionization coefficient, p is the gas pressure in torr and x is the distance to which the streamer has extended in the gap. When $E_r = E$ and $x = d$ the equation above simplifies into;

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

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

1.11 Breakdown in non-uniform field and Corona Discharges

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

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

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

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

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

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

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

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

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

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

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

1.12 Post-Breakdown Phenomena and Applications

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

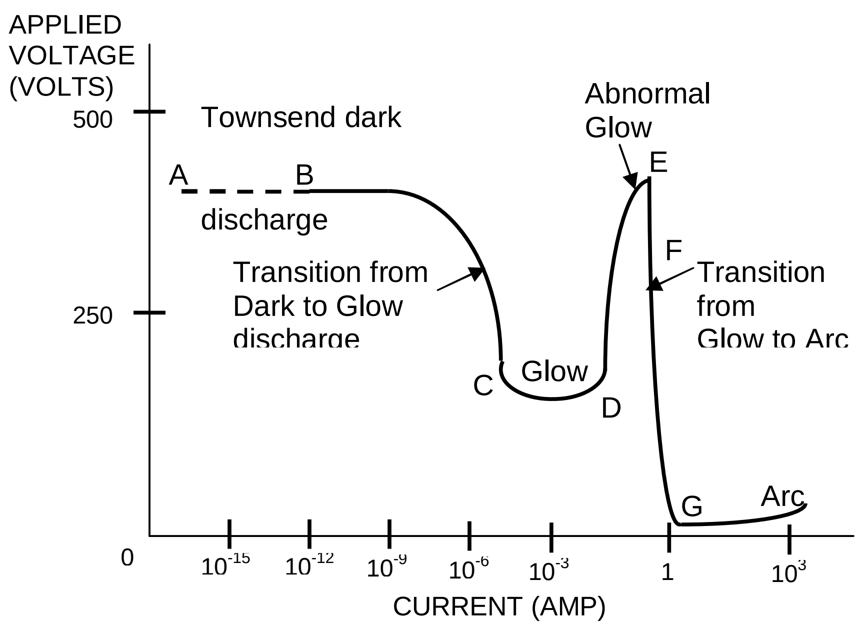


Fig.1.8 DC. voltage current characteristic at an electrical discharge with electrodes having no sharp points or edges

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

Atmospheric pressure air plasmas have potential applications in biomedical and surface treatment, chemical and biological decontamination, aerodynamic flow control, and combustion. Many of these applications require diffuse non-thermal i.e., glow discharges to meet requirements of large volume, low power, high chemical reactivity, and low gas temperature. At atmospheric pressure, glow discharges in air easily transition into spark discharges that significantly heat the gas, which is problematic for applications sensitive to temperature.

1.12.1 Glow Discharge(low-current, high-voltage discharge.)

A glow discharge is characterized by a diffused luminous glow. The color of the glow discharge depends on the cathode materials and the gas used. The glow discharge covers the cathode partly and the space between the cathode and the anode will have intermediate dark and bright regions. In a glow discharge the voltage drop between the electrodes is substantially constant, ranging from 75 to 300 V over a current range of 1 mA to 100 mA depending on the type of the gas. The properties of the glow discharge are used in many practical applications, such as, voltage regulation (VR) tubes, for rectification and as an amplifier. Corona is the name given to glow discharges at high pressure near points of high fields, usually caused by a small radius of curvature. Points are an obvious place for corona, and this is their intention in lightning rods. High tension conductors are another good place, but here it is very undesirable.

1.12.2 Arc Discharge(a high-current, low-voltage discharge)

If the current in the gap is increased to about 1 A or more, the voltage across the gap suddenly reduces to a few volts (20-50 V). The discharge becomes very luminous and noisy (region EG). The current density over the cathode region increases to very high values of 10^3 to $10^7 \, A/cm^2$. Arcing is associated with high temperature, ranging from 1000˚C to several thousands degrees celcius. The discharge contain very high density of electrons and positive ions, and called as arc plasma. The study of arcs is important in circuit breakers and other switch contacts. It is convenient high temperature high intensity light source. It is used for welding and cutting of metals. It is the light source in lamps such as carbon arc lamp. High temperature plasmas are used for generation of electricity through magneto-hydro dynamic or nuclear fusion processes.

It was Humphrey Davy who investigated the basic spark gap and the nature of the arc between the conductors.

1.13 Write a brief note on CORONA

If the_field is uniform , then an increase in voltage(A.C.) directly leads to breakdown without any preliminary discharge.

However in non-uniform geometry , the increase in a.c. voltage will cause a luminous discharge with the production of hissing noise at points with highest electric field intensity.

This form of discharge is termed as Corona discharge and is accompanied by the formation of ozone , as is indicated by the characteristic order of this gas.

If the voltage is d.c., then the appearance will be different . The positive wire will be having a uniform glow and negative wire has a more patchy glow often accompanied by streamers.

An important point in connection with corona that it is accompanied by a loss of power and this means that there is a flow of current to the wire. The current waveform is nonsinusoidal and the non-sinusoidal drop of volts caused by it may be more important than loss of power. It gives rise to radio interference.

The loss of power during corona discharge leads to deterioration of consulation due to combined action of the bombardment of ions and of the chemical compounds formed during discharges.

1.13.1 Practical Importance of Corona:

1.)Under normal conditions the loss of power due to corona is of no good importance , and consequently corona calculations do not enter directly into transmission line design. The basis of such design is entirely financially the most economical line being the most acceptable.

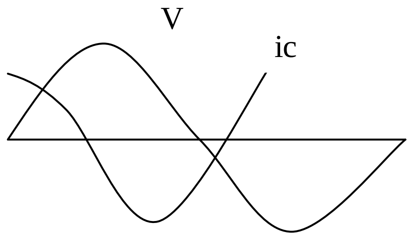
2.)The nonsinusoidal coronal current causes a nonsinusoidal drop of volts and these may cause some interference with neighboring communication (Carrardig TV) circuits due to electromagnetic and electrostatic induction .The current contains large third harmonic.

3.)Average corona loss on several lines from 345 KV to 750 KV gave 1 to 20 KW/Km in fair weather the higher values referring to higher voltages . In foul-weather the losses can go upto 300 KW/Km.

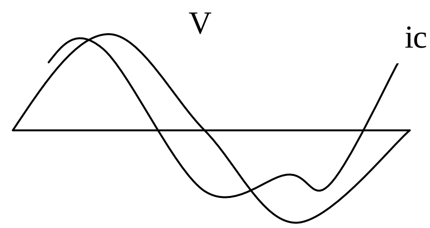
A reasonable estimate of the yearly average loss for 400 Km line is 2 KW/Km to 10 KW/Km and 20-40 KW/Km for 800 Km lines and it is 10% of I^2R loss.

None the less, during rainy months , the generating station has to supply heavy corona loss.

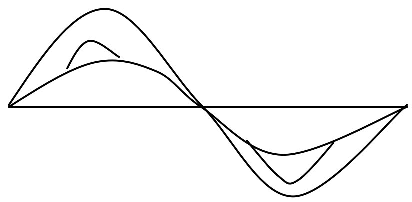
When a line is energized and no corona is present , the current is a pure sine wave and capacitive.It leads the voltage by 90^O as shown in Fig(a).With corona it calls, for a loss component and a typical waveform of the total current is as shown in Fig(b). When the two components are separated ,the resulting inphase component has a waveform which is not purely sinusoidal (Fig.(c)). It is still a current at power frequency , but only the fundamental component of this distorted current can result in power loss.



(a)



(b)



(c)

4.)An advantage of corona is that it reduces transients , since charges induced on the line by lightning or other causes will be partially dissipated as a corona loss . In this way it acts as a safety value , and in one or two cases , lines have been purposely designed to have an operating voltage near to critical voltage in order to do away with the necessity for, and expense of lightning arrestor gear. An objection to this scheme is that the critical voltage is not fixed for a given line , but may vary considerably with changes in weather.

5.)Audible noise: generation and characteristics.

When corona is present on the conductors EHV lines generate audible noise which is especially high during foul weather . The noise is in broad band , which extends from a very low frequency to about 20 KHz. Corona discharges generate positive and negative ions which are alternatively attracted and repelled by the periodic reversal of polarity of the ac excitation . Their movement gives rise to sound pressure waves at frequencies of twice the power frequency and its multiples in addition to the broadband spectrum which is the result of random motions of the ions as shown in Fig. below. The noise has a pure tone superimposed on the broad band noise. Due to difference in ionic motion between ac and dc excitations, dc lines extend only a broad band noise and it is nearly same for fair and foul weather conditions. Since AN (audible noise) is man-made , measured in the same manner as other types of man-made noise such as aircraft noise, transformer hum etc.

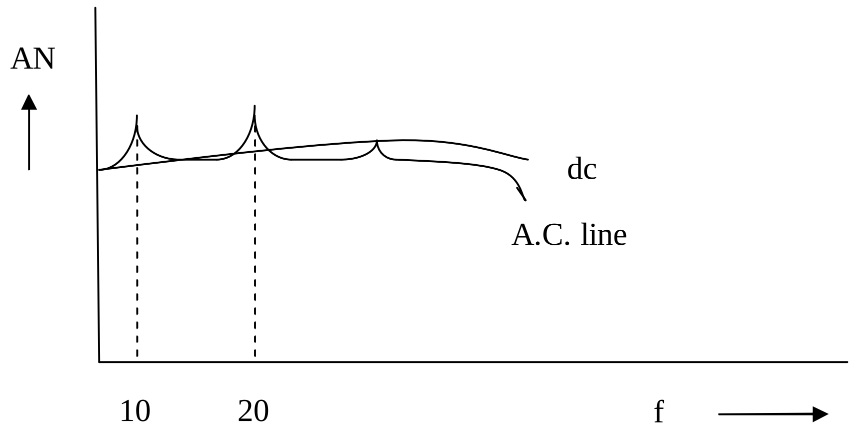


Fig.1.9 Audible noise spectra from ac and dc transmission lines

Audible noise can become a serious problem from a "psycho-acoustics" point of view, leading to insanity due to loss of sleep at night to inhabitants residing close to an lhv line. This problem came into focus in the 1960s with the energisation of 500kV lines in the USA. Regulation bodies have not as yet fixed limits to AN from power transmission lines since such regulations do not exist for other manmade sources of noise. The problem is left as a social one which has to be settled by public opinion.

The audible noise generated by a line is a function of the following factors:

1. The surface voltage greadient on conductor.
2. The number of sub conductors in the bundle.
3. Conductor diameter.
4. Atmospheric conditions.
5. The lateral distance(aerial distance) from the line conductors to the point where noise is to be evaluated.

The AN limits are:

- No complaints: less than 52.5dB
- Few complaints: 52.5 to 59 dB
- Many complaints: greater than 59dB

<u>Radio interference:</u>

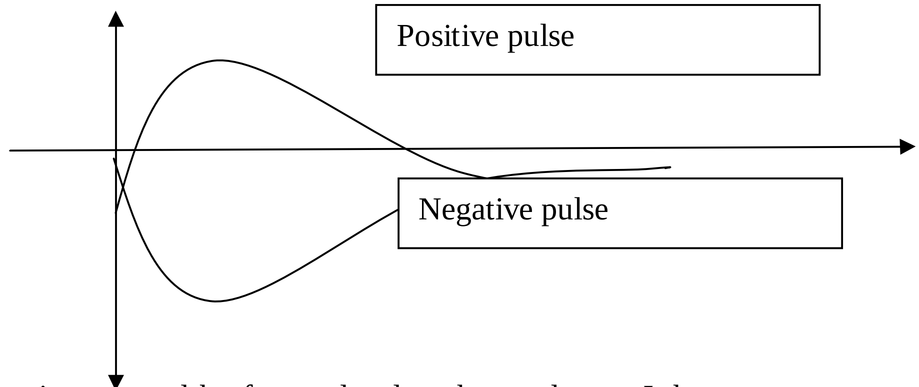
There are in general two types of corona discharge from transmission line conductors

1. Pulse less or glow corona
2. Pulse type or streamer corona.

Both give rise to energy loss, but only the pulse type of ma gives interference to radio broadcast in the range of 5MHz to 1.6MHz. Besides thin, sparked discharges from bnroken insul;ators and loose guy wives interfere with TV reception in the 80-200MHz range. Corona on conductors also causes interference to carrier communication and signalling in the frequency range 30kHz to 500kHz.

Mechanism of generation of pulse type corona:

In most gas discharge phenomenon, under high impressed electric fields, free electrons and charged particles(ions) are created in space which contain very few initial electrons. We can expect therefore a build up of resulting current in the conductor, from a zero value to a maximum or peak. Once the peak value is reached there is a fall in current because of lowering of electric field due to relatively heavy immobile space chargew cloud which lowers the velocity of ions. We can therefore expect pulses to be generated with short rest times and relatively longer fall times.



The repetition rate of pulses is governed by factors local to the conductor. It has been observed that only one pulse usually occurs during a positive half that only one pulse usually occurs during a positive half cycle in fair weather and could increase to 10 in rain if the conductor is +ve.

The situation when the conductor is negative is reverse. The electron avalanche moves away from conductor. Heavy positive ions more in the direction of high field. The lighter electrons move rapidly away from the conductor and the electrical field near the conductor regains its original value for the next pulse generation quicker than the positive case. Therefore negative pulses are smaller in amplitude, have much smaller rise and fall times but much higher repetition rates than positive pulses. The negative pulses are called Trichel pulses. Typical average values of pulse properties:

Type	Time to crest (ns)	Time to 50% on tail(ns)	Peak value of current (in mA)	Repetition rate pulses per second	
				AC	DC
Positive	50	200	100	50	1000
Negative	20	50	10	100*p.f.	10000

Pulses are larger as the diameter of conductor increases because the reduction in electric field strength as one moves away from the conductor is not as steep as for a small conductor so that conditions for longer pulse duration are more favourable.

RI level is governed by amplitude, wave shape and repetition rate of pulses.

1.14 Practical considerations in using gases for insulation purposes

The gases find wide application in power system to provide insulation to various electrical equipments 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(widely used and cheapest) (*ii*) oxygen (*iii*) hydrogen(better arc quenching) (*iv*) nitrogen (*v*) CO2 and (*vi*) electronegative gases like sulphur hexafluoride,(SF_6) (outstanding arc quenching and dielectric strength) or arcton(or Chlorodifluoromethane (HCFC 22)) etc.
For high voltage power applications, the gaseous insulation should possess the following properties

(a)high dielectric strength,
(b) thermal stability and chemical inactivity towards materials of construction,
(c) non-flammability and physiological intertness,
(d) low temperature of condensation,
(e) good heat transfer(Thermal Conductivity), and
(/) Commercial availability at moderate cost
Dielectric strength of a gaseous dielectric is the most important property for practical use. The dielectric strength of gases is comparable with those of solid and liquid dielectrics (see Fig. 1.9). In recent years, the dielectric properties of many complex chlorinated and flourinated molecular compounds have also been studied. These are shown in Fig. 1.10. This feature of high dielectric strength of gases is attributed to the molecular complexity and the high rates of electron attachment.

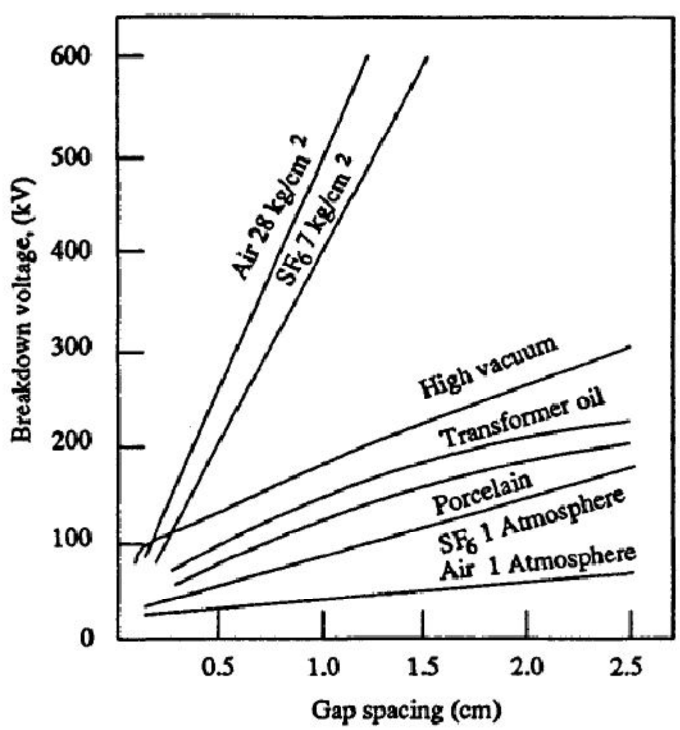


Fig.1.9 DC breakdown strength of typical solid, liquid, gas and vacuum insulations in uniform fields.

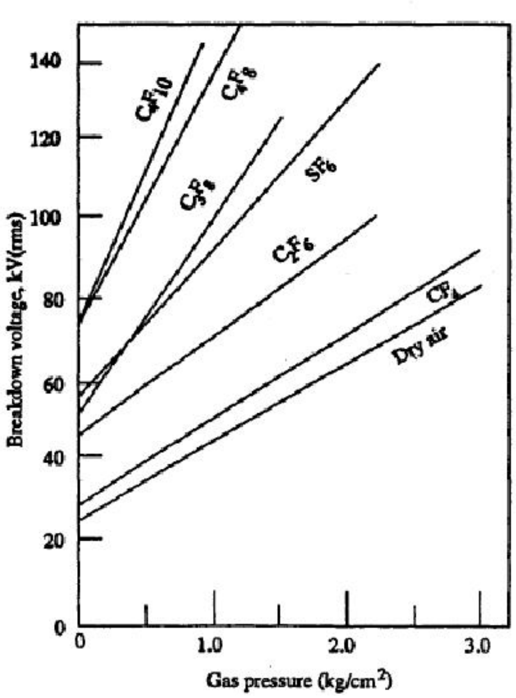


Fig.1.10 Breakdown Strength of insulating gases for 75cm diameter uniform field electrodes having 12mm gap.

SF_6 has high dielectric strength and low liquification temperature, and it can be used over a wide range of operating conditions. SF_6 was also found to have excellent arc-quenching properties. Therefore, it is widely used as an insulating as well as arc-quenching medium in high voltage apparatus such as high voltage cables, current and voltage transformers, circuit breakers and metal encapsulated substations. It may also be noted that addition of 30% SF_6 to air (by volume) increases the dielectric strength of air by 100%. One of the qualitative effects of mixing SF_6 to air is to reduce the overall cost of the gas, and at the same time attaining relatively high dielectric strength or simply preventing the onset of corona at desired operating voltages.

Old End Semester University questions

1. Derive the current growth equation in electronegative gases.

2.Differentiate elastic and inelastic collision. Explain how Townsend criterion enables the breakdown voltage of the gap.

3. In an experiment to measure α for a certain gas, it was found that the steady current is 3.8×10^{-8} A at a voltage of 8 kV and at a distance of 4 mm between the plane electrodes. Keeping the field constant and reducing the distance to 1 mm resulted in a current of 3.8×10^{-9} A.

(a) Calculate α;

(b)Calculate the number of electrons emitted from the cathode to anode;

(c) Determine the electrode spacing that would lead to an electron multiplication factor of 10^{-8}.

4.What is Paschen's law? How do you account for the minimum voltage under a given PD condition? State its value for Air

5.Two plane circular electrodes of diameter=40cm each and separated by 5 mm gap shows a current of 100nA on application of 10 kV at NTP. Keeping the applied field constant and reducing the distance to 2mm results a current of 4000pA. Calculate Townsend's primary ionization coefficient.

6.Define statistical time lag and formative time lag to breakdown. Show with V-t diagram, that sphere to sphere gap can be used for protection of Bushing as well as Transformers. Rod-rod gap is for Bushing protection only.

MODULE-II

CONDUCTION AND BREAKDOWN IN LIQUID DIELECTRICS

2.1Introduction

Liquid dielectrics are used mainly spreading through in high voltage cables and capacitors and for filling transformers, circuit breakers, etc. In addition to their function as a dielectric, liquid dielectrics have additional functions in certain applications. For example, liquid dielectrics act as heat transfer agents(i.e. for cooling) in transformers and as arc quenching media in circuit breakers. Petroleum oils are most commonly used as liquid dielectrics. For certain applications Synthetic hydrocarbons and halogenated hydrocarbons and for very high temperature applications, silicone oils and fluorinated hydrocarbons are used. In recent times, certain vegetable oils and esters are also being used.

Liquid dielectrics normally are mixture of hydrocarbons and are weakly polarized. When used for electrical insulation purposes they should be free from moisture, products of oxidation, and other contaminants. The most important factor that affects the electrical strength of insulating oil is the presence of water in the form of fine droplets suspended in the oil. The presence of even 0.01 % water in transformer oil reduces the electrical strength to 20 % of the dry oil value. The dielectric strength of the oil reduces more sharply, if it contains fibrous impurities in addition to water. The three most important properties, of liquid dielectrics are

(i)the electrical conductivity,

(ii)dielectric constant, and

(iii)the dielectric strength.

In addition, the physical and chemical properties such as viscosity, thermal stability, specific gravity, etc. are also important. Examples for the breakdown strength at 20˚C on 2.5 mm standard sphere gap are15 kV/mm for Transformer Oil, 30 kV/mm for Cable Oil, 20 kV/mm for Capacitor Oil, 20-25 kV/mm for Askarels, 30-40 kV/mm for Silicone Oils. In practice, the choice of a liquid dielectric for a given application is made mainly on the basis of its **chemical stability**.

In addition, other factors like ***saving of space, cost, previous usage, and susceptibility to the environmental influences*** are also considered. In capacitors, replacement of the capacitor oil by askarel spreading through in the overall size of the capacitor by more than 30%. In practice, a liquid found satisfactory over a long period of usage is preferred to a new one. Petroleum liquid are widely used because of their low cost.

2.2 PURE LIQUIDS AND COMMERCIAL LIQUIDS

Pure liquids are those which are chemically pure and do not contain any other impurity even in traces of 1 in 10^9, and are structurally simple.

Examples of such simple pure liquids are :

n-hexane (C_6H_{14}). n-heptane (C_7H_{16}) and other paraffin hydrocarbons.

By using simple and pure liquids, it is easier to separate out the various factors that influence condition and breakdown in them.

On the other hand, the commercial liquids which are insulating liquids like oils, not chemically pure, normally consist of mixture of complex organic molecules which cannot be easily specified or reproduced in a series of experiments.

2.2.1 Purification

The main impurities in liquid dielectrics are dust, moisture, dissolved, gases and ionic impurities. Various methods employed for purification are filtration (through mechanical filters, spray filters, and electrostatic filters), centrifuging, degassing and distillation, and chemical treatment (adding ion exchange material such as alumina, fuller's earth etc. filtering).

Dust particles when present become charged and reduce the breakdown strength of the liquid dielectrics, and they can be removed by careful filtration.

Liquid will normally contain moisture and dissolved gases in small quantities. Gases like oxygen and carbon dioxide significantly affect the breakdown strength of the liquids, and hence it is necessary to control the amount of gas present. This is done by distillation and degassing.

Ionic impurity in liquids, like water vapor which easily dissociates, leads to very high conductivity and heating of the liquid depending on the applied electric field. Water is removed using drying agents or by vacuum drying.

Sometimes, liquids are shaken with concentrated sulphuric acid to remove wax and residue and washed with caustic soda and distilled water. A commonly used closed-cycle liquid purification system to prepare liquids as per the above requirements is shown in Fig.2.1.

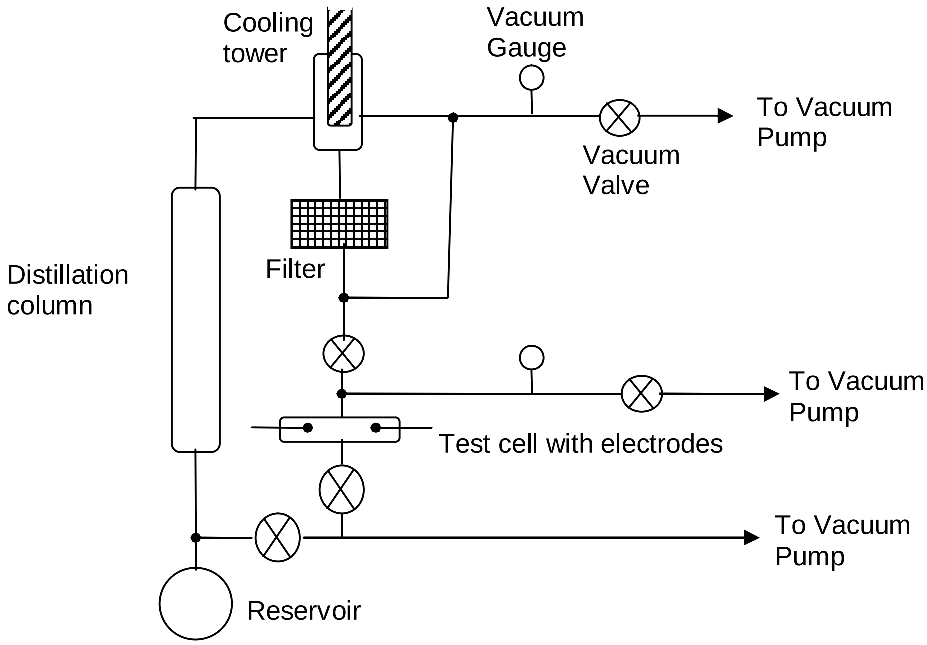


Fig. 2.1 Liquid purification system with test cell.

This system provides for cycling the liquids. The liquid from the reservoir flows through the distillation column where ionic impurities are removed. Water is removed by drying agents or frozen out in the low-temperature bath. The gases dissolve in the liquid are removed by passing them through the cooling tower and/or pumped out by the vacuum pumps. The liquids then passes thought the filter where dust particles are removed. The liquid thus purified is then use in the test cell. The used liquid then flows back into the reservoir. The vacuum system thus helps to remove the moisture and other gaseous impurities.

OIL Breakdown Tests

Breakdown tests are normally conduced using test cell. For testing pure liquids, the test cells used are small so that less quantity of liquid is used during testing. Also, test cells are usually an integral part of the purification system as shown in Fig. 3.1. The electrodes used for breakdown voltage measurement are usually spheres of 0.5 to 1 cm in diameter with gap spacing of about 100-200 µm. The gas is accurately controlled by using a micrometer. Electrode separation is very critical in measurement with liquids, and also the electrode surface smoothness and the presence of oxide films have a marked influence on the breakdown strength. The test voltages required for these tests are usually low, of the order of 50-100 kV, because of small electrode spacing. The breakdown strengths and d.c conductivities obtained in pure liquids are very high, of the order of 1 MV/cm and 10^{-18}-10^{-20} mho/cm respectively, the conductivity being measured at electric field of the order of 1 kV/cm. However, the corresponding values in commercial liquids are relatively low.

2.2 CONDUCTION AND BREAKDOWN IN PURE LIQUIDS

When low electric fields less than 1 kV/cm are applied, conductivities of 10^{-18} - 10^{-20} mho/cm are obtained. These are probably due to the impurities remaining after purification. However, when the fields are high (>100kV/cm) the currents not only increase rapidly, but also undergo violent fluctuations which will die down after some time. A typical mean value of the conduction current in hexane is shown in Fig. 2.2. This is the condition nearer to breakdown.

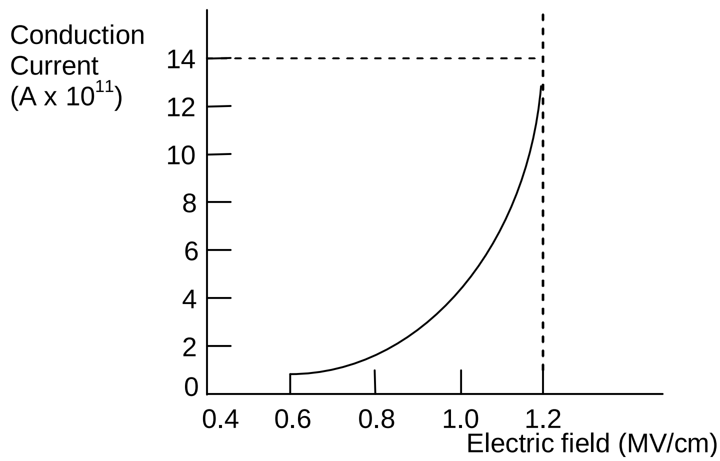


Fig.2.2 Conduction current-electric field characteristics in hexane at high fields

However, if this figure is redrawn starting from very small currents, a current-electric field characteristics as shown in Fig. 2.3, can be obtained. This curve will have three distinct regions as shown. At very low fields the current is due to the dissociation of ions. With intermediate fields the current reaches a saturation value, and at high fields the current generated because of the field-aided electron emission from the cathode gets multiplied in the liquid medium by a Townsend type of mechanism .The current multiplication also occurs from the electrons generated at the interfaces of liquid and impurities. The increase in current by these processes continues till breakdown occurs. The exact mechanism of current growth is not known; however, it appears that the electrons are generated from the cathode by field emission of electrons.

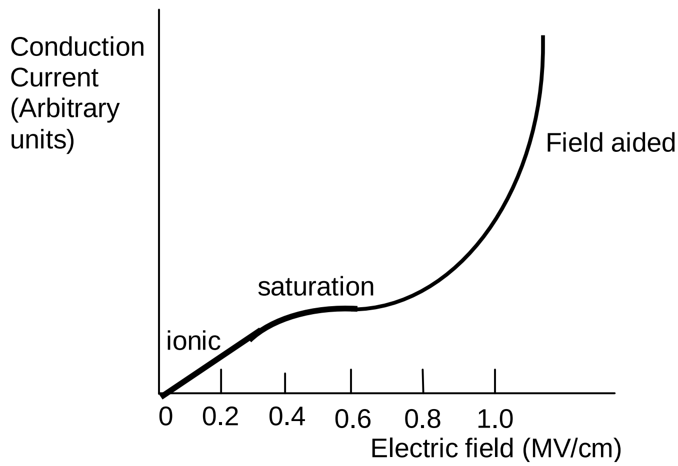


Fig.2.3 Conduction current-electric field characteristics
in hydrocarbon liquid

The electrons so liberated get multiple by a process similar to Townsend's primary and secondary ionization in gases As the breakdown field is approaches, the current increases rapidly due to process similar to the primary ionization process and also the positive ions reaching the cathode generate secondary electrons, leading breakdown. The breakdown voltage depends on the field, gap separation, cathode work-function, and the temperature of the cathode. In addition, the liquid viscosity, the liquid temperature, the density, and the molecular structure of the liquid also influence the breakdown strength of the liquid. Typical maximum breakdown strengths of some highly purified liquids and liquefied gases are given in Table 2.1.

Table 2.1 Maximum Breakdown strength of some liquid

Liquid	Maximum breakdown strength (MV/cm)
Hexane	1.1-1.3
Benzene	1.1
Transformer oil	1.0
Silicone	1.0-1.2
Liquid Oxygen	2.4
Liquid Nitrogen	1.6-1.9
Liquid Hydrogen	1.0
Liquid Helium	0.7
Liquid Argon	1.1-1.42

It has been observed that the increase in breakdown strength is more, if the dissolved gases are electronegative in character (like oxygen). Similarly, the increase in the liquid hydrostatic pressure increases the breakdown strength.

To sum up, this type of breakdown process in pure liquids, called the electronic breakdown, involves emission of electrons at fields greater than 100 kV/cm. This emission occurs either at the electrode surface irregularities or at the interfaces of impurities and the liquid. These electrons get further multiplied by Townsend's type of primary and secondary ionization processes, leading to breakdown.

2.3 CONDUCTION AND BREAKDOWN IN COMMERCIAL LIQUIDS

As already mentioned 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 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) Electronic breakdown**
- **b) Suspended Particle Mechanism**
- **c) Cavitation and Bubble Mechanism**
- **d) Stressed Oil Volume Mechanism**

2.3.1 Electronic breakdown

Both the field emission and the field-enhanced thermionic emission mechanisms discussed earlier have been considered responsible for the current at the cathode. Conduction studies in insulating liquids at high fields show that most experimental data for current fit well the Schottky-type equation in which the current is temperature dependent. Breakdown measurements carried out over a wide range of temperatures, however, show little temperature dependence. This suggests that the cathode process is field emission rather than thermionic emission. It is possible that the return of positive ions and particularly positively charged foreign particles to the cathode will cause local field enhancement and give rise to local electron emission. Once the electron is injected into the liquid it gains energy from the applied field. In the electronic theory of breakdown it is assumed that some electrons gain more energy from the field than they lose in collisions with molecules. These electrons are accelerated until they gain sufficient energy to ionize molecules on collisions and initiate avalanche. The condition for the onset of electron avalanche is obtained by equating the gain in energy of an electron over its mean free path to that required for ionization of the molecule.

$$eE\lambda = ch\nu$$

where E is the applied field, λ the electron mean free path, $h\nu$ the quantum of energy lost in ionizing the molecule and c an arbitrary constant. The electronic theory satisfactorily predicts the relative magnitude of breakdown strength of liquids, but the observed formative time lags are much longer than predicted by electronic theory.

2.3.2 Suspended Particle Theory

Solid impurities may be present in the liquid either as fibres or as dispersed solid particles and their presence of solid impurities cannot be avoided. The permittivity of these particles ϵ_1 will be different from the permittivity of the liquid ϵ_2. If we consider these impurities to be spherical particles of radius r, and if the applied field is E, then the particles experience of force F, where

$$F = r^3 \frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + 2\epsilon_2} E \frac{dE}{dX} \tag{2.1}$$

This force is directed towards areas of maximum stress, if $\varepsilon_2 > \varepsilon_1$, for example, in the case 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. $\varepsilon_2 < \varepsilon_1$, the force will be in the direction of areas of lower stress (opposite direction). 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 area of maximum stress. If the number of particles is large, they become aligned due to these forces, and thus form a stable chain bridging the electrode gap causing a breakdown between the electrodes.

The force given by eqn (2.1) increases as the permittivity of the suspended particle (ε) increases, and for a conducting particle for which $\epsilon_1 \to \infty$ the force becomes

$F = F_\infty = r^3 E \text{ grad } E$

Thus the force will urge the particle to move to the strongest region of the field.

In a uniform field gap or sphere gap of small spacing the strongest field is in the uniform region.In this region grad E is equal to zero so that the particle will remain in equilibrium there. Accordingly, particles will be dragged into the uniform field region. If the permittivity of the particle is higher than that of the medium, then its presence in the uniform field region will cause flux concentration at its surface. Other particles will be attracted into the region of higher flux concentration and in time will become aligned head to tail to form a bridge across the gap. The field in the liquid between the particles will be enhanced, and if it reaches critical value breakdown will follow.

The movement of particles by electrical force is opposed by viscous drag, and since the particles are moving into the region of high stress, diffusion must also be taken into account.

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 value of the breakdown strength of the liquids containing solid impurities was 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.

2.3.3. 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 vapor bubble formed is responsible for breakdown. The following processes have been suggested to be responsible for the formation of the vapor bubbles:

a) Gas pockets at the surface 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; and
d) Vaporization of the liquid by corona type discharges from sharp points and irregularities on the electrode surfaces.

Once a bubble is formed it will elongated (long and thin) 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 electric field in a spherical gas bubble which is immersed in a liquid of permittivity ε_2 is given by $E_b = 3E_0/(\varepsilon_2+2)$ **;** where E_0 is the field in the liquid in the absence of the bubble. When the field E_b becomes equal to the gaseous ionization field, discharge takes place which will lead to decomposition of the liquid and breakdown may follow. Kao has developed more accurate expression for the breakdown field as

$$E_0 = \frac{1}{(\varepsilon_1 - \varepsilon_2)}\left[\frac{2\pi\sigma\left(2_{\varepsilon 1+\varepsilon 2}\right)}{r}\left\{\sqrt{\frac{V_h}{(2rE_0)}} - 1\right\}\right]^{\frac{1}{2}} \qquad (2.2)$$

where σ is the surface tension of the liquid, ε_1 is the permittivity of the liquid, ε_2 is the permittivity of the gas bubble, r is the initial radius of the bubble assumed as a sphere and V_b is the voltage drop in the bubble (corresponding to minimum on the Paschen's curve). From this equation it can be seen that the breakdown strength depends on the initial size of the bubble which in turn is influenced by the hydrostatic pressure and temperature of the liquid. But 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.

In general, the cavitation and bubble theories try to explain the highest breakdown strengths obtainable, considering the cavities or bubbles formed in the liquid dielectrics.

2.3.4. 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 link". 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 (E_{max}) contour and 0.9 (E_{max}) contour. 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. 2.4.

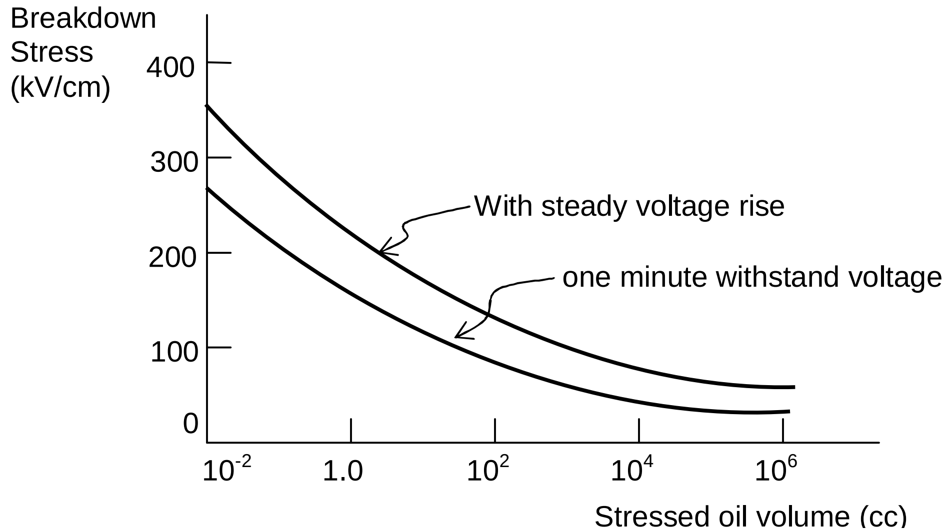


Fig 2.4 Power frequency (50 Hz) a.c breakdown stress as function of stressed oil volume

2.4 CONCLUSIONS

All the theories discussed above do not consider the dependence of breakdown strength on the gap length. They all try to account for the maximum obtainable breakdown strength only. However, the experimental evidence showed that the breakdown strength of a liquid depends on the gap length, given by the following expression,

$$V_b = Ad^n$$

where, d=gap length,
A=constant,and
n=constant,always less than 1.

The breakdown voltage also depends on the nature of the voltage, the mode in which the voltage is applied, and the time of application. The above relationship is of practical importance, and the electrical stress of given oil used in design is obtained from this. During the last ten years, research work is directed on the measurements of discharge inception (starting) levels in oil and the breakdown strengths of large volumes of oil under different conditions.

It may be summarized that the actual mechanism of breakdown in oil is not a simple phenomenon and the breakdown voltages are determined by experimental investigations only. Electrical stresses obtained for small volumes should not be used in the case of large volumes.

QUESTIONS

1. Explain the phenomena of electrical conduction in liquids. How does it differs from those in gases?
2. What are the commercial liquids dielectrics, and how are they different from pure liquids dielectrics?
3. What are the factors that influence conduction in pure liquid dielectrics and in commercial liquid dielectrics?
4. Explain the various theories that explain breakdown in commercial liquids dielectrics.
5. What is "stressed oil volume theory", and how does it explain breakdown in large volumes of commercial liquid dielectrics?
6. State the electrical properties which are essential for electrical performance of Liquid Dielectrics.

BREAKDOWN IN SOLID DIELECTRICS

3.1 INTRODUCTION

Solid dielectric materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusion, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength compared to liquids and gases.

Studies of the breakdown of solid dielectrics are of extreme importance in insulation studies. When breakdown occurs, solids get permanently damaged while gases fully and liquids partly recover their dielectric strength after the applied electric field removed.

The mechanism of breakdown is a complex phenomenon in the case of solids, and varies depending on the time of application of voltage as shown in Fig. 3. 1.

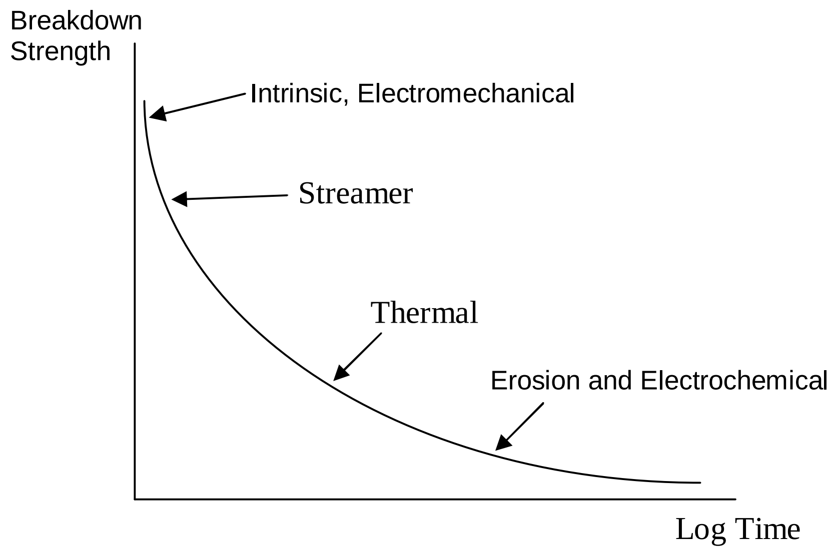


Fig.3.1Variation of breakdown strength with time after application of voltage

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
(f)breakdown due to internal discharges.

3.2 INTRINSIC BREAKDOWN

When voltages are applied only for short durations of the order of 10^8 s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. Experimentally, this highest dielectric strength can be obtained only under the best experimental conditions when all extraneous influences have been isolated and the value depends only on the structure of the material and the temperature. The maximum electrical strength recorder is 15 MV/cm for polyvinyl-alcohol at -196^{0}C. The maximum strength usually obtainable ranges from 5 MV/cm.

Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process.

Based on this principle, two types of intrinsic breakdown mechanisms have been proposed.

i) Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10^{-8} s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur. When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valence band to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown.

ii) Avalanche or Streamer Breakdown

This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collision. Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap.

An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron. 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.

3.3 ELECTROMECHANICAL BREAKDOWN

When solid dielectrics are subjected to high electric fields, failure occurs due to electrostatic compressive forces which can exceed the mechanical compressive strength. If the thickness of the specimen is d_0 and is compressed to thickness d under an applied voltage V, then the electrically developed compressive stress is in equilibrium if

$$\varepsilon_0\varepsilon_r \frac{V^2}{2d^2} = Y\ln\left[\frac{d_0}{d}\right] \qquad (3.1)$$

where Y is the Young's modulus. From Eq. (3.1)

$$V^2 = d^2\left[\frac{2Y}{\varepsilon_0\varepsilon_r}\right]\ln\left[\frac{d_0}{d}\right] \qquad (3.2)$$

Usually, mechanical instability occurs when

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

Substituting this Eq.3.2, the highest apparent electric stress before breakdown,

$$E_{max} = \frac{V}{d_0} = 0.6\left[\frac{Y}{\varepsilon_0\varepsilon_r}\right]^{\frac{1}{2}} \qquad (3.3)$$

The above equation is only approximate as Y depends on the mechanical stress. Also when the material is subjected to high stresses the theory of elasticity does not hold good, and plastic deformation has to be considered.

3.4 THERMAL BREAKDOWN

In general, the breakdown voltage of a solid dielectric should increase with its thickness. But this is true only up to a certain thickness above which the heat generated in the dielectric due to the flow of current determines the conduction.

When an electric field is applied to a dielectric, conduction current however small it may be, flows through the material. The current heats up the specimen and the temperature rise. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. Equilibrium is reached when the heat used to raise the temperature of the dielectric, plus the heat radiated out, equals the heat generated. The heat generated under d. c. stress E is given as

$W_{d.c.} = E^2\sigma \text{ W/cm}^3$ (3.4) where σ is the d. c. conductivity of the specimen.

Under a. c. fields, the heat generated

$W_{a.c.} = \frac{E^2 f_{\varepsilon r} \tan\delta}{1.8\times10^{12}} \text{ W/cm}^3$ (3.5) where, f= frequency in Hz, $\delta =$ loss angle of the dielectric material, and E= rms value. The heat dissipated (W_r) is given by

$W_r = C_v \frac{dT}{dt} + \text{div (K grad T)}$ (3.6) where, C_v= specific heat of the specimen,

T = temperature of the specımen, K = thermal conductivity of the specimen, and
t = time over which the heat is dissipated.

Equilibrium is reached when the heat generated $(W_{d.c} \text{ or } W_{a.c})$ becomes equal to the heat dissipated (W_r). In actual practice there is always some heat that is radiated out.

Breakdown occurs when $W_{d.c.} \text{or } W_{a.c.}$ exceeds W_r. The thermal instability condition is shown in Fig. 3.2. Here, the heat lost is shown by a straight line, while the heat generated at fields $E_1 \text{and } E_2$ is shown by separate curves. At field E_2 breakdown occurs both at temperatures $T_A \text{and } T_B$ heat generated is less than the heat lost for the field E_2, and hence the breakdown will not occur.

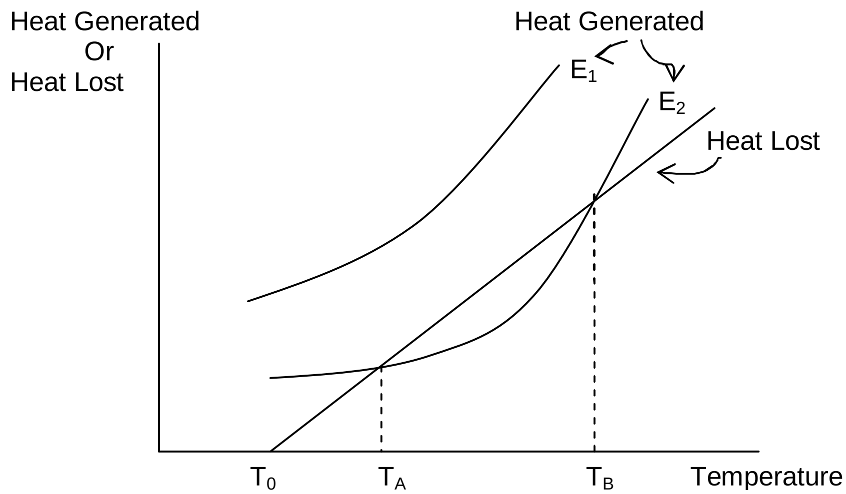


Fig.3.2 Thermal instability in solid dielectrics

The thermal breakdown voltages of various materials under d.c. and a.c. fields are shown in the table 3.1
.

Table 3.1

Material	Maximum thermal breakdown stress in MV/cm d.c.	a.c.
Muscovite mica	24	7.18
Rock salt	38	1.4
High grade porcelain	-	2.8
H.V. Steatite	-	9.8
Quartz-perpendicular to axis	1200	-
-parallel to axis	66	-
Capacitor paper	-	3.4-4.4
Polythene	-	3.5
Polystyrene	-	5.0

It can be seen from this table 3.1 that since the power loss under a.c. fields is higher, the heat generation is also high, and hence the thermal breakdown stresses are lower under a.c. conditions than under d.c. conditions.

3.5 BREAKDOWN OF SOLID DIELECTRICS IN PRACTICE

There are certain types of breakdown which do not come under either intrinsic breakdown, but actually occur after prolonged operation. These are, for example, breakdown due to tracking in which dry conducting tracks act as conducting paths on the insulator surfaces leading to gradual breakdown along the surface of the insulator. Another type of breakdown in this category is the electrochemical breakdown caused by chemical transformations such as electrolysis, formation of ozone, etc. In addition, failure also occurs due to partial discharges which are brought about in the air pockets inside the insulation. This type of breakdown is very important impregnated paper insulation used in high voltage cables and capacitors.

3.5.1 Chemical and Electrochemical Deterioration and Breakdown

In the presence of air and other gases some dielectric materials undergo chemical changes when subjected to continuous stresses. Some of the important chemical reactions that occur are:

-Oxidation: In the presence of air or oxygen, material such as rubber and polyethylene undergo oxidation giving rise to surface cracks.

-Hydrolysis: When moisture or water vapor is present on the surface of a solid dielectric, hydrolysis occurs and the material loses their electrical and mechanical properties. Electrical properties of materials such as paper, cotton tape, and other cellulose materials deteriorate very rapidly due to hydrolysis. Plastics like polyethylene undergo changes, and their service life considerably reduces.

-Chemical Action: Even in the absence of electric fields, progressive chemical degradation of insulating materials can occur due to a variety of processes such as chemical instability at high temperatures, oxidation and cracking in the presence of air and ozone, and hydrolysis due to moisture and heat. Since different insulating materials come into contact with each other in any practical reactions occur between these various materials leading to reduction in electrical and mechanical strengths resulting in a failure.

The effects of electrochemical and chemical deterioration could be minimized by carefully studying and examining the materials. High soda content glass insulation should be avoided in moist and damp conditions, because sodium, being very mobile, leaches to the surface giving rise to the formation of a strong alkali which will cause deterioration. It was observed that this type of material will lose its mechanical strength within 24 hrs, when it is exposed to atmospheres having 100% relative humidity at 70^0 C. In paper insulation, even if partial discharges are prevented completely, breakdown can occur due to chemical degradation. The chemical and electrochemical deterioration increases very rapidly with temperature, and hence high temperatures should be avoided.

3.5.2 Breakdown Due to Treeing and Tracking

When a solid dielectric subjected to electrical stresses for a long time fails, normally two kinds of visible markings are observed on the dielectric material. They are:

a) the presence of a conducting path across the surface of the insulation:

b) a mechanism whereby leakage current passes through the conducting path finally leading to the formation of a spark. Insulation deterioration occurs as a result of these sparks.

The spreading of spark channels during tracking, in the form of the branches of a tree is called treeing.

Consider a system of a solid dielectric having a conducting film and two electrodes on its surface. In practice, the conducting film very often is formed due to moisture. On application of voltage, the film starts conducting, resulting in generation of heat, and the surface starts becoming dry. The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface. With organic insulating materials such as paper and bakelite, the dielectric carbonizes at the region of sparking, and the carbonized regions act as permanent conducting channels resulting in increased stress over the rest of the region. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomenon, called tracking is common between layers of bakelite, paper and similar dielectrics built of laminates.

On the other hand treeing occurs due to the erosion of material at the tips of the spark. Erosion results in the roughening of the surfaces, and hence becomes a source of dirt and contamination. This causes increased conductivity resulting either in the formation of conducting path bridging the electrodes or in a mechanical failure of the dielectric.

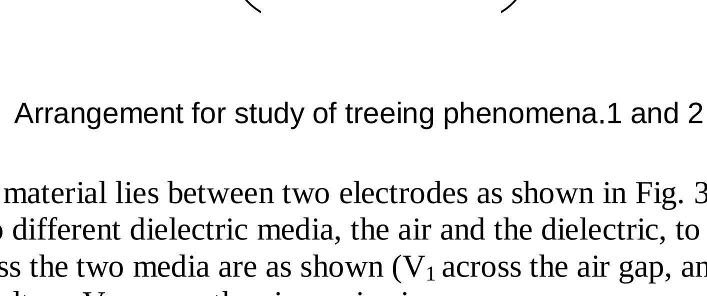


Fig.3.3 Arrangement for study of treeing phenomena.1 and 2 are electrodes.

When a dielectric material lies between two electrodes as shown in Fig. 3.3, there is possibility for two different dielectric media, the air and the dielectric, to come series. The voltages across the two media are as shown (V_1 across the air gap, and V_2 across the dielectric). The voltage V_1 across the air gap is given as,

$$V_1 = \frac{V.d_1}{d_1 + \left(\frac{\varepsilon_1}{\varepsilon_2}\right) d_2} \qquad (3.7)$$

where V is the applied voltage.

Since $\varepsilon_2 \rangle \varepsilon_1$ most of the voltage appears across d_1, the air gap. Sparking will occur in the air gap and charge accumulation takes place on the surface of the insulation. Sometimes the spark erodes the surface of the insulation. As time passes, break-down channels spread through the insulation in an irregular "tree' like fashion leading to the formation of conducting channels. This kind of channeling is called treeing.
Under a.c. voltage conditions treeing can occur in a few minute or several hours. Hence, care must be taken to see that no series air gaps or other weaker insulation gaps are formed.

Usually, tracking occurs even at very low voltage of the order of about 100 V, whereas treeing requires high voltages. For testing of tracking, low and medium voltage tracking tests are specified. These tests are done at low voltages but for times of about 100 hr or more. The insulation should not fail. Sometimes the tests are done using 5 to 10 kV with shorter durations of 4 to 6 hour. The numerical value that initiates or causes the formation of a track is called "tracking index" and this is used to qualify the surface properties of dielectric materials.

Treeing can be prevented by having clean, dry, and undamaged surfaces and a clean environment. The materials chosen should be resistant to tracking. Sometimes moisture repellant greases are used. But this needs frequent cleaning and regressing. Increasing creeping distances should prevent tracking, but in practice the presence of moisture films defeat the purpose.
Usually, treeing phenomena is observed in capacitors and cables, and extensive work is being done to investigate the real nature and causes of this phenomenon.

3.5.3 Breakdown Due to Internal Discharges

Solid insulating materials, and to a lesser extent liquid dielectrics contain voids or cavities within the medium or at the boundaries between the dielectric and the electrodes. These voids are generally filled with a medium of lower dielectric strength, and the dielectric constant of the medium in the voids is lower than that of the insulation. Hence, the electric field strength in the voids is higher than that across the dielectric. Therefore, even under normal working voltages the field in the voids may exceed their breakdown value, and breakdown may occur.

Let us consider a dielectric between two conductors as shown in Fig. 3.4.a. If we divide the insulation into three parts, an electrical network of $C_1, C_2, \text{and } C_3$ can be formed as shown in Fig. 3.4.b. In this, C_1 represents the capacitance of the void or cavity, C_2 is the capacitance of the dielectric which is in series with the void, and C_3 is the capacitance of the dielectric

.

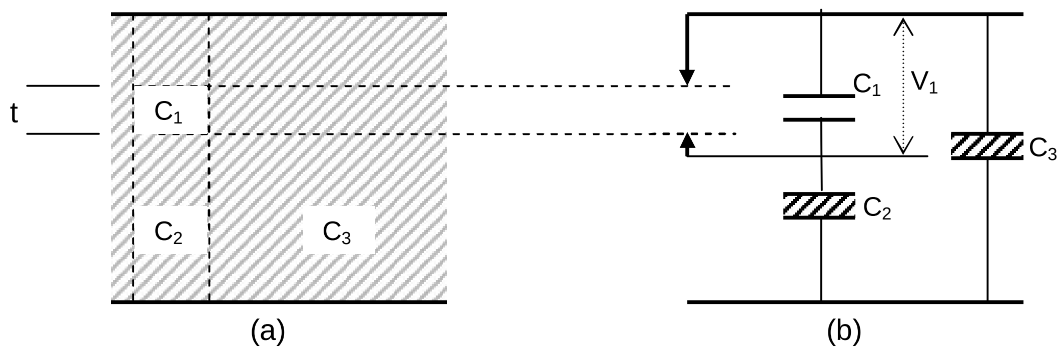


Fig.3.4 Electrical discharge in a cavity and its equivalent circuit

.
When the applied voltage is V, the voltage across the void, V_1 is given by the same equation as (3.7)

$$V_1 = \frac{Vd_1}{d_1 + \left(\frac{\varepsilon_0}{\varepsilon_1}\right)d_2}$$

where d_1 and d_2 are the thickness of the void and the dielectric, respectively, having permittivities ε_0 and ε_1. Usually $d_1 \langle d_2$, and if we assume that the cavity is filled with a gas, then

$$V_1 = V_{\varepsilon r}\left(\frac{d_1}{d_2}\right)$$

(3.8) where ε_r is the relative permittivity of the dielectric.

When a voltage V is applied, V_1 reaches the breakdown strength of the medium in the cavity (V_i) and breakdown occurs. V_i is called the "discharge inception voltage". When the applied voltage is a.c., breakdown occurs on both the half cycles and the number of discharges will depend on the applied voltage. When the first breakdown across the cavity occurs the breakdown voltage across it becomes zero. When once the voltage V_1 becomes zero, the spark gets extinguished and again the voltage rises till breakdown occurs again. This process repeats again and again, and current pulses will be obtained both in the positive and negative half cycles.

These internal discharges (also called partial discharges) will have the same effect as "treeing" on the insulation. When the breakdown occurs in the voids, electrons and positive ions are formed. They will have sufficient energy and when they reach the void surfaces they may break the chemical bonds. Also, in each discharge there will be some heat dissipated in the cavities, and this will carbonize the surface of the voids and will caused erosions of the material. Channels and pits formed on the cavity surfaces increase the conduction. Chemical degradation may also occur as a result of the activate discharge products formed during breakdown.

All these effect will result in a gradual erosion of the material and consequent reduction in the thickness of insulation leading to breakdown. The life of the insulation with internal discharges depends upon the applied voltage and the number of discharges. Breakdown by this process may occur in a few or days or may take a few years.

3.6 BREAKDOWN OF COMPOSITE INSULATION

A single material rarely constitutes the insulation in equipment. Two or more insulating materials are used either due to design considerations or due to practical difficulties of fabrication.

In certain cases the behavior of the insulation system can be predicted by the behavior of the components. But in most cases, the system as a whole has to be considered. The following considerations determine the performance of the system as a whole:

- (i) The stress distribution at different parts of the insulation system is distorted due to the component dielectric constant and conductivities,
- (ii) the breakdown characteristics at the surface are affected by the insulation boundaries of various components,
- (iii) the internal or partial discharge products of one component invariably affect the other components in the system, and
- (iv) the chemical ageing products of one component also affect the performance of other components in the system.

Another important consideration is the economic life of the system; the criterion being the ultimate breakdown of the solid insulation. The end point is normally reached by through puncture, thermal runaway, electrochemical breakdown, or mechanical failure leading to complete electrical breakdown of the system. Hence, tests for assessing the life of insulation (ageing) are very necessary.

Ageing is the process by which the electrical and mechanical properties of insulation normally becomes worse in condition (deteriorate) with time. Ageing occurs mainly due to oxidation, chemical degradation, irradiation, and electron and ion bombardment on the insulation. Tracking is another process by which ageing of the insulation occurs. Usually partial discharge tests are used in ageing studies to estimate the discharge magnitudes, discharge inception, and extinction voltages. Change of loss angle ($\tan\delta$) during electrical stressing provides information of the deterioration occurring in insulation systems. The knowledge of the mechanical stresses in the insulation, controlling of the ambient conditions such as temperature and humidity, and a study of the gaseous products evolved during ageing processes will also help to control the breakdown process in composite insulation. Finally, stress control in insulation systems to avoid high electric stress regions is an important factor in controlling the failure of insulation systems.

Questions

3.1 What do you understand by 'intrinsic strength' of a solid dielectric? How does breakdown occur due to electrons in solid dielectric?

3.2 What is 'thermal breakdown' in solid dielectrics, and how is practically more significant than other mechanism?

3.3 How does the 'internal discharge' phenomenon lead to breakdown in solid dielectrics?

TEXT / REFERENCE BOOKS

1. M. S. Naidu and V. Kamaraju, ‘High Voltage Engineering’, 5thEdition Tata McGraw Hill Publishing Co. Ltd., New Delhi, 2013.
2. E.Kuffel and M.Abdullah, “High Voltage Engineering” -Per gammon Press, Oxford, 1970.
3. C.L.WADHWA, “High Voltage Engineering” -New Age International (P) Ltd, Publishers, 2007
4. E.Kuffel and W.s. Zaengal, “High Voltage Engineering Fundamentals”,2nd Edition, Butterworth Heinemann, 2000.
5. H.M.Ryam, “High voltage Engineering and testing”, 2nd Edition, 2001, IEEE power and energy series 32.

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - III

High Voltage Engineering – SEE1402

UNIT 3

GENERATION OF HIGH VOLTAGES AND CURRENTS

Different forms of high voltages are classified as

- High D.C. Voltages
- High A.C. Voltages of power frequency.
- High A.C. Voltages of high frequency.
- High transient or impulse voltages of very short duration such as lightning over voltages.
- Transient voltages of longer duration such as switching surges.

3.1 Generation of High DC Voltages Using Voltage Multiplier Circuits

Generation of high d.c. voltages is mainly required in research work in the areas of pure and applied physics. Sometimes, high direct voltages are needed in insulation tests on cables and capacitors. Impulse generator charging units also require high d.c. voltages of about 100 to 200 kV. Normally, for the generation of d.c. voltages of up to 100 kV, electronic valve rectifiers are used and the output currents are about 100 mA. 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. When higher d.c. voltages are needed, a voltage doubler or cascaded rectifier doubler circuits are used. Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level. 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.

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 doubler circuits. 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 may be used instead of conventional a.c. supply and the circuit becomes compact A typical circuit of this form is shown in fig. 3.1.

The pulses generated in the anode circuit of the valve P are rectified and the voltage is cascaded to give an output of $2nV_{max}$ across the load R_L. A trigger voltage pulse of triangular waveform (ramp) is given to make the valve switched on and off. A d.c. power supply of about 500 V applied to the pulse generator, is sufficient to generate a high voltage d.c. of 50 to 100 kV with suitable number of stages.

Cockcroft-Walton voltage multiplier circuit

Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Fig.3.2. The first stage, i.e. D_1, D_2, C_1, C_2 and the transformer *T* are identical as in the voltage doubler. For higher output voltage of 4, 6, ... 2n of the input voltage V, the circuit is repeated with cascade or series connection. Thus, the condenser C_4 is charged to $4V_{max}$ and C_{2n} to $2nV_{max}$ above the earth potential. But the volt across any individual condenser or rectifier is only $2V_{max}$.

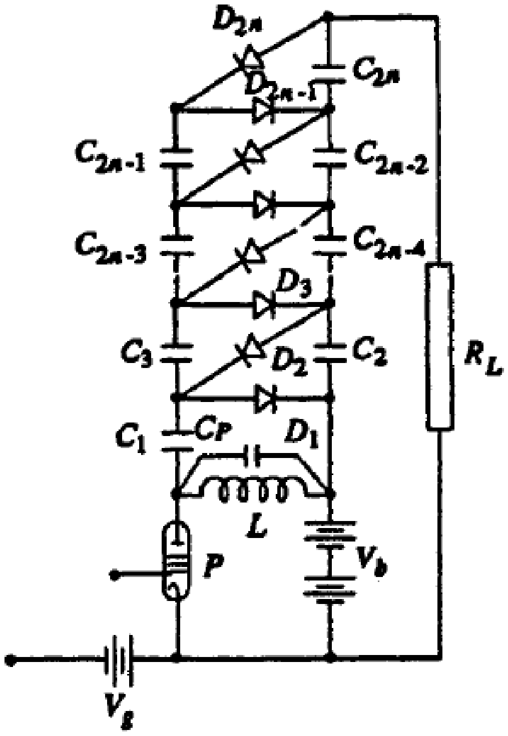


Figure 3.1 Cascaded rectifier units with pulse

The rectifiers D_1, D_3, ...D_{2n-1} shown in Fig. 3.2 operate and conduct during the positive half cycles while the rectifiers D_2, D_4... D_{2n} conduct during the negative half cycles. Typical current and voltage waveforms of such a circuit are shown in Figs. 3.3 and 3.5 respectively. The voltage on *C2* is the sum of the input a.c. voltage, V_{ac} and the voltage across condenser C_1,V_{C1}. The mean voltage on C_2 is less than the positive peak charging voltage (V_{ac} + V_{c1}).

The voltages across other condensers C_2 to C_{2n} 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 V_{ac} *(n1+ n2 + ...)*, where *n1, n2,...* are factors when ripple and regulation are considered in the next rectifier. The ripple voltage δV and the voltage drop ΔV in a cascaded voltage multiplier unit are shown in Fig. 3.4.

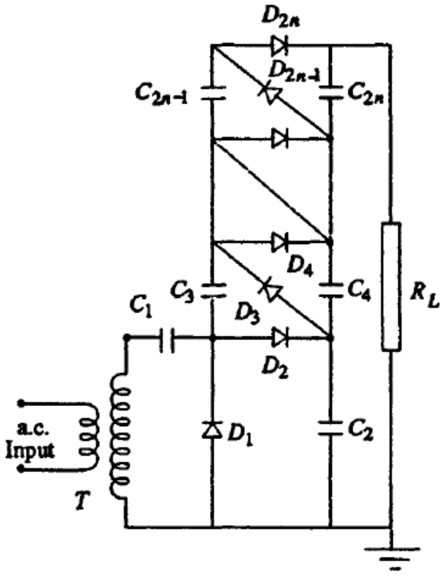


Figure 3.2 Cockcroft-Walton voltage multiplier circuit

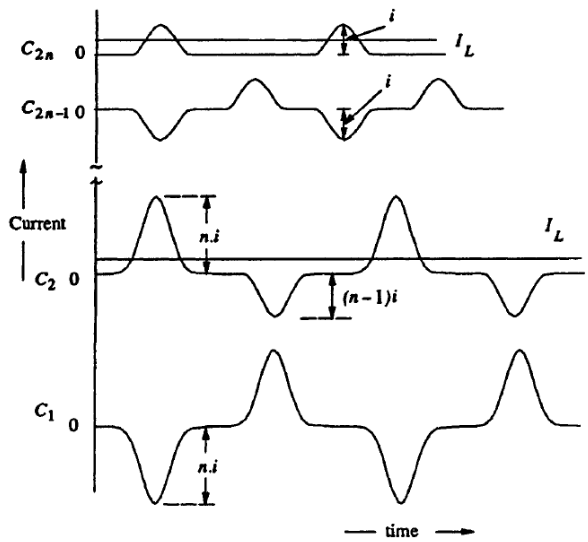


Figure 3.3 Schematic current waveforms across first and last capacitors

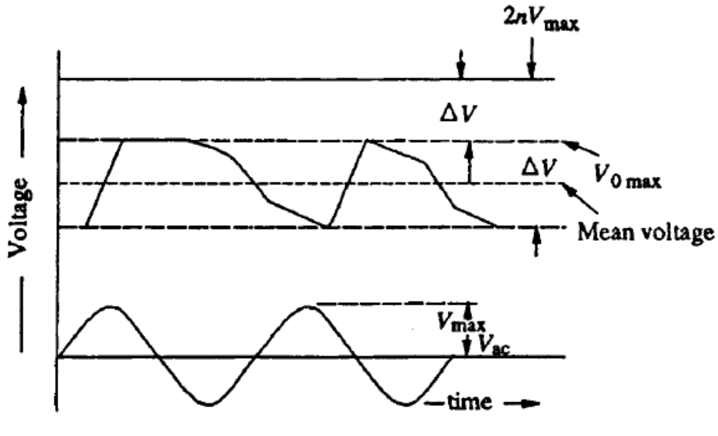


Figure 3.4 Ripple voltage and voltage drop

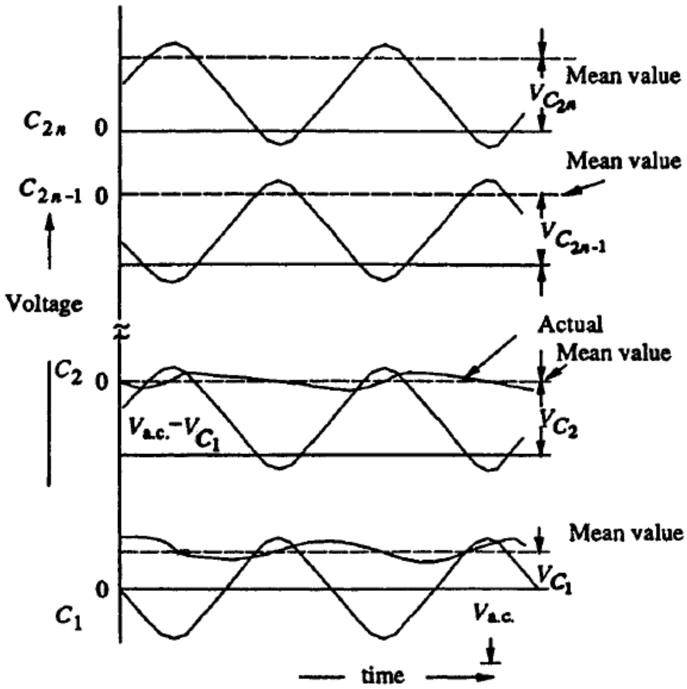


Figure 3.5 Schematic voltage waveforms across first and last capacitors

Figure 3.6 Real time Cockcroft-Walton voltage multiplier circuit

3.2 Van de Graaff Generator

The Van de Graaff generator is an electrostatic machine which generates very high voltages, with small output current.

The schematic diagram of a Van de Graaff generator is shown in Fig. 3.7. 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 at a speed of 1000 to 2000 metres per minute. The potential of the high voltage electrode above the earth at any instant is $V = Q/C$, where Q *is* the charge stored and C is the capacitance of the high voltage electrode to earth.

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 high voltage 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.

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.

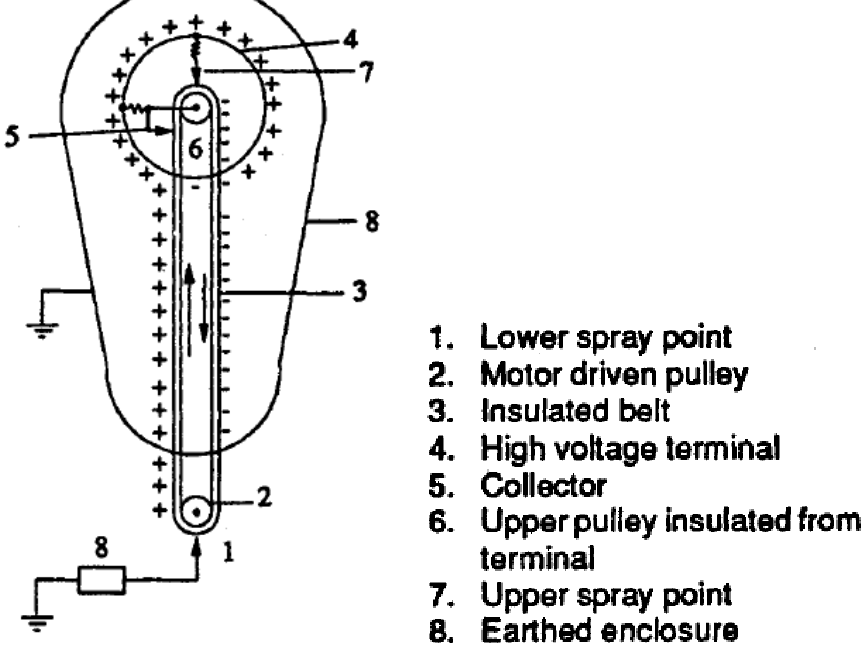


Figure 3.7 Van de Graaff generator

3.3 Generation of High Alternating Voltages using Cascade Transformers

Cascading a number of single identical units makes transportation, production and erection simpler. The cascading principle is illustrated with the basic scheme shown in Fig. 3.8 below in which it can be seen that output of a stage transformer becomes input for the next stage. The HV supply is connected to the primary winding "1" of transformer I, designed for a HV output of V. The other two transformers too are connected in the same fashion. The excitation winding "3" of Transformer I supplies the primary voltage for the second transformer unit II; both windings are dimensioned for the same low voltage, and the potential gain is fixed to the same value V. The HV or secondary windings "2" of both units are connected in series, so that a voltage of 2 V is produced at the output of 2nd unit.

The unit III is added in the same way. The tanks or vessels containing the active parts (core and windings) are indicated by dashed lines. For a metal tank construction and the HV windings shown in this basic scheme, the core and the tank of each unit would acquire the HV level of the previous unit as indicated. Only the tank of transformer I is earthed. The tanks of transformers II and III are at high potentials, namely V and 2 V above earth, and must therefore be suitably insulated, hence raised above the ground on solid post insulators. Through HV bushings the leads from the excitation windings "3", as well as the tapings of the HV windings "2", are brought to the next transformer.

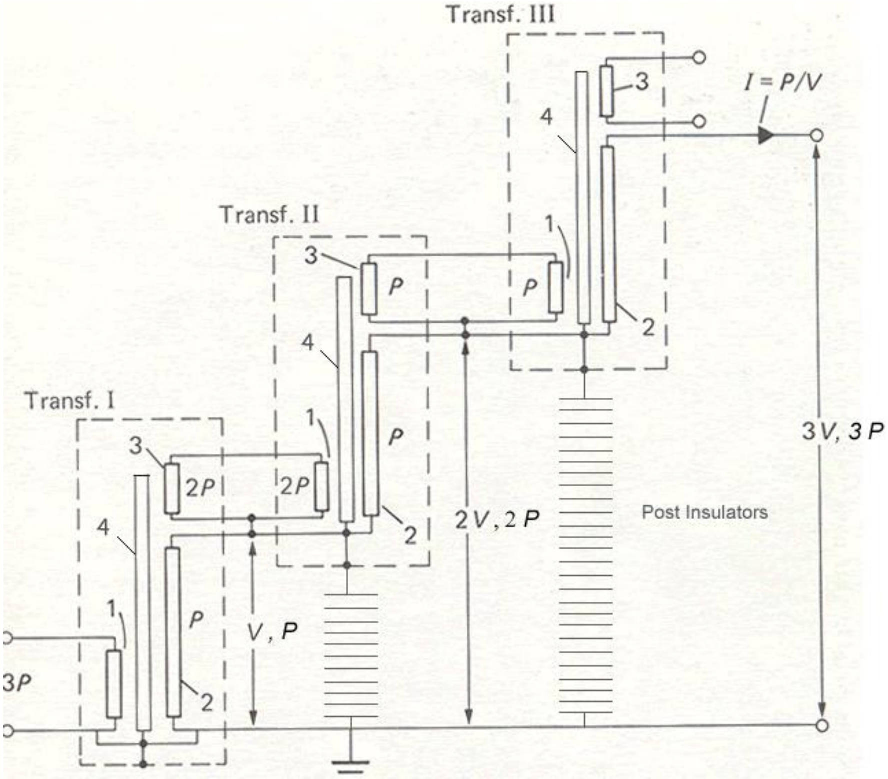


Figure 3.8 Cascaded Transformers

For voltages higher than about 600 kV, the cascade of such transformers is a big advantage. The weight and the size of the testing set is sub-divided into single units of smaller size and lower weight. The transportation and erection of the test set in cascade becomes simpler. However, there is a disadvantage that the primary windings of the lower stages are more heavily loaded with higher current in such sets.

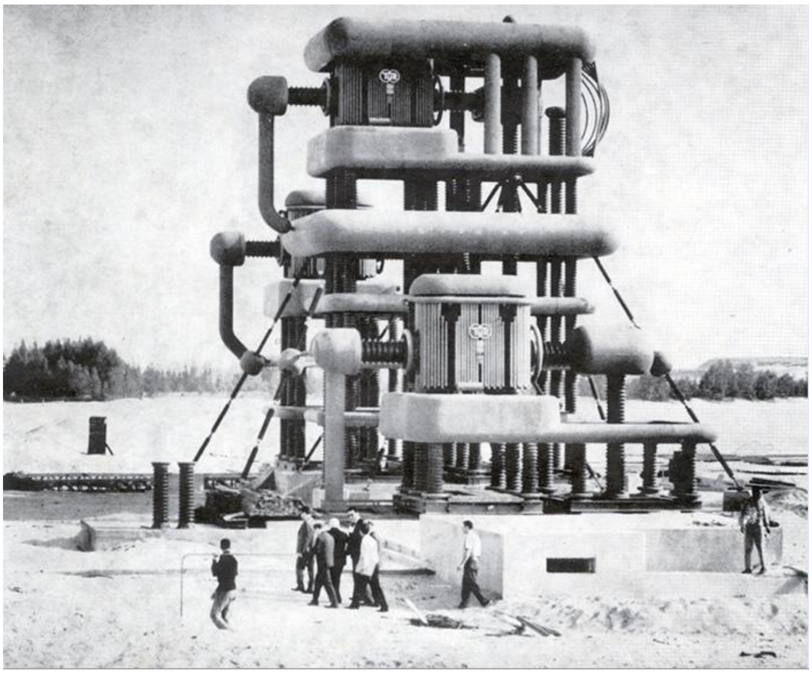


Figure 3.9 A real time cascade transformer of rating 3 x 750 = 2250 kV

3.4 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.10µs and decay time to 50% of the peak value of the order of 30 to 200 µs. The wave shapes are arbitrary, but mostly unidirectional.

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 µs, fall time to 50% peak value of 50 µs, 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 Fig. 3.10, 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 O_1. O_1 is taken as the virtual origin. 1.25 times the interval between times t_1 and t_2 corresponding to points *C* and *D* (projections on the time axis) is defined as the front time, i.e. 1.25 $(O_1t_2-O_2t_1)$. The point *E* is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis is t_4.Ot_4 is defined as the fall or tail time. In case the point *C* is not clear or missing from the wave shape record, the point corresponding to 30% peak value F is taken and its projection t'_1 is located on time axis.

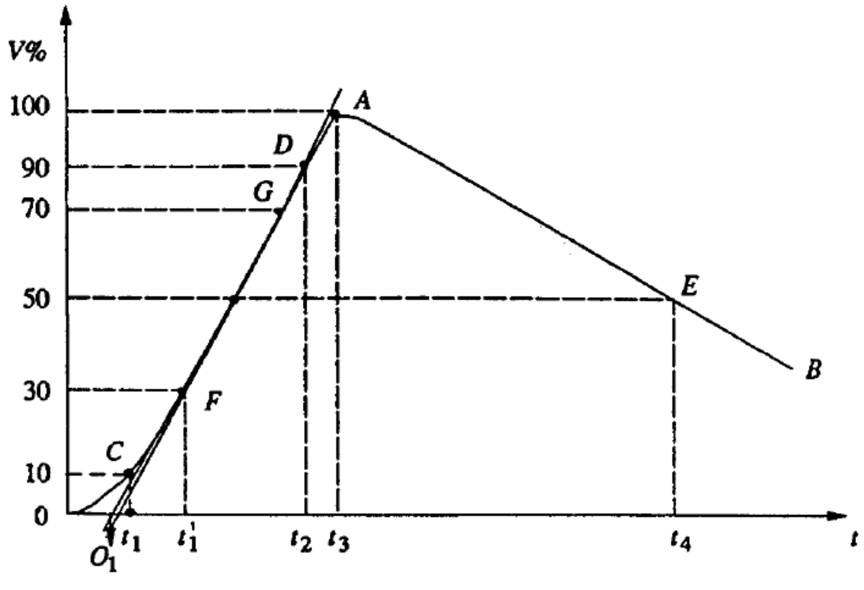


Figure 3.10 Impulse waveform

3.5 Marx Circuit

A multistage impulse generator requires several components pans for flexibility and for the production of the required wave shape. These may be grouped as follows:

D.C. Charging Set

The charging unit should be capable of giving a variable d.c. voltage of either polarity to charge the generator capacitors to the required value.

Charging Resistors

These will be non-inductive high value resistors of about 10 to 100 kilo-ohms. Each resistor will be designed to have a maximum voltage between 50 and 100 kV.

Generator Capacitors and Spark Gaps

These are arranged vertically one over the other with all the spark gaps aligned. The capacitors are designed for several charging and discharging operations. On dead short circuit, the capacitors will be capable of giving 10 kA of current. The spark gaps will be usually spheres or hemispheres of 10 to 25 cm diameter. Sometimes spherical ended cylinders with a central support may also be used.

Wave-shaping Resistors and Capacitors

Resistors will be non-inductive wound type and should be capable of discharging impulse currents of 1000 A or more. Each resistor will be designed for a maximum voltage of 5O to 100 kV. The resistances are bifilar wound or non-inductive thin flat insulating sheets. In some cases, they are wound on thin cylindrical formers and are completely enclosed. The load capacitor may be of compressed gas or oil filled with a capacitance of 1 to 10 µF.

Triggering System

This consists of trigger spark gaps to cause spark breakdown of the gaps.

Voltage Dividers

Voltage dividers of either damped capacitor or resistor type and an oscilloscope with recording arrangement are provided for measurement of the voltages across the test object. Sometimes a sphere gap is also provided for calibration purposes.

In the circuit, the generator capacitance C_1 is to be first charged and then discharged into the wave shaping circuits. A single capacitor C_1 may be used for voltages up to 200 kV. Beyond this voltage, a single capacitor and its charging unit may be too costly, and the size becomes very large. The cost and size of the impulse generator increases at a rate of the square or cube of the voltage rating. Hence, for producing very high voltages, a bank of capacitors are charged in parallel and then discharged in series. The arrangement for charging the capacitors in parallel and then connecting them in series for discharging was originally proposed by Marx. Nowadays modified Marx circuits are used for the multistage impulse generators.

Usually the charging resistance R_s is chosen to limit the charging current to about 50 to 100 mA, and the generator capacitance C is chosen such that the product CR_s is about 10 s to 1 min. The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage *V.* Thus, all the capacitances are charged to the voltage *V* in about 1 minute. When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means. Thus, all the capacitors *C* get connected in series and discharge into the load capacitance or the test object. The discharge time constant CR_1/n (for *n* stages) will be very very small (microseconds), compared to the charging time constant CR_s which will be few seconds. Hence, no discharge takes place through the charging resistors R_s.

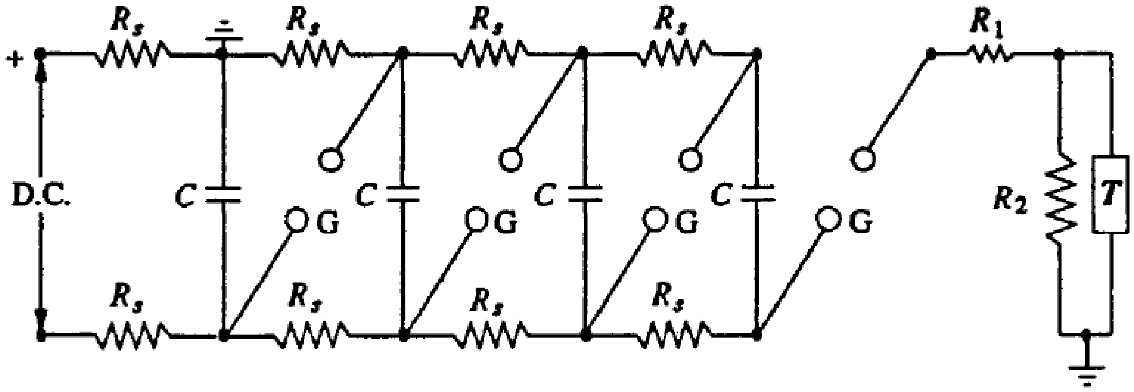


Figure 3.11 Schematic Diagram of Marx circuit arrangement for multistage impulse generator

3.6 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 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. 3.12. *C* 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.

For producing large values of impulse currents, a number of capacitors are charged in parallel and discharged in parallel into the circuit. The arrangement of capacitors is shown in Fig 3.13. In order to minimize the effective inductance, the capacitors are subdivided into smaller units. If there are n_1 groups of capacitors, each consisting of n_2 units and if L_0 is the inductance of the common discharge path, L_1 is that of each group and L_2 is that of each unit, then the effective inductance *L* is given by

$$L = L_0 + \frac{L_1}{n} + \frac{L_2}{n_1 n_2} \qquad 3.1$$

Also, the arrangement of capacitors into a horse-shoe shaped layout minimizes the effective load inductance.

The essential parts of an impulse current generator are:

- a d.c. charging unit giving a variable voltage to the capacitor bank,
- capacitors of high value (0.5 to 5 μF) each with very low self-inductance, capable of giving high short circuit currents,
- an additional air cored inductor of high current value,
- proper shunts and oscillograph for measurement purposes, and
- a triggering unit and spark gap for the initiation of the current generator.

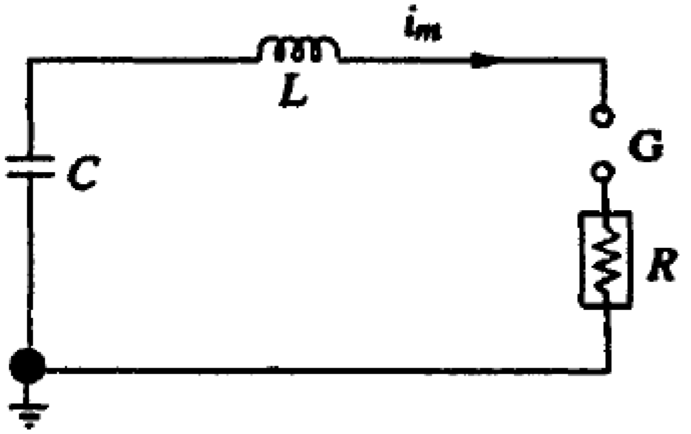


Figure 3.12 Basic circuit of an impulse current generator

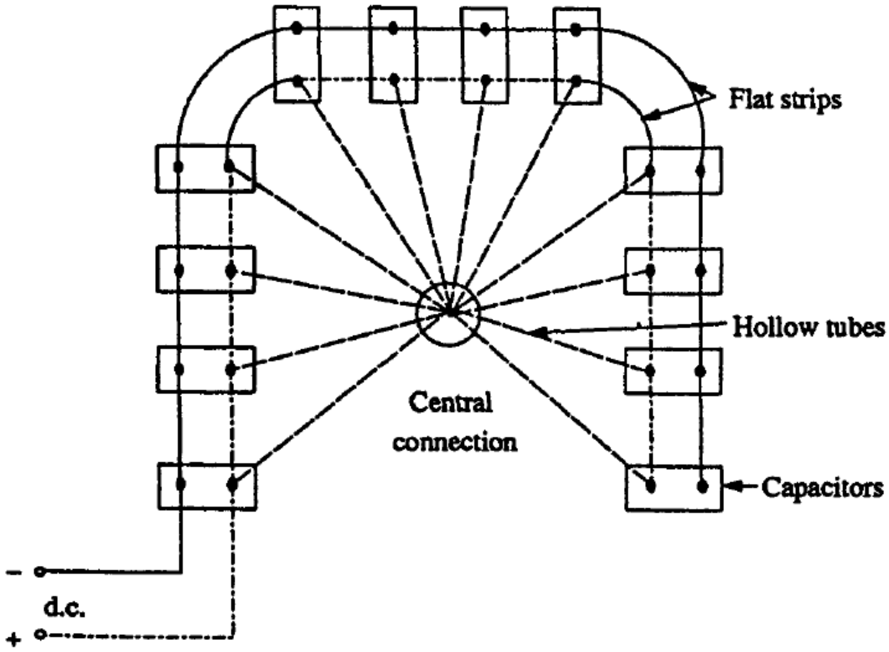


Figure 3.13 Arrangements of capacitors for impulse current generator

3.7 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 ultraviolet 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 3.14 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_1 and R_L. 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 thyratron conducts on receiving the pulse from the switch S and produces a negative pulse through the capacitance C_1 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 begins before the start of the impulse generator voltage. The resistance R_2 ensures decoupling 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. 3.15 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 Fig. 3.16. 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 occurs. The trigatron gap is polarity sensitive and a proper polarity pulse should be applied for correct operation.

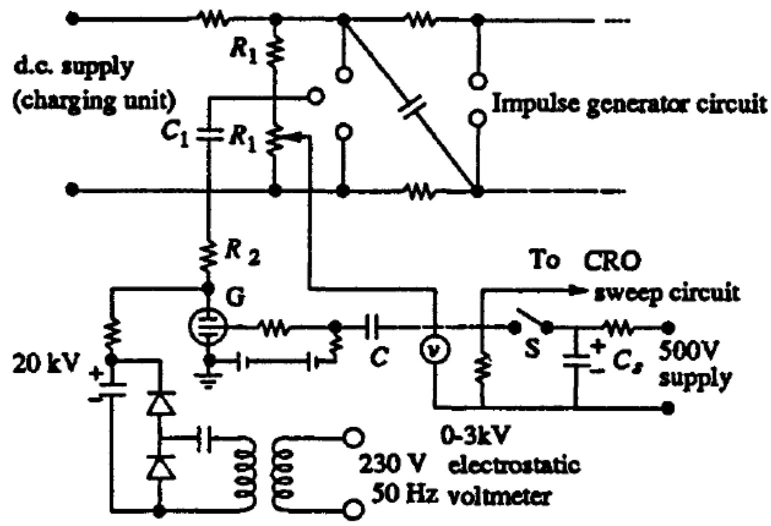


Figure 3.14 Tripping of an impulse generator using a three electrode gap

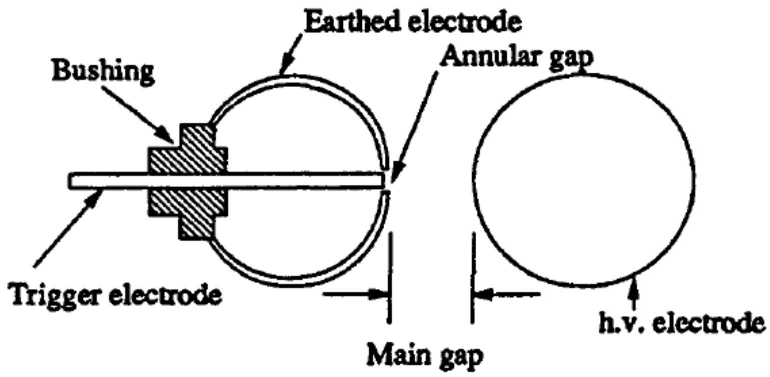


Figure 3.15 Trigatron gap

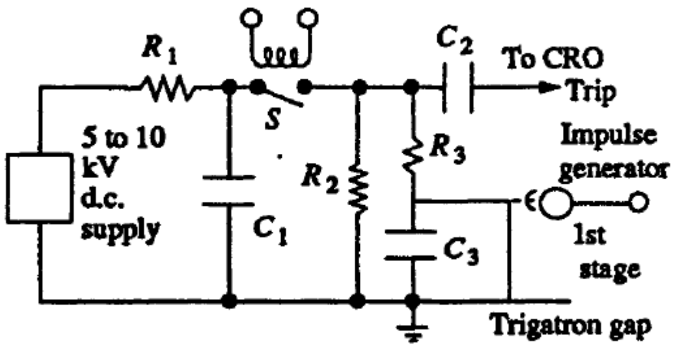


Figure 3.16 Tripping circuit using trigatron gap

3.8 Generation of Switching Surges

Now-a-days in extra high voltage transmission lines and power systems, switching surge is an important factor that affects the design of insulation. All transmission lines rated for 220 kV and above, incorporate switching surge spark over voltage for their insulation levels. A switching surge is a short duration transient voltage produced in the system due to a sudden opening or closing of a switch or circuit breaker or due to an arcing at a fault in the system. The waveform is not unique. The transient voltage may be an oscillatory wave or a damped oscillatory wave of frequency ranging from few hundred hertz to few kilo hertz. It may also be considered as a slow rising impulse having a wave front time of 0.1 to 10 ms, and a tail time of one to several milliseconds. Thus, switching surges contain larger energy than the lightning impulse voltages.

Several circuits have been adopted for producing switching surges. They are grouped as (i) impulse generator circuit modified to give longer duration wave shapes, (ii) power transformers or testing transformers excited by d.c. voltages giving oscillatory waves and these include Tesla coils. Figure 3.17 shows the impulse generator circuits modified to give switching surges. The arrangement is the same as that of an impulse generator.

Switching surges of very high peaks and long duration can be obtained by using the circuit shown in Fig. 3.18. An impulse generator condenser C_1 charged to a low voltage d.c. (20 to 25 kV) is discharged into the low voltage winding of a power or testing transformer. The high voltage winding is connected in parallel to a load capacitance C_2 a potential divider R_2 a sphere gap S, and the test object. Through an autotransformer action, switching surge of proper wave shape can be generated across the test object. The efficiency obtained by this method is high but the transformer should be capable of withstanding very high voltages.

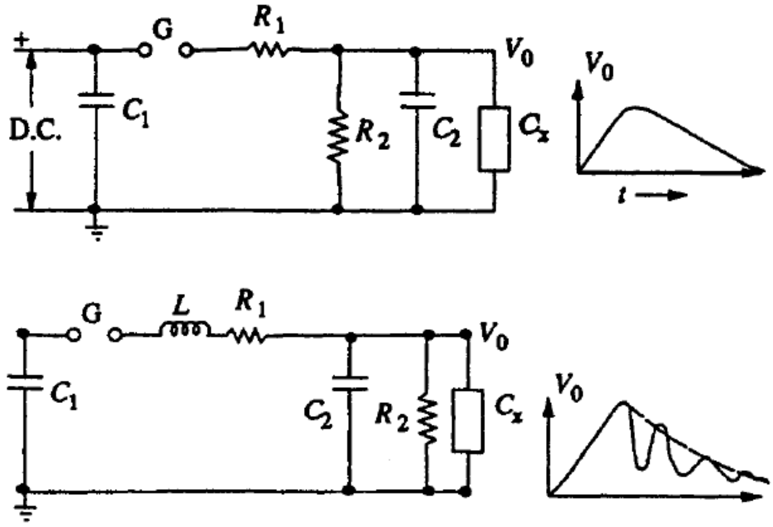


Figure 3.17 Circuit for producing Switching Surges

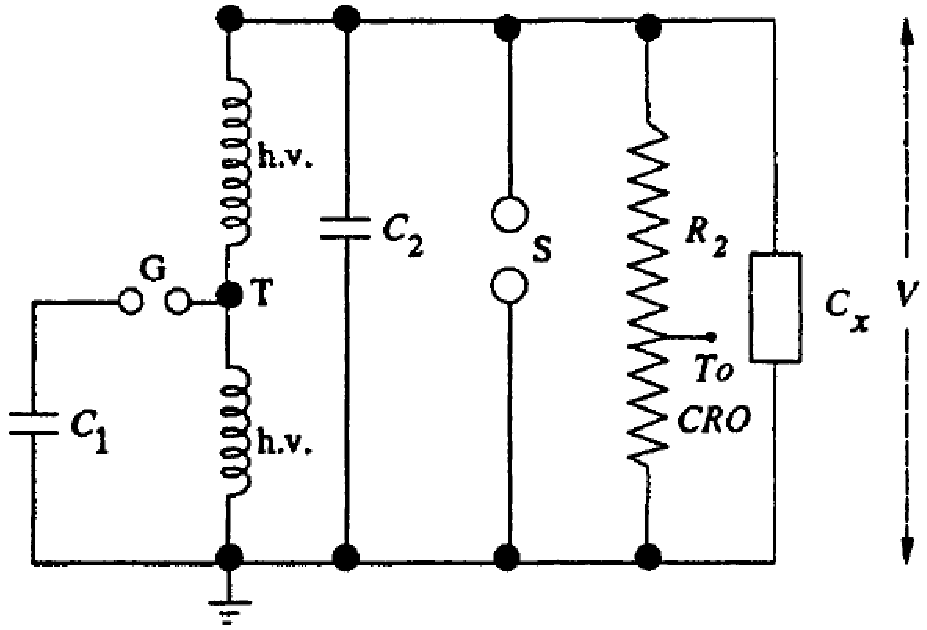


Figure 3.18 Circuit for producing switching surges using transformer

3.9. Generation of High Frequency AC Voltages

High frequency high voltages are required for rectifier d.c. power. 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:

- the absence of iron core in transformers and hence saving in cost and size,
- pure sine wave output,
- slow build-up of voltage over a few cycles and hence no damage due to switching surges, and
- Uniform distribution of voltage across the winding coils due to subdivision 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. 3.19. 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 C_1. A spark gap G connected across the primary is triggered at the desired voltage V_1 which induces a high self-excitation in the secondary. The primary and the secondary windings (L_1 and L_2) 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 C_1 and C_2.

The output voltage V_2 is a function of the parameters L_1, L_2 C_1, C_2 and the mutual inductance M. usually, the winding resistances will be small and contribute only for damping of the oscillations.

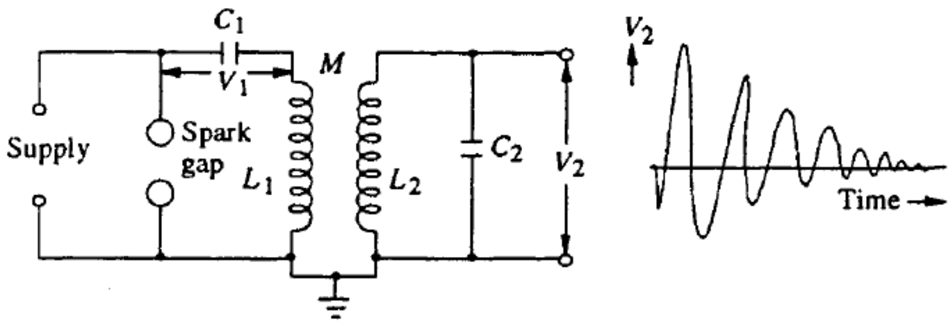


Figure 3.19 Testla coil equivalent circuit

TEXT / REFERENCE BOOKS

1. M. S. Naidu and V. Kamaraju, ‘High Voltage Engineering’, 5thEdition Tata McGraw Hill Publishing Co. Ltd., New Delhi, 2013.
2. E.Kuffel and M.Abdullah, “High Voltage Engineering” -Per gammon Press, Oxford, 1970.
3. C.L.WADHWA, “High Voltage Engineering” -New Age International (P) Ltd, Publishers, 2007
4. E.Kuffel and W.s. Zaengal, “High Voltage Engineering Fundamentals”,2nd Edition, Butterworth Heinemann, 2000.
5. H.M.Ryam, “High voltage Engineering and testing”, 2nd Edition, 2001, IEEE power and energy series 32.

SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - IV

High Voltage Engineering – SEE1402

UNIT 4

MEASUREMENT OF HIGH VOLTAGES AND CURRENTS

High DC voltage measurement techniques

High Resistance with series ammeter

7.1.1 High Ohmic Series Resistance with Microammeter

High d.c. voltages are usually measured by connecting a very high resistance (few hundreds of megaohms) in series with a microammeter as shown in Fig. 7.1. Only the current I flowing through the large calibrated resistance R is measured by the moving coil microammeter. The voltage of the source is given by

$$V = I R$$

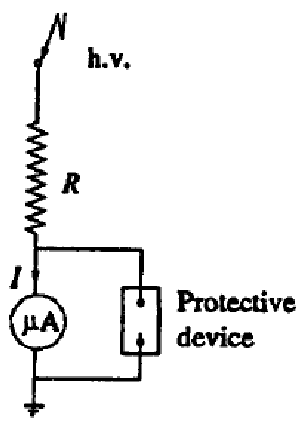


Fig. 7.1 Series resistance micrometer

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. A value of less than 5 kV/cm in air or less than 20 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}/°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 operation had very good temperature stability. The limitations in the series resistance design are:

(*i*) power dissipation and source loading,
(*ii*) temperature effects and long time 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%.

7.1.2 Resistance Potential Dividers for d.c. Voltages

A resistance potential divider with an electrostatic or high impedance voltmeter is shown in Fig. 7.2. The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement. The high voltage magnitude is given by $[(R_1 + R_2)/R_2]v_2$, where v_2 is the d.c. voltage across the low voltage arm R_2. 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. 7.3. 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.

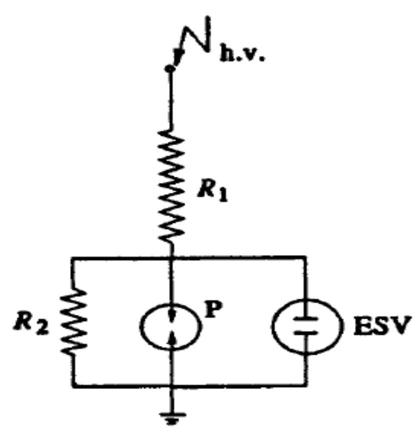


Fig. 7.2 Resistance potential divider with an electrostatic voltmeter

P — Protective device
ESV — Electrostatic volt-meter

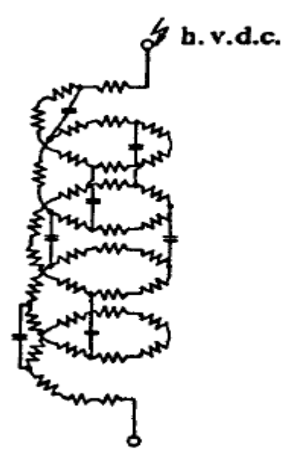


Fig. 7.3 Series resistor with parallel capacitors for potential linearization for transient voltages

7.1.3 Generating Voltmeters

High voltage measuring devices employ generating principle when source loading is prohibited (as with Van de Graaff 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.

Principle of Operation

The charge stored in a capacitor of capacitance C is given by $q = CV$. If the capacitance of the capacitor varies with time when connected to the source of voltage V, the current through the capacitor,

$$i = \frac{dq}{dt} = V\frac{dC}{dt} + C\frac{dV}{dt} \tag{7.1}$$

For d.c. voltages $dV/dt = 0$. Hence,

$$i = \frac{dq}{dt} = V\frac{dC}{dt} \tag{7.2}$$

If the capacitance C varies between the limits C_0 and $(C_0 + C_m)$ sinusoidally as

$$C = C_0 + C_m \sin \omega t$$

the current i is

$$i = i_m \cos t\ \omega t$$

where

$$i_m = V C_m \omega$$

(i_m is the peak value of the current). The rms value of the current is given by:

$$i_{rms} = \frac{VC_m\omega}{\sqrt{2}} \tag{7.3}$$

For a constant angular frequency ω, the current is proportional to the applied voltage V. More often, the generated current is rectified and measured by a moving coil meter. Generating voltmeter can be used for a.c. voltage measurements also provided the angular frequency ω is the same or equal to half that of the supply frequency.

A generating voltmeter with a rotating cylinder consists of two excitating 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 whose arithmetic mean may be calculated from:

$$i = \frac{n}{30}\Delta C\, V, \qquad \text{where } \Delta C = C_{max} - C_{min}$$

For a symmetric voltage $C_{min} = 0$. When the voltage is not symmetrical, one of the electrodes is grounded and C_{min} has a finite value. The factor of proportionality $\frac{n}{30} \cdot \Delta C$ is determined by calibration.

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 C_{max} and the crest value occur at the same instant.

Generating voltmeters employ rotating sectors or vanes for variation of capacitance. Figure 7.4 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 S_0, S_1, and S_2. The rotor S_0 is driven at a constant speed by a synchronous motor at a suitable speed (1500, 1800, 3000, or 3600 rpm). The rotor vanes of S_0 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

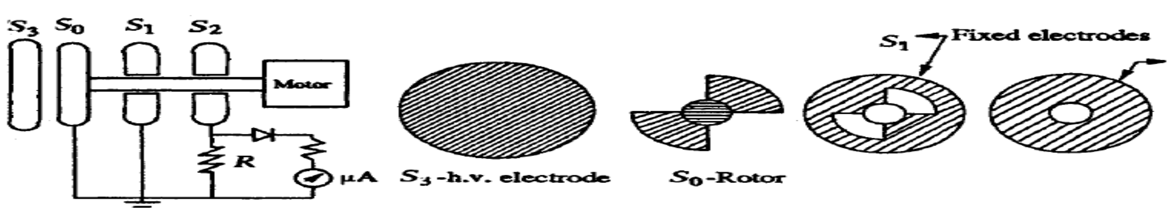


Fig. 7.4 Schematic diagram of a generating voltmeter (rotating vane type)

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 Graaff 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, and
(*iii*) disturbance in position and mounting of the electrodes make the calibration invalid.

7.2.2 Capacitance Potential Dividers and Capacitance Voltage Transformers

The errors due to harmonic voltages can be eliminated by the use of capacitive voltage dividers with an electrostatic voltmeter or a high impedance meter such as a V.T.V.M. If the meter is connected through a long cable, its capacitance has to be

taken into account in calibration. Usually, a standard compressed air or gas condenser is used as C_1 (Fig. 7.10), and C_2 may be any large capacitor (mica, paper, or any low loss condenser). C_1 is a three terminal capacitor and is connected to C_2 through a shielded cable, and C_2 is completely shielded in a box to avoid stray capacitances. The applied voltage V_1 is given by

$$V_1 = V_2 \left(\frac{C_1 + C_2 + C_m}{C_1} \right) \quad (7.13)$$

where C_m is the capacitance of the meter and the connecting cable and the leads and V_2 is the meter reading.

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 a V.T.V.M. or an electrostatic voltmeter, a CVT can be connected to a low impedance device like a wattmeter pressure coil or a relay coil. CVT can supply a load of a few VA. The schematic diagram of a CVT with its equivalent circuit is given in Fig. 7.11. C_1 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 C_2. The transformer ratio is chosen on economic grounds, and the h.v. winding rating may be 10 to 30 kV with the l.v. 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

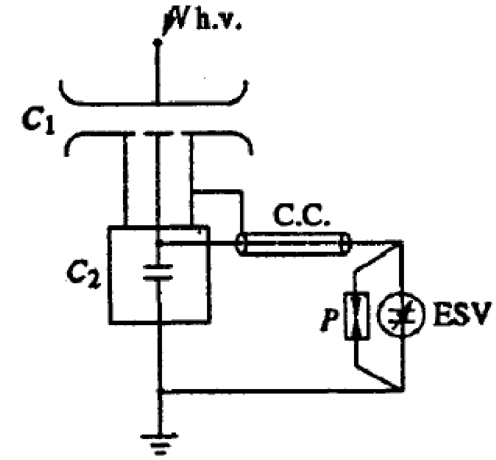


Fig. 7.10 Capacitance potential divider

C_1 — Standard compressed gas h.v. condenser
C_2 — Standard low voltage condenser
ESV — Electrostatic voltmeter
P — Protective gap
C.C. — Connecting cable

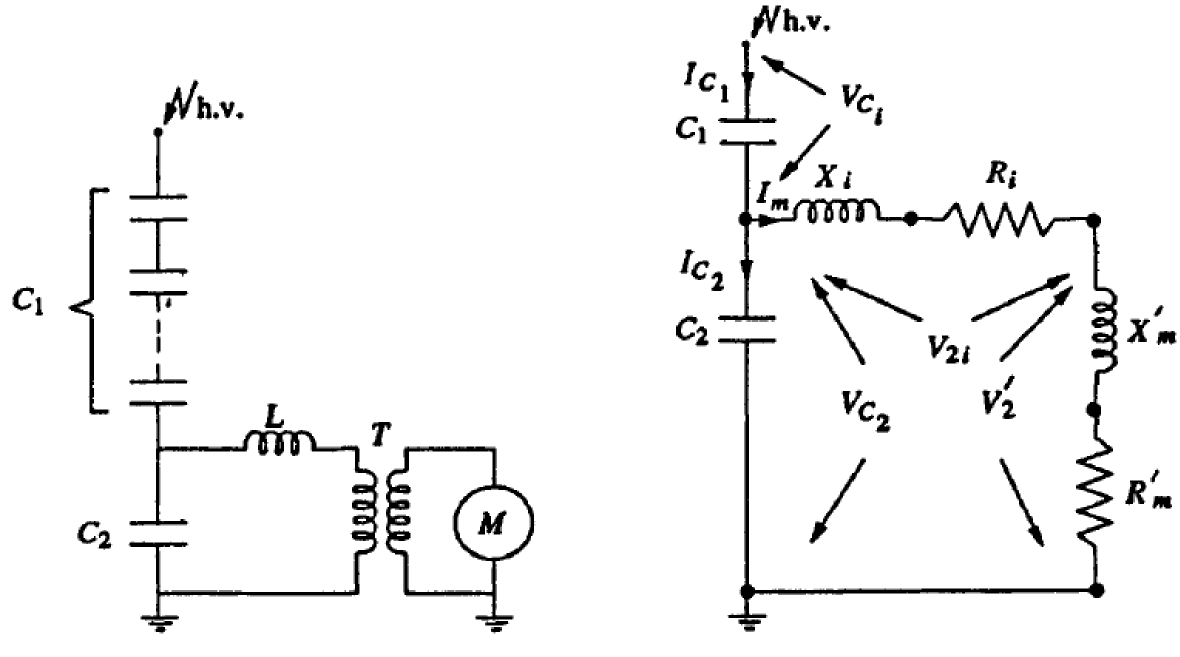
$$\omega (L + L_T) = \frac{1}{\omega(C_1 + C_2)} \tag{7.14}$$

where, L = inductance of the choke, and

L_T = equivalent inductance of the transformer referred to h.v. side.

The voltage V_2 (meter voltage) will be in phase with the input voltage V_1.

The phasor diagram of CVT under resonant conditions is shown in Fig. 7.11. The meter is taken as a resistive load, and X'_m is neglected. The voltage across the load referred to the divider side will be $V'_2 = (I'_m R'_m)$ and $V_{C_2} = V'_2 + I_m(R_e + X_e)$. It is clear from the phasor diagram that V_1 (input voltage) = $(V_{C_1} + V_{C_2})$ and is in phase



(a) Schematic representation (b) Equivalent circuit

Fig. 7.11 Capacitive voltage transformer (CVT)

with V_2', the voltage across the meter. R_e and X_e include the potential transformer resistance and leakage reactance. Under this condition, the voltage ratio becomes

$$a = (V_1/V_2) \simeq (V_{C_1} + V_{Ri} + V_2')/V_2' \tag{7.15}$$

(neglecting the voltage drop $I_m \cdot X_e$ which is very small compared to the voltage V_{C_1}) where V_{Ri} is the voltage drop in the transformer and choke windings.

The advanges 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.

7.2.4 Electrostatic Voltmeters

Principle

In electrostatic fields, the attractive force between the electrodes of a parallel plate condenser is given by

$$F = \left|\frac{-\delta W_s}{dS}\right| = \left|\frac{\delta}{\delta S}\left(\tfrac{1}{2}CV^2\right)\right| = \left|\tfrac{1}{2}V^2\frac{\delta C}{\delta S}\right|$$

$$= \tfrac{1}{2}\varepsilon_0 V^2\frac{A}{S^2} = \tfrac{1}{2}\,\varepsilon_0 A\left(\frac{V}{s}\right)^2 \qquad (7.18)$$

where,
V = applied voltage between plates,
C = capacitance between the plates,
A = area of cross-section of the plates,
s = separation between the plates,
ε_0 = permittivity of the medium (air or free space), and
W_s = work done in displacing a plate

When one of the electrodes is free to move, the force on the plate can be measured by controlling it by a spring or balancing it with a counter weight. For high voltage measurements, a small displacement of one of the electrodes by a fraction of a millimetre to a few millimetres is usually sufficient for voltage measurements. As the force is proportional to the square of the applied voltage, the measurement can be made for a.c. or d.c. voltages.

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 counterweight 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 ($R \geq 10^{13}\ \Omega$). Hence they are considered as devices with high input impedance. The upper frequency limit for a.c. applications is determined from the following considerations:

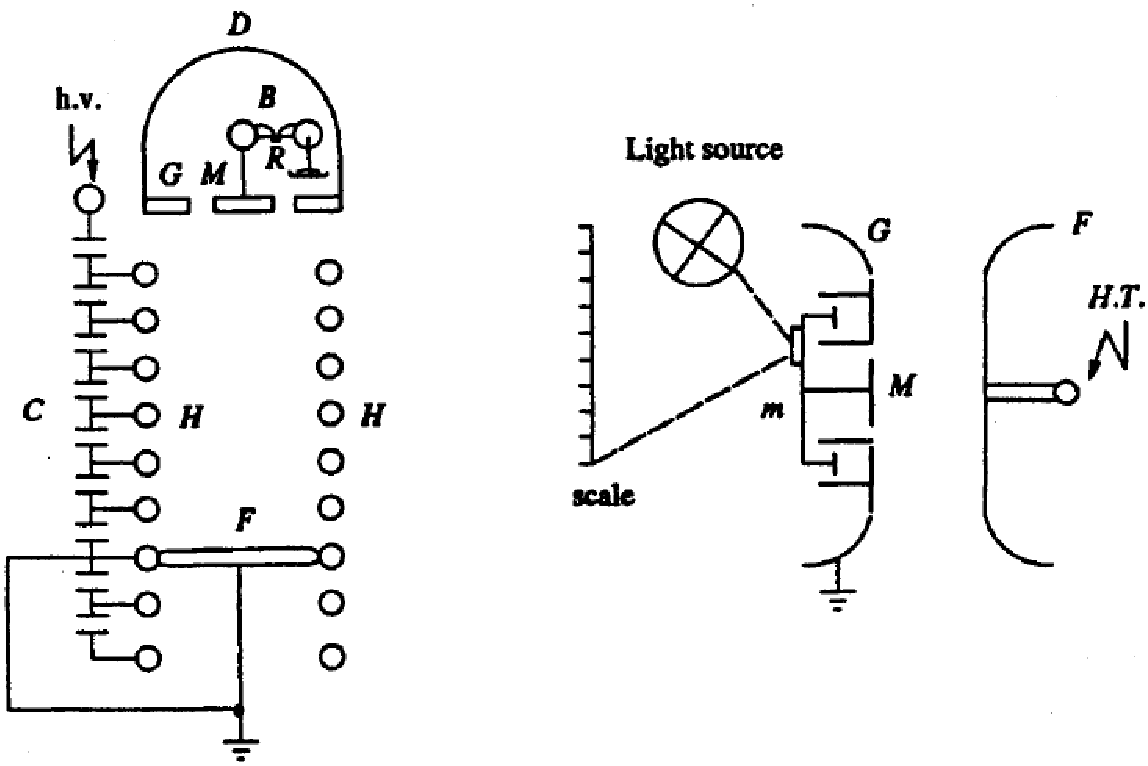
(*i*) natural frequency of the moving system,

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

(*iii*) the *R-C* behaviour of the retaining or control spring (due to the frictional resistance and elastance).

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. 7.13. 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 is 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



(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

Fig. 7.13 Electrostatic voltmeter

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 kV rms and above.

The constructional details of an absolute electrostatic voltmeter is given in Fig. 7.13a. 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 a beam 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 15 atm. Working stresses as high as 100 kV/cm may be used in an electrostatic meter in vacuum. With compressed gas or vacuum as medium, the meter is compact and much smaller in size.

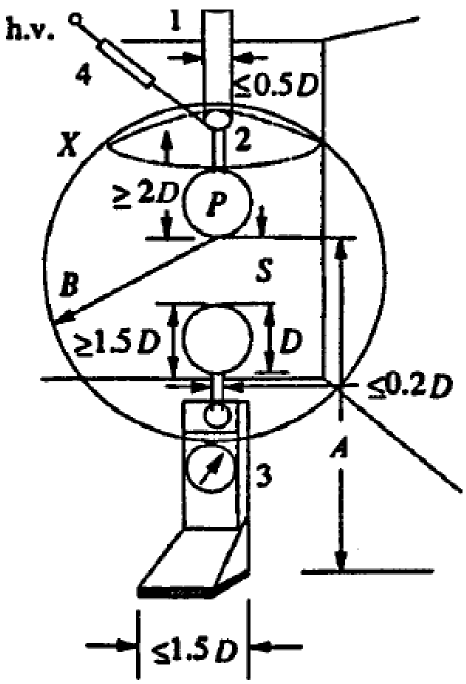
SPHERE GAPS

7.2.6 Spark Gaps for Measurement of High d.c., a.c. and Impulse Voltages (Peak Values)

A uniform field spark gap will always have a sparkover 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 sparkover voltage of 30 kV (peak) at 1 cm spacing in air at 20°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 $\geq 0.5\ \mu$ s). As such, sphere gaps can be used for radio frequency a.c. voltage peak measurements also (up to 1 MHz).

Sphere Gap Measurements

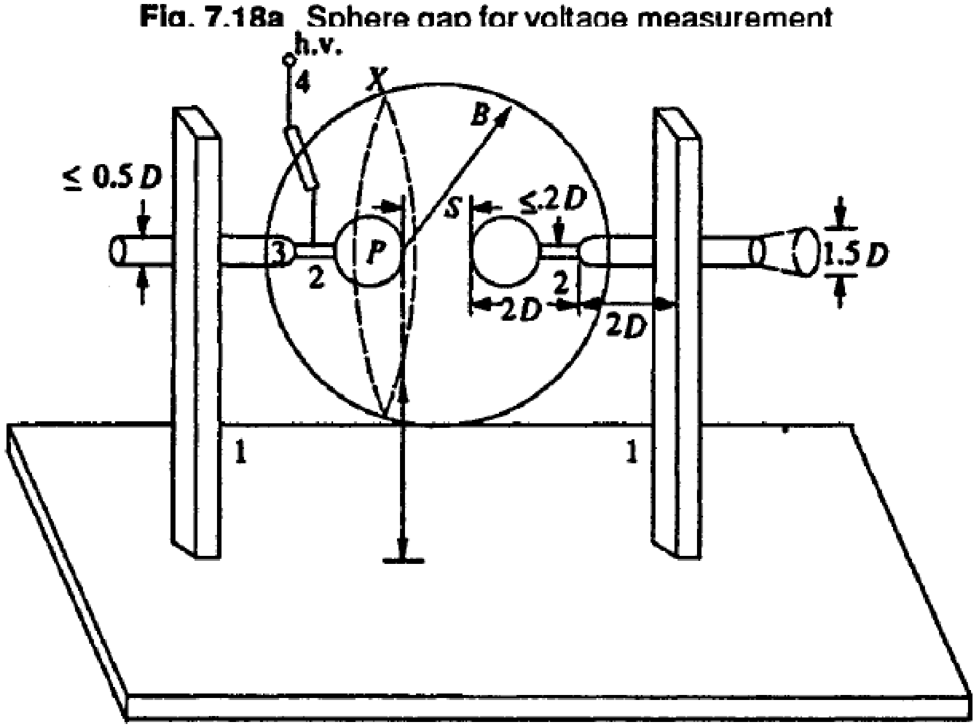
Sphere gaps can be arranged either (*i*) vertically with lower sphere grounded, or (*ii*) horizontally with both spheres connected to the source voltage or one sphere grounded. In horizontal configurations, it is generally arranged such that both spheres are symmetrically at high voltage above the ground. The two spheres used are identical in size and shape. The schematic arrangement is shown in Figs. 7.18a and 7.18b. The voltage to be measured is applied between the two spheres and the distance



1 — Insulator support
2 — Sphere shank
3 — Operating gear and motor for changing gap distance
4 — H.V. connection
P — Sparking point
D — Diameter of the sphere
S — Spacing
A — Height of *P* above earth
B — Radius of the clearance from external structures
X — High voltage lead should not pass through this plane within a distance *B* from *P*

(a) Vertical arrangement of sphere gap

Fig. 7.18a Sphere gap for voltage measurement



(b)

Fig. 7.18b Horizontal arrangement of sphere gap (Legend as in Fig. 7.18a) or spacing S between them gives a measure of the sparkover 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 than 500 Ω in the case of impulse voltages.

In the case of a.c. peak value and d.c. voltage measurements, the applied voltage is uniformly increased until sparkover 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 and 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 sparkover voltage measurement is to be made before actual measurements are made.

The flashover voltage for various gap distances and standard diameters of the spheres used are given in Tables 7.3 and 7.4 respectively. The values of sparkover voltages are specified in BS : 358, IEC Publication 52 of 1960 and IS : 1876 of 1962. The clearances necessary are shown in Figs. 7.18a and 7.18b for measurements to be within ±3%. The values of *A* and *B* indicated in the above figures are given in Table 7.5.

Sphere Gap Construction and Assembly

Sphere gaps are made with two metal spheres of identical diameters *D* with their shanks, operating gear, and insulator supports (Fig. 7.18a or b). Spheres are generally made of copper, brass, or aluminium; the latter is used due to low cost. The standard diameters for the spheres are 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150, and 200 cm. The spacing is so designed and chosen such that flashover occurs near the sparking point *P*. The spheres are carefully designed and fabricated so that their surfaces are smooth and the curvature is uniform. The radius of curvature measured with a spherometer at various points over an area enclosed by a circle of 0.3 *D* around the sparking point should not differ by more than ±2% of the nominal value. The surface of the sphere should be free from dust, grease, or any other coating. The surface should be maintained clean but need not be polished. If excessive pitting occurs due to repeated sparkovers, they should be smoothened. The dimensions of the shanks used, the grading ring used (if necessary) with spheres, the ground clearances, etc. should follow the values indicated in Figs. 7.18a and 7.18b and Table 7.5. The high voltage conductor should be arranged such that it does not affect the field configuration. Series resistance connected should be outside the shanks at a distance 2*D* away from the high voltage sphere or the sparking point *P*.

Irradiation of sphere gap is needed when measurements of voltages less than 50 kV are made with sphere gaps of 10 cm diameter or less. The irradiation may be obtained from a quartz tube mercury vapour lamp of 40 W rating. The lamp should be at a distance *B* or more as indicated in Table 7.5.

Table 7.5 Clearances for Sphere Gaps

D (cm)	Value of A: Max	Value of A: Min	Value of *B* (min)
up to 6.25	7 *D*	9 *D*	14*S*
10 to 15	6 *D*	8 D	12*S*
25	5 *D*	7 *D*	10*S*
50	4 *D*	6 D	8*S*
100	3.5 *D*	5 D	7*S*
150	3 *D*	4 D	6*S*
200	3 *D*	4 D	6*S*

A and *B* are clearances as shown in Figs. 7.18a and 7.18b.
D = diameter of the sphere; S = spacing of the gap; and $S/D \leq 0.5$.

Factors Influencing the Sparkover Voltage of Sphere Gaps

Various factors that affect the sparkover 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.

Detailed investigations of the above factors have been made and analysed by Craggs and Meek[1], Kuffel and Abdullah[2], Kuffel[15], Davis and Boulder[16], and several other investigators. Only a few important factors are presented here.

(I) Effect of nearby earthed objects

The effect of nearby earthed objects was investigated by Kuffel[14] by enclosing the earthed sphere inside an earthed cylinder. It was observed that the sparkover voltage is reduced. The reduction was observed to be

$$\Delta V = m \log (B/D) + C \tag{7.21}$$

where, ΔV = percentage reduction,

B = diameter of earthed enclosing cylinder,

D = diameter of the spheres,

S = spacing, and m and C are constants.

The reduction was less than 2% for $S/D \leq 0.5$ and $B/D \geq 0.8$. Even for $S/D \approx 1.0$ and $B/D \geq 1.0$ the reduction was only 3%. Hence, if the specifications regarding the clearances are closely observed the error is within the tolerances and accuracy specified. The variation of breakdown voltage with A/D ratio is given in Figs. 7.19a and b for a 50 cm sphere gap. The reduction in voltage is within the accuracy limits, clearances are closely observed the error is within the tolerances and accuracy specified. The variation of breakdown voltage with A/D ratio is given in Figs. 7.19a and b for a 50 cm sphere gap. The reduction in voltage is within the accuracy limits, if S/D is kept less than 0.6. A in the above ratio A/D is the distance from sparking point to horizontal ground plane (also shown in Fig. 7.19).

(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 sparkover 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 gaps of gap spacing less than 1 cm for obtaining consistent values.

(iv) Effect of polarity and waveform

It has been observed that the sparkover 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 1/50 μ s waveform. Similarly, the wave front and wave tail durations also influence the breakdown voltage. For wave fronts of less than 0.5 μ s 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.

MEASUREMENT OF HIGH D.C. A.C, AND IMPULSE CURRENTS

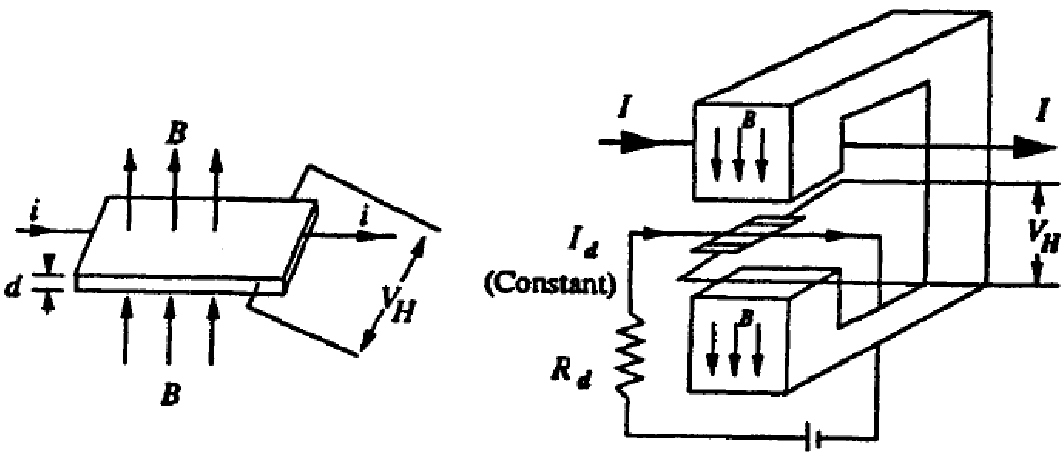
Hall Generators for d.c. Current Measurements

The principle of the "Hall effect" is made use of in measuring very high direct currents. If an electric current flows through a metal plate located in a magnetic field perpendicular to it, Lorenz forces will deflect the electrons in the metal structure in a direction normal to the direction of both the current and the magnetic field. The charge displacement generates an emf in the normal direction, called the "Hall voltage". The Hall voltage is proportional to the current i, the magnetic flux density B, and the reciprocal of the plate thickness d; the proportionality constant R is called the "Hall coefficient".

$$V_H = R\frac{B_i}{d} \tag{7.34}$$

For metals the Hall coefficient is very small, and hence semi-conductor materials are used for which the Hall coefficient is high.

In large current measurements, the current carrying conductor is surrounded by an iron cored magnetic circuit, so that the magnetic field intensity $H = (I/\delta)$ is produced in a small air gap in the core. The Hall element is placed in the air gap (of thickness δ), and a small constant d.c. current is passed through the element. The schematic arrangement is shown in Fig. 7.43. The voltage developed across the Hall element in the normal direction is proportional to the d.c. current I. It may be noted that the Hall coefficient R depends on the temperature and the high magnetic field strengths, and suitable compensation has to be provided when used for measurement of very high currents.



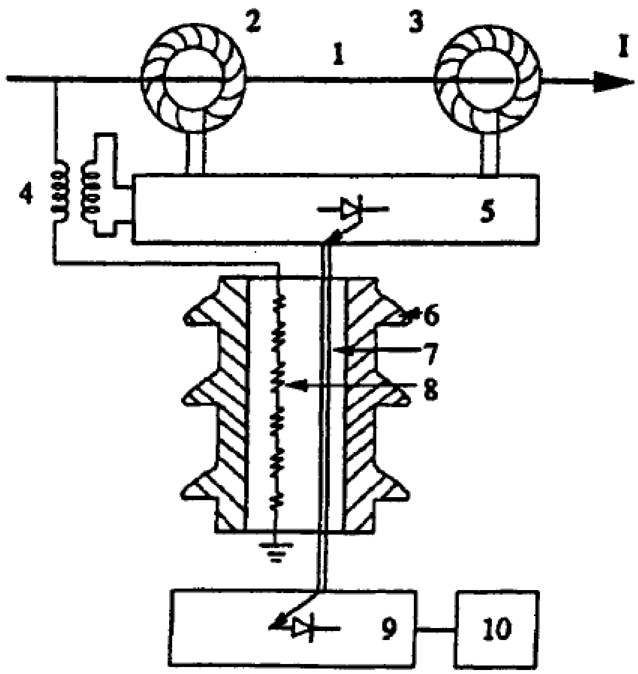
$$V_H = R \cdot \frac{Bi}{d}; \; R = \text{Hall coefficient}$$

(a) Hall effect (b) Hall generator

Fig. 7.43 Hall generator for measuring high d.c. currents

7.3.2 Measurement of High Power Frequency Alternating Currents

Measurement of power frequency currents are normally done using current transformers only, as use of current shunts involves unnecessary power loss. Also the current transformers provide electrical isolation from high voltage circuits in power systems. Current transformers used for extra high voltage (EHV) systems are quite different from the conventional designs as they have to be kept at very high voltages from the ground. A new scheme of current transformer measurements introducing



1. EHV conductor
2. Current sensing transformer
3. Power supply C.T.
4. Power supply P.T.
5. Analog-digital signal converter
6. Insulator for EHV
7. Electro-optical glass fibre
8. Series high ohmic resistance
9. Digital-analog converter
10. Indicating or recording unit

Fig. 7.44 Current transformer with electro-optical signal converter for EHV systems

electro-optical technique is described in Fig. 7.44. A voltage signal proportional to the measuring current is generated and is transmitted to the ground side through an electro-optical device. Light pulses proportional to the voltage signal are transmitted by a glass-optical fibre bundle to a photodetector and converted back into an analog voltage signal. Aceuracies better than ±0.5% have been obtained at rated current as well as for high short circuit currents. The required power for the signal converter and optical device are obtained from suitable current and voltage transformers as shown in the Fig. 7.44.

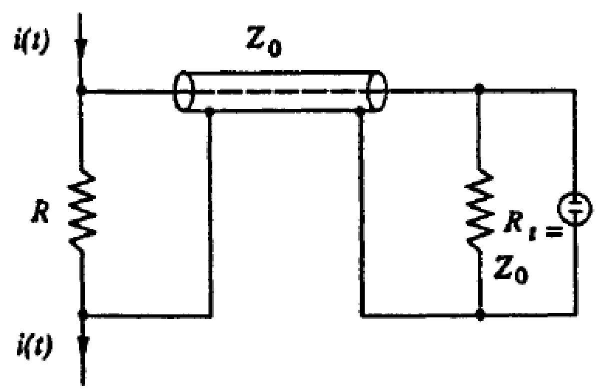
7.3.3 Measurement of High Frequency and Impulse Currents

In power system applications as well as in other scientific and technical fields, it is often necessary to determine the amplitude and waveforms of rapidly varying high currents. High impulse currents occur in lightning discharges, electrical arcs and post arc phenomenon studies with circuit breakers, and with electric discharge studies in plasma physics. The current amplitudes may range from a few amperes to few hundred kiloamperes. The rate of rise for such currents can be as high as 10^6 to 10^{12} A/s, and rise times can vary from few microseconds to few nano seconds. In all such cases the sensing device should be capable of measuring the signal over a wide frequency band. The methods that are frequently employed are (*i*) resistive shunts, (*ii*) magnetic potentiometers or probes, and (*iii*) the Faraday and Hall effect devices.

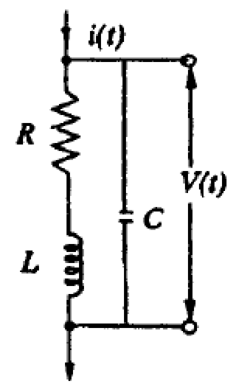
The accuracy of measurement varies from 1 to 10%. In applications where only peak value measurement is required, peak reading voltmeters described in Sec. 7.2.8 may be employed with a suitable shunt.

Resistive shunts

The most common method employed for high impulse current measurements is a low ohmic pure resistive shunt shown in Fig. 7.45. The equivalent circuit is shown in Fig. 7.45b. The current through the resistive element R produces a voltage drop $v(t) = i(t)R$. The voltage signal generated is transmitted to a CRO through a coaxial cable of surge impedance Z_0. The cable at the oscilloscope end is terminated by a resistance $R_i = Z_0$



(a) Ohmic shunt



(b) Equivalent circuit of the shunt

Fig. 7.45 Calibrated low ohmic shunt and its equivalent circuit for impulse current measurements to avoid reflections. The resistance element, because of its large dimensions will have a residual inductance L and a terminal capacitance C. The inductance L may be neglected at low frequencies (ω), but becomes appreciable at higher frequencies (ω) when ωL is of the order of R. Similarly, the value of C has to be considered when the reactance $1/\omega C$ is of comparable value. Normally L and C become significant above a frequency of 1 MHz. The resistance value usually ranges from 10 $\mu\Omega$ to few milliohms, and the voltage drop is usually about a few volts. The value of the resistance is determined by the thermal capacity and heat dissipation of the shunt.

The voltage drop across the shunt in the complex frequency domain may be written as:

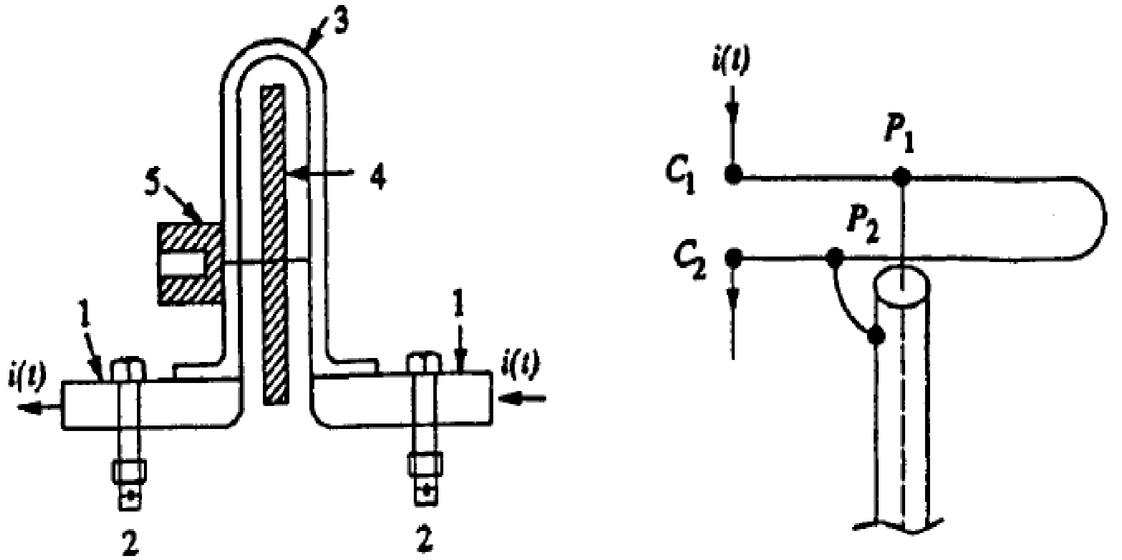
$$V(s) = \frac{(R + Ls)}{(1 + RCs + LCs^2)} I(s) \tag{7.35}$$

where s is the complex frequency or Laplace transform operator and $V(s)$ and $I(s)$ are the transformed quantities of the signals $v(t)$ and $i(t)$. With the value of C neglected it may be approximated as:

$$V(s) = (R + Ls)I(s) \tag{7.36}$$

It may be noted here that the stray inductance and capacitance should be made as small as possible for better frequency response of the shunt. The resistance shunt is usually designed in the following manner to reduce the stray effects.

(*a*) Bifilar flat strip design,
(*b*) coaxial tube or Park's shunt design, and
(*c*) coaxial squirrel cage design



(a) Schematic arrangement

(b) Connection for potential and current terminals

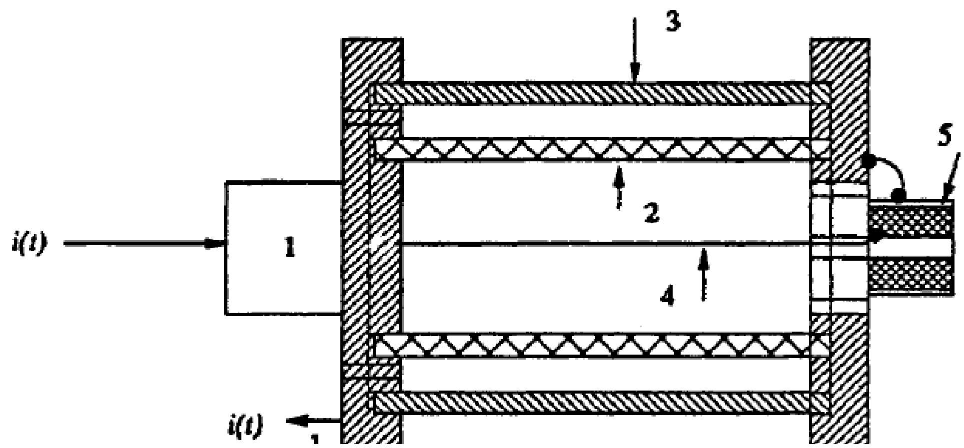
1. Metal base
2. Current terminals (C_1 and C_2)
3. Bifilar resistance strip
4. Insulating spacer (teflon or bakelite)
5. Coaxial UHF connector

P_1, P_2 — Potential terminals

Fig. 7.46 Bifilar flat strip resistive shunt

(a) Bifilar Strip Shunt

The bifilar design (Fig. 7.46) consists of resistor elements wound in opposite directions and folded back, with both ends insulated by a teflon or other high quality insulation. The voltage signal is picked up through a ultra high frequency (UHF) coaxial connector. The shunt suffers from stray inductance associated with the resistance element, and its potential leads are linked to a small part of the magnetic flux generated by the current that is measured. To overcome these problems, coaxial shunts are chosen.



1. Current terminals
2. Coaxial cylindrical resistive element
3. Coaxial cylindrical return conductor (copper or brass tube)
4. Potential pick up lead
5. UHF coaxial connector

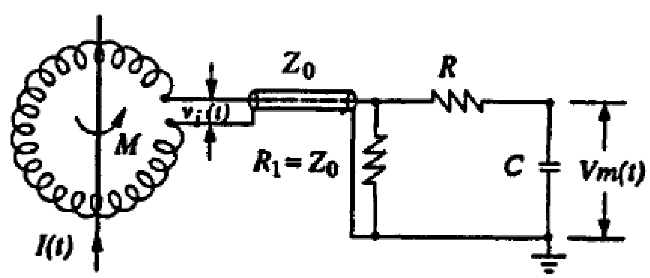
Fig. 7.47 Schematic arrangement of a coaxial ohmic shunt

Measurement of High Impulse Currents Using Magnetic Potentiometers (Rogowski Coils) and Magnetic Links

If a coil is placed surrounding a current carrying conductor, the voltage signal induced in the coil is $v_i(t) = MdI(t)/dt$ where M is the mutual inductance between the conductor and the coil, and $I(t)$ is the current flowing in the conductor. Usually, the coil is wound on a nonmagnetic former of toroidal shape and is coaxially placed surrounding the current carrying conductor. The number of turns on the coil is chosen to be large, to get enough signal induced. The coil is wound cross-wise to reduce the leakage inductance. Usually an integrating circuit (see Fig. 7.52) is employed to get the output signal voltage proportional to the current to be measured. The output voltage is given by

$$V_m(t) = \frac{1}{CR}\int_0^t v_i(t) = \frac{M}{CR} I(t) \tag{7.42}$$

Rogowski coils with electronic or active integrator circuits have large bandwidths (about 100 MHz). At frequencies greater than 100 MHz the response is affected by



$V_i(t)$ — Induced voltage in the coil $= M\frac{d[I(t)]}{dt}$

Z_0 — Coaxial cable of surge impedance Z_0

R-C — Integrating network

Fig. 7.52 Rogowski coil for high impulse current measurements

the skin effect, the capacitance distributed per unit length along the coil, and due to the electromagnetic interferences. However, miniature probes having nanosecond response time are made using very few turns of copper strips for UHF measurements.

Magnetic Links

Magnetic links are short high retentivity steel strips arranged on a circular wheel or drum. These strips have the property that the remanent magnetism for a current pulse of 0.5/5 μ s is same as that caused by a d.c. current of the same value. Hence, these can be used for measurement of peak value of impulse currents. The strips will be kept at a known distance from the current carrying conductor and parallel to it. The remanent magnetism is then measured in the laboratory from which the peak value of the current can be estimated. These are useful for field measurements, mainly for estimating the lightning currents on the transmission lines and towers. By using a number of links, accurate measurement of the peak value, polarity, and the percentage oscillations in lightning currents can be made.

Other Techniques for Impulse Current Measurements

(*a*) *Hall Generators*

Hall generators described earlier can be used for a.c. and impulse current measurements also. The bandwidth of such devices was found to be about 50 MHz with suitable compensating devices and feedback. The saturation effect in magnetic core can be minimized, and these devices are successfully used for post arc and plasma current measurements.

(*b*) *Faraday Generator or Ammeter*

When a linearly polarized light beam passes through a transparent crystal in the presence of a magnetic field, the plane of polarization of the light beam undergoes rotation.

The angle of rotation α is given by:

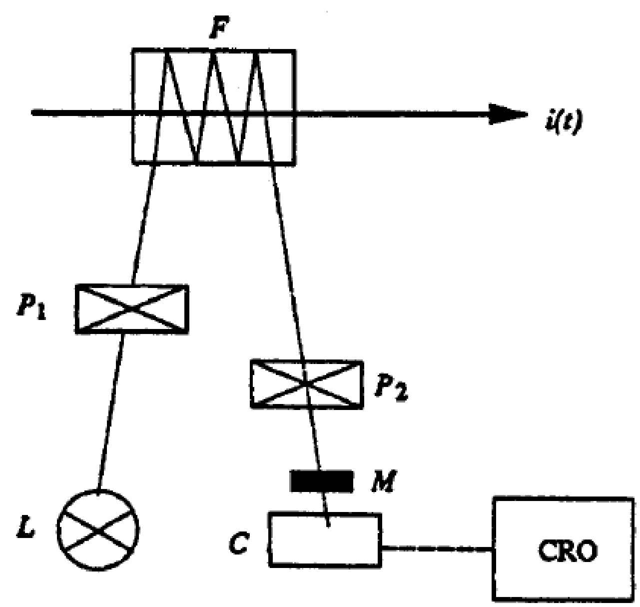
$$\alpha = VBl \tag{7.43}$$

where, $V =$ a constant of the crystal which depends on the wavelength of the light,

$B =$ magnetic flux density, and

$l =$ length of the crystal.

To measure the waveform of a large current in a EHV system an arrangement shown in Fig. 7.53 may be employed. A beam of light from a stabilized light source is passed through a polarizer P_1 to fall on a crystal F placed parallel to the magnetic field produced by the current I. The light beam undergoes rotation of its plane of polarization. After passing through the analyser, the beam is focused on a photo-multiplier, the output of which is fed to a CRO. The output beam is filtered through a filter M, which allows only the monochromatic light. The relation between the oscillograph display and the current to be measured are complex but can be determined. The advantages of this method are that (*i*) there is no electric connection between the source and the device, (*ii*) no thermal problems even for large currents of several kiloamperes, and (*iii*) as the signal transmission is through an optical system, no insulation problems or difficulties arise for EHV systems. However, this device does not operate for d.c. currents.



L — Light source
P1 — Polarizer
P2 — Analyser
F — Crystal
CRO — Recording oscillograph
M — Filter
C — Photo-multiplier

Fig. 7.53 Magneto-optical method of measuring impulse currents

7.4 CATHODE RAY OSCILLOGRAPHS FOR IMPULSE VOLTAGE AND CURRENT MEASUREMENTS

When waveforms of rapidly varying signals (voltages or currents) have to be measured or recorded, certain difficulties arise. The peak values of the signals in high voltage measurements are too large, may be several kilovolts or kiloamperes. Therefore, direct measurement is not possible. The magnitudes of these signals are scaled down by voltage dividers or shunts to smaller voltage signals. The reduced signal $V_m(t)$ is normally proportional to the measured quantity. The procedure of transmitting the signal and displaying or recording it is very important. The associated electromagnetic fields with rapidly changing signals induce disturbing voltages, which have to be avoided. The problems associated in the above procedure are discussed in this section.

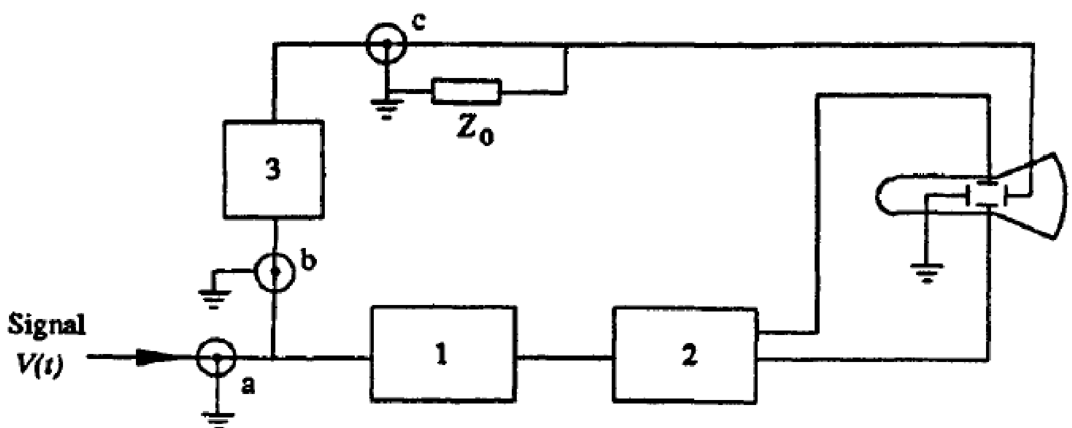
7.4.1 Cathode Ray Oscillographs for Impulse Measurements

Modern oscillographs are sealed tube hot cathode oscilloscopes with photographic arrangement for recording the waveforms. The cathode ray oscilloscope for impulse work normally has input voltage range from 5 mV/cm to about 20 V/cm. In addition, there are probes and attenuators to handle signals up to 600 V (peak to peak). The bandwidth and rise time of the oscilloscope should be adequate. Rise times of 5 n s and bandwidth as high as 500 MHz may be necessary.

Sometimes high voltage surge test oscilloscopes do not have vertical amplifier and directly require an input voltage of 10 V. They can take a maximum signal of about 100 V (peak to peak) but require suitable attenuators for large signals.

Oscilloscopes are fitted with good cameras for recording purposes. Tektronix model 7094 is fitted with a lens of 1 : 1.2 polaroid camera which uses 10,000 ASA film which possesses a writing speed of 9 cm/n s.

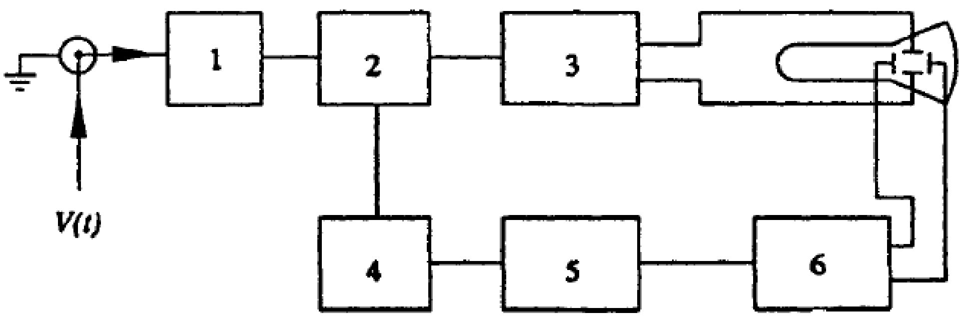
With rapidly changing signals, it is necessary to initiate or start the oscilloscope time base before the signal reaches the oscilloscope deflecting plates, otherwise a portion of the signal may be missed. Such measurements require an accurate initiation of the horizontal time base and is known as triggering. Oscilloscopes are normally provided with both internal and external triggering facility. When external triggering is used, as with recording of impulses, the signal is directly fed to actuate the time



1. Trigger amplifier
2. Sweep generator
3. External delay line

(a) Vertical amplifier input
(b) Input to delay line
(c) Output of delay line to CRO *Y* plates

Fig. 7.54a Block diagram of a surge test oscilloscope (older arrangement)



1. Plug-in amplifier
2. *Y* amplifier
3. Internal delay line
4. Trigger amplifier
5. Sweep generator
6. *X* amplifier

Fig. 7.54b Simplified block diagram of surge test oscilloscopes (recent schemes)

base and then applied to the vertical or *Y* deflecting plates through a delay line. The delay is usually 0.1 to 0.5 μ s. The delay is obtained by:

(1) A long interconnecting coaxial cable 20 to 50 m long. The required triggering is obtained from an antenna whose induced voltage is applied to the external trigger terminal.

(2) The measuring signal is transmitted to the CRO by a normal coaxial cable. The delay is obtained by an externally connected coaxial long cable to give the necessary delay. This arrangement is shown in Fig. 7.54.

(3) The impulse generator and the time base of the CRO are triggered from an electronic tripping device. A first pulse from the device starts the CRO time base and after a predetermined time a second pulse triggers the impulse generator.

TEXT / REFERENCE BOOKS

1. M. S. Naidu and V. Kamaraju, 'High Voltage Engineering', 5thEdition Tata McGraw Hill Publishing Co. Ltd., New Delhi, 2013.
2. E.Kuffel and M.Abdullah, "High Voltage Engineering" -Per gammon Press, Oxford, 1970.
3. C.L.WADHWA, "High Voltage Engineering" -New Age International (P) Ltd, Publishers, 2007
4. E.Kuffel and W.s. Zaengal, "High Voltage Engineering Fundamentals",2nd Edition, Butterworth Heinemann, 2000.
5. H.M.Ryam, "High voltage Engineering and testing", 2nd Edition, 2001, IEEE power and energy series 32.

SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited "A" Grade by NAAC | 12B Status by UGC | Approved by AICTE
www.sathyabama.ac.in

SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - V
High Voltage Engineering – SEE1402

UNIT V

TESTING OF ELECTRICAL APPARATUS & INSULATION CO-ORDINATION

TESTS ON INSULATORS

10.1.2 Tests on Insulators

The tests that are normally conducted are usually subdivided as (i) type tests, and (ii) the routine tests. Type tests are intended to prove or check the design features and the quality. The routine tests are intended to check the quality of the individual test piece. Type tests are done on samples when new designs or design changes are introduced, whereas the routine tests are done to ensure the reliability of the individual test objects and quality and consistency of the materials used in their manufacture.

High voltage tests include (i) the power frequency tests, and (ii) impulse tests. All the insulators are tested for both categories of test.

Power Frequency Tests

(a) Dry and Wet Flashover Tests In these tests the a.c. voltage of power frequency is applied across the insulator and increased at a uniform rate of about 2 per cent per second of 75% of the estimated test voltage, to such a value that a breakdown occurs along the surface of the insulator. If the test is conducted under normal conditions without any rain or precipitation, it is called "dry flashover test". If the test is done under conditions of rain, it is called "wet flashover test". In general, wet tests are not intended to reproduce the actual operating conditions, but only to provide a criterion based on experience that a satisfactory service operation will be obtained. The test object is subjected to a spray of water of given conductivity by means of

nozzles. The spray is arranged such that the water drops fall approximately at an inclination of 45° to the vertical. The test object is sprayed for at least one minute before the voltage application, and the spray is continued during the voltage application. The characteristics of the spray are

(*i*)	Precipitation rate	: 3 ± 10% (mm/min)
(*ii*)	direction	: 45° to the vertical
(*iii*)	conductivity of water	: 100 micro Siemens ± 10%
(*iv*)	water temperature	: ambient ±15°C

The International Electrotechnical Commission (IEC) in its recent document (No. 42 of 1972) has revised the test procedure and precipitation conditions as follows.
Average precipitation rate:

vertical component = 1 to 1.5 mm/min

horizontal component = 1 to 1.5 mm/min

limits for individual measurements = 0.5 to 2.0 mm/min.

temperature of collected water = ambient temperature ±15° C.

and the conductivity of water corrected to 20°C = 100 ± 15 micro Siemens

Specifications are being modified for application of 15 positive and 15 negative impulses (reference 14). Two in each set are allowed to flashover. If more than two flashovers occur in each set, then the insulator is deemed to have failed the test. This procedure is satisfactorily equivalent to the one mentioned above.

(b) Wet and Dry Withstand Tests (One Minute) In these tests, the voltage specified in the relevant specification is applied under dry or wet conditions for a period of one minute with an insulator mounted as in service conditions. The test piece should withstand the specified voltage.

Impulse Tests

(a) Impulse Withstand Voltage Test This test is done by applying standard impulse voltage of specified value under dry conditions with both positive and negative polarities of the wave. If five consecutive waves do not cause a flashover or puncture, the insulator is deemed to have passed the test. If two applications cause flashover, the object is deemed to have failed. If there is only one failure, additional

ten applications of the voltage wave are made. If the test object has withstood the subsequent applications, it is said to have passed the test.

(b) Impulse Flashover Test The test is done as above with the specified voltage. Usually, the probability of failure is determined for 40% and 60% failure values or 20% and 80% failure values, since it is difficult to adjust the test voltage for the exact 50% flashover values. The average value of the upper and the lower limits is taken. The insulator surface should not be damaged by these tests, but slight marking on its surface or chipping off of the cement is allowed.

(c) Pollution Testing Because of the problem of pollution of outdoor electrical insulation and consequent problems of the maintenance of electrical power systems, pollution testing is gaining importance. The normal types of pollution are (i) dust, micro-organisms, bird secretions, flies, etc., (ii) industrial pollution like smoke, petroleum vapours, dust, and other deposits, (iii) coastal pollution in which corrosive and hygroscopic salt layers are deposited on the insulator surfaces, (iv) desert pollution in which sand storms cause deposition of sand and dust layers, (v) ice and fog deposits at high altitudes and in polar countries. These pollutions cause corrosion, non-uniform gradients along the insulator strings and surface of insulators and also cause deterioration of the material. Also, pollution causes partial discharges and radio interference. Hence, pollution testing is important for extra high voltage systems.

At present there is no standard pollution test available. The popular test that is normally done is the salt fog test. In this test, the maximum normal withstand voltage is applied on the insulator and then artificial salt fog is created around the insulator by jets of salt water and compressed air. If the flashover occurs within one hour, the test is repeated with fog of lower salinity, otherwise, with a fog of higher salinity. The maximum salinity at which the insulator withstands three out of four tests without flashover is taken as the representative figure. Much work is yet to be done to standardize the test procedures.

10.1.3 Testing of Bushings

Power Frequency Tests

(a) Power Factor—Voltage Test In this test, the bushing is set up as in service or immersed in oil. It is connected such that the line conductor goes to the high voltage side and the tank or earth portion goes to the detector side of the high voltage Schering bridge. Voltage is applied up to the line value in increasing steps and then reduced. The capacitance and power factor (or tan δ) are recorded at each step. The characteristic of power factor or tan δ versus applied voltage is drawn. This is a normal routine test but sometimes may be conducted on percentage basis.

(b) Internal or Partial Discharge Test This test is intended to find the deterioration or failure due to internal discharges caused in the composite insulation of the bushing. This is done by using internal or partial discharge arrangement (see Sec. 9.4). The voltage versus discharge magnitude as well as the quadratic rate gives an excellent record of the performance of the bushing in service. This is now a routine test for high voltage bushings.

(c) Momentary Withstand Test at Power Frequency This is done as per the Indian Standard Specifications, IS: 2099, applied to bushings. The test voltage is specified in the specifications. The bushing has to withstand without flashover or puncture for a minimum time (~ 30s) to measure the voltage. At present this test is replaced by the impulse withstand test.

(d) One Minute Wet Withstand Test at Power Frequency The most common and routine tests used for all electrical apparatuses are the one minute wet, and dry

voltage withstand tests. In wet test, voltage specified is applied to the bushing mounted as in service with the rain arrangement as described earlier. A properly designed bushing has to withstand the voltage without flashover for one minute. This test really does not give any information for its satisfactory performance in service, while impulse and partial discharge tests give more information.

(e) Visible Discharge Test at Power Frequency This test is intended for determining whether the bushing is likely to give radio interference in service, when the voltage specified in IS: 2099 is applied. No discharge other than that from the arcing horns or grading rings should be visible to the observers in a dark room. The test arrangement is the same as that of the withstand test, but the test is conducted in a dark room.

Impulse Voltage Tests

(a) Full Wave Withstand Test The bushing is tested for either polarity voltages as per the specifications. Five consecutive full waves of standard waveform are applied, and, if two of them cause flashover, the bushing is said to have failed in the test. If only one flashover occurs, ten additional applications are done. The bushing is considered to have passed the test if no flashover occurs in subsequent applications.

(b) Chopped Wave Withstand and Switching Surge Tests The chopped wave test is sometimes done for high voltage bushings (220 kV and 400 kV and above). Switching surge flashover test of specified value is now-a-days included for high voltage bushings. The tests are carried out similar to full wave withstand tests.

Thermal Tests

(a) Temperature Rise and Thermal Stability Tests The purpose of these tests is to ensure that the bushing in service for long does not have an excessive temperature rise and also does not go into the "thermal runaway" condition of the insulation used.

Temperature rise test is carried out in free air with an ambient temperature below 40°C at a rated power frequency (50 Hz) a.c. current. The steady temperature rise above the ambient air temperature at any part of the bushing should not exceed 45°C. The test is carried out for such a long time till the temperature is substantially constant, i.e. the increase in temperature rate is less than 1°C/hr. Sometimes, the bushings have to be operated along with transformers, of which the temperature reached may exceed 80°C. This temperature is high enough to produce large dielectric losses and thermal instability. For high voltage bushings this is particularly important, and hence the thermal stability test is done for bushings rated for 132 kV and above. The test is carried out with the bushing immersed in oil at a maximum temperature as in service, and the voltage applied is 86% of the nominal system voltage. This is approximately $\sqrt{2}$ times the working voltage of the bushing and hence the dielectric losses are about double the normal value. The additional losses account for the conductor ohmic losses. It has been considered unnecessary to specify the thermal stability test for oil-impregnated paper bushings of low ratings; but for the large high voltage bushings (1600 A, 400 kV transformer bushings, etc.), the losses in the conductor may be high enough to outweigh the dielectric losses.

It may be pointed out here, that the thermal stability tests are type tests. But in the case of large sized high voltage bushings, it may be necessary to make them routine tests.

10.2 TESTING OF ISOLATORS AND CIRCUIT BREAKERS

10.2.1 Introduction

In this section, the testing of isolators and circuit breakers is covered, giving common characteristics for both. While these characteristics are directly relevant to the testing of circuit breakers, they are not much relevant as far as the testing of isolators are concerned since isolators are not used for interrupting high currents. At best, they interrupt small currents of the order of 0.5 A (for rated voltages of 420 kV and below) which may be the capacitive currents of bushings, busbars etc. In fact, the definition of an Isolator or a Disconnector as per IS: 9921 (Part I) - 1981 is as follows:

An isolator or a disconnector is a mechanical switching device, which provides in the open position, an isolating distance in accordance with special requirements. An isolator is capable of opening and closing a circuit when either negligible current is broken or made or when no significant change in the voltage across the terminals of each of the poles of the isolator occurs. It is also capable of carrying currents under normal circuit conditions, and carrying for a specified time, currents under abnormal conditions such as those of a short circuit.

Thus, most of the discussion here refers to the testing of circuit breakers.

Testing of circuit breakers is intended to evaluate (a) the constructional and operational characteristics, and (b) the electrical charactristics of the circuit which the switch or the breaker has to interrupt or make. The different characteristics of a circuit breaker or a switch may be summarized as per the following groups.

(i) (a) The electrical characteristics which determine the arcing voltage, the current chopping characteristics, the residual current, the rate of decrease of conductance of the arc space and the plasma, and the shunting effects in interruption.

(b) Other physical characteristics including the media in which the arc is extinguished, the pressure developed or impressed at the point of interruption, the speed of the contact travel, the number of breaks, the size of the arcing chamber, and the materials and configuration of the circuit interruption.

(ii) The charateristics of the circuit include the degree of electrical loading, the normally generated or applied voltage, the type of fault in the system which the breaker has to clear, the time of interruption, the time constant, the natural frequency and the power factor of the circuit, the rate of rise of recovery voltage, the restriking voltage, the decrease in the a.c. component of the short circuit current, and the degree of asymmetry and the d.c. component of the short circuit current.

To assess the above factors, the main tests conducted on the circuit breakers and isolator switches are

(*i*) the dielectric tests or overvoltage tests,
(*ii*) the temperature rise tests,
(*iii*) the mechanical tests, and
(*iv*) the short circuit tests

Dielectric tests consist of overvoltage withstand tests of power flequency, lightning and switching impulse voltages. Tests are done for both internal and external insulation with the switch or circuit breaker in both the open and closed positions. In the open position, the test voltage levels are 15% higher than the test voltages used when the breaker is in closed position. As such there is always the possibility of line to ground flashover. To avoid this, the circuit breaker is mounted on insulators above the ground, and hence the insulation level of the body of the circuit breaker is raised.

The impulse tests with the lightning impulse wave of standard shape are done in a similar manner as in the case of insulators. In addition, the switching surge tests with switching overvoltages are done on circuit breakers and isolators to assess their performance under overvoltages due to switching operations.

Temperature rise and mechanical tests are tube tests on circuit breakers and are done according to the specifications (reference 17).

10.2.2 Short Circuit Tests

The most important tests carried out on circuit breakers are short circuit tests, since these tests assess the primary performance of these devices, i.e. their ability to safely interrupt the fault currents. These tests consists of determining the making and breaking capacities at various load currents and rated voltages. In the case of isolators, the short circuit tests are conducted only with the limited purpose to determine their capacity to carry the rated short circuit current for a given duration; and no breaking or making current test is done.

The different methods of conducting short circuit tests are

(I) Direct Tests

(a) using a short circuit generator as the source
(b) using the power utility system or network as the source.

(II) Synthetic Tests

(a) Direct Testing in the Networks or in the Fields Circuit breakers are sometimes tested for their ability to make or break the circuit under normal load

conditions or under short circuit conditions in the network itself. This is done during period of limited energy consumption or when the electrical energy is diverted to other sections of the network which are not connected to the circuit under test. The advantages of field tests are:

(*i*) The circuit breaker is tested under actual conditions like those that occur in a given network.

(*ii*) Special occasions like breaking of charging currents of long lines, very short line faults, interruption of small inductive currents, etc. can be tested by direct testing only.

(*iii*) to assess the thermal and dynamics effects of short circuit currents, to study applications of safety devices, and to revise the performance test procedures, etc.

The disadvantages are:

(*i*) The circuit breaker can be tested at only a given rated voltage and network capacity.

(*ii*) The necessity to interrupt the normal services and to test only at light load conditions.

(*iii*) Extra inconvenience and expenses in installation of controlling and measuring equipment in the field.

(b) Direct Testing in Short Circuit Test Laboratories In order to test the circuit breakers at different voltages and at different short circuit currents, short circuit laboratories are provided. The schematic layout of a short circuit testing laboratory is given in Fig. 10.3. It consists of a short circuit generator in association with a master circuit breaker, resistors, reactors and measuring devices. A make switch initiates the short circuit and the master circuit breaker isolates the test device from the source at the end of a predetermined time set on a test sequence controller. Also, the master circuit breaker can be tripped if the test device fails to operate properly. Short circuit generators with induction motors as prime movers are also available.

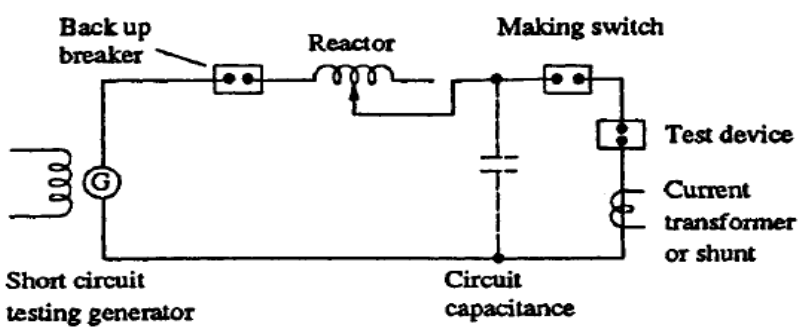
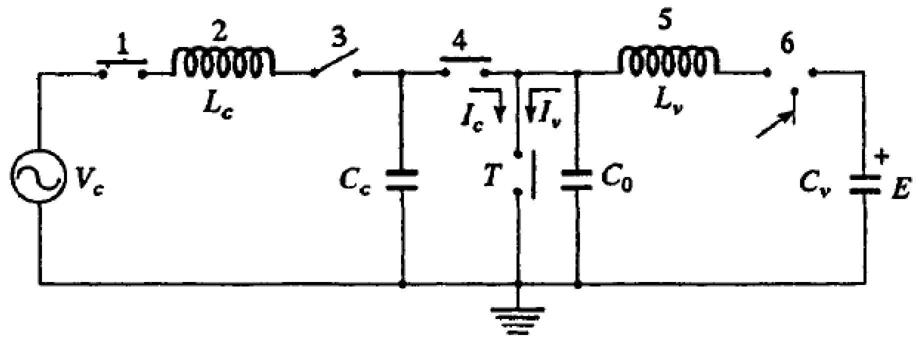


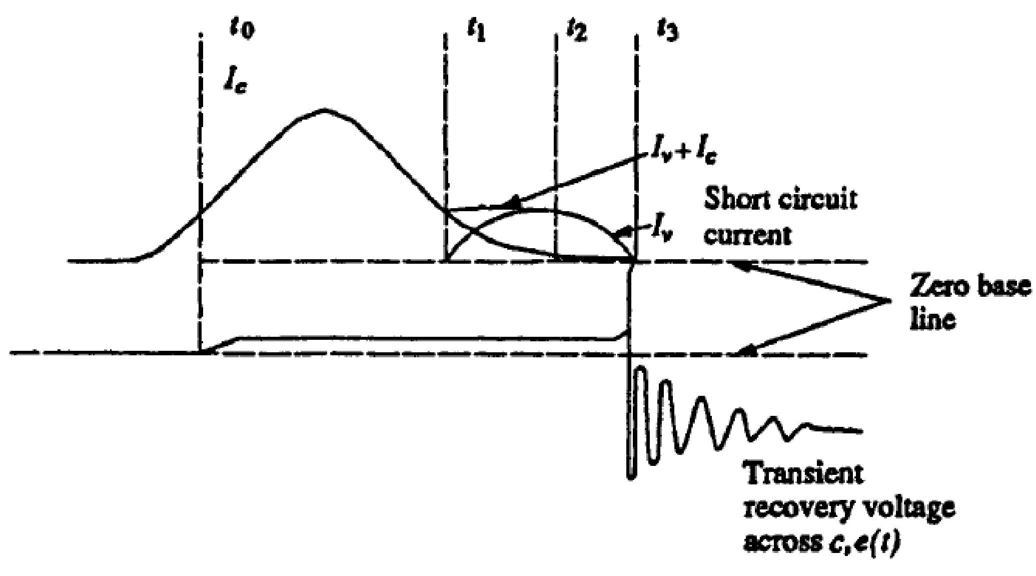
Fig. 10.3 Schematic diagram showing basic elements of a short circuit testing laboratory

(c) Synthetic Testing of Circuit Breakers Due to very high interrupting capacities of circuit breakers, it is not economical to have a single source to provide the required short circuit and the rated voltage. Hence, the effect of a short circuit is obtained as regards to the intensity of the current and the recovery voltage as a combination of the effects of two sources, one of which supplies the a.c. current and the other the high voltage.

In the initial period of the short circuit test, the a.c. current source supplies the heavy current at a low voltage, and then the recovery voltage is simulated by a source of comparatively high voltage of small current capacity. A schematic diagram of a synthetic testing station is shown in Fig. 10.4.



(b)



V_c – Low voltage, high current generator; L_c – Current controlling inductance (2); 1 – Master breaker; 3 – Main switch; (T – Circuit breaker) under test; 4 – Auxiliary breaker; (L_V – Voltage waveform) controlling choke (5); 6 – Trigger gap; (C_V – Capacitor charged to) E_V to give necessary recovery

Trigger gap; (C_v – Capacitor charged to) E_v to give necessary recovery voltage; (C_0 – Capacitor to control) the frequency of the transient recovery voltage; t_0 – Opening of auxiliary circuit breaker (4); t_1 – Trigger gap 6 is fired; t_2 – Auxiliary circuit breaker clears and interrupts I_c; t_3 – I_v becomes zero

Fig. 10.4 (a) Schematic diagram of synthetic testing of circuit breakers

(b) Current and recovery voltage waveforms across the test circuit breaker

With the auxiliary breaker (3) and the test breaker (T) closed, the closing of the making switch (1) causes the current to flow in the test circuit breaker. At some instant say t_0, the test circuit breaker (T) begins to operate and the master circuit breaker (1) becomes ready to clear the generator circuit. At some times t_1, just before the zero of the generator current, the trigger gap (6) closes and the higher frequency current from the discharging capacitor C_v also flows through the arc. At time t_2, when the generator

current is zero, the circuit breaker (1) clears that circuit, leaving only the current from C_v which has the required rate of change of current at its zero flowing in the test circuit breaker. At the zero of this current, full test voltage will be available. The closing of gap (6) would be a little earlier in time than shown in Fig.10.4, but it has been drawn as shown for clarity at current zeros. It is important to see that the high-current source is disconnected and a high-voltage source applied with absolute precision (by means of an auxiliary circuit breaker) at the instant of circuit breaking.

(d) Composite Testing In this method, the breaker is first tested for its rated breaking capacity at a reduced voltage and afterwards for rated voltage at a low current. This method does not give a proper estimate of the breaker performance.

(e) Unit Testing When large circuit breakers of very high voltage rating (220 kV and above) are to be tested and where more than one break is provided per pole, the breaker is tested for one break at its rated current and the estimated voltage. In actual practice, the conditions of arc in each gap may not be identical and the voltage distribution along several breaks may be uneven. Hence, certain uncertainty prevails in the testing of one break.

(f) Testing Procedure The circuit breakers are tested for their (i) breaking capacity B, and (ii) making capacity M. The circuit breaker, after the calibration of the short circuit generator, is tested for the following duty cycle.

(1) *B*-3-*B*-3-*B* at 10% of the rated symmetrical breaking capacity
(2) *B*-3-*B*-3-*B* at 30% of the rated symmetrical breaking capacity
(3) *B*-3-*B*-3-*B* at 60% of the rated symmetrical breaking capacity
(4) *B*-3-*MB*-3*MB*-*MB* at 100% breaking capacity with the recovery voltage not less than 95% of the rated service voltage.

The power factor in these tests is generally between 0.15 and 0.3. The numral 3 in the above duty cycle indicates the time interval in minutes between the tests.

(g) Asymmetrical Tests One test cycle is repeated for the asymmetrical breaking capacity in which the d.c. component at the instant of contact separation is not less than 50% of the a.c. component.

10.3 TESTING OF CABLES

Cables are very important electrical apparatus for transmission of electrical energy by underground means. They are also very important means for transmitting voltage signals at high voltages. For power engineers, large power transmission cables are of importance, and hence testing of power cables only is considered here. Of the different electrical and other tests prescribed, the following are important to ensure that cables withstand the most severe conditions that are likely to arise in service.

Different tests on cables may be classified into

(*i*) mechanical tests like bending test, dripping and drainage test, and fire resistance and corrosion tests,
(*ii*) thermal duty tests,
(*iii*) dielectric power factor tests,

(*iv*) power frequency withstand voltage tests,
(*v*) impulse withstand voltage tests,
(*vi*) partial discharge tests, and
(*vii*) life expectancy tests.

Here only the electrical tests are described, i.e. tests (*iii*) to (*vii*).

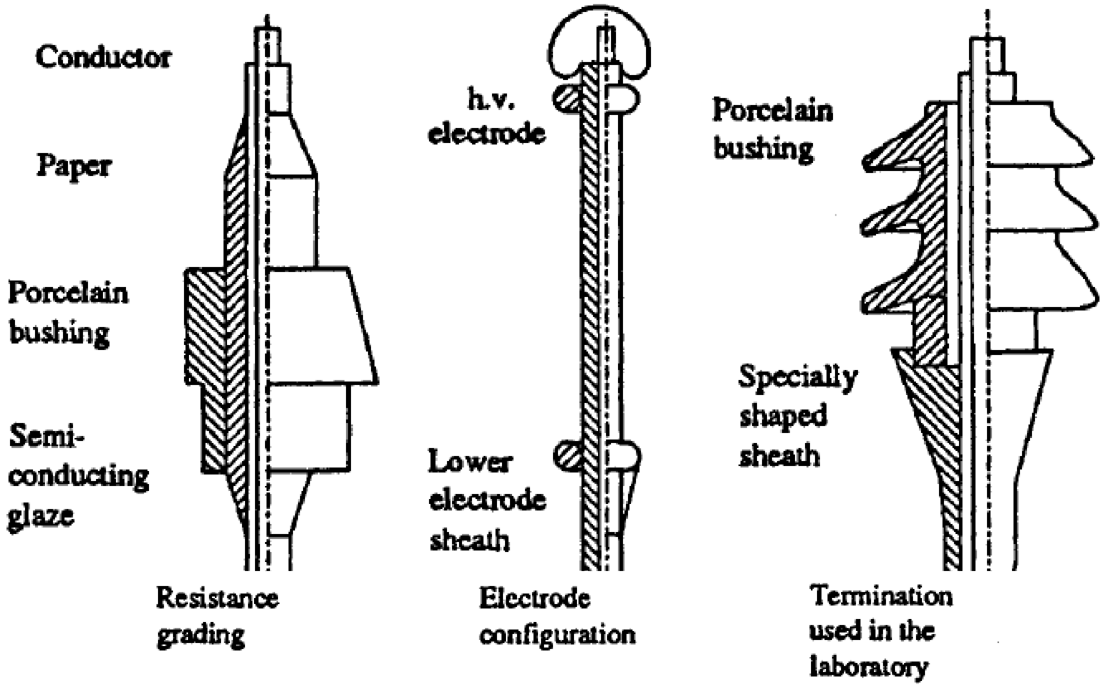


Fig. 10.5 Cable and terminals

10.3.1 Preparation of the Cable Samples

For overvoltage and withstand tests, samples have to be carefully prepared and terminated; otherwise, excessive leakage or end flashovers may occur during testing. The normal length of the cable sample used varies from about 50 cm to 10 m. The terminations are usually made by shielding the end conductor with stress shields or terminations to relieve the ends from excessive high electrical stresses. A few terminations are shown in Fig. 10.5. During power factor tests, the cable ends are provided with shields so that the surface leakage current is avoided from the measuring circuits.

10.3.2 Dielectric Power Factor Test

The dielectric power factor test is done using the high voltage Schering bridge (see Section 9.3.4). The power factor or dissipation factor tan δ is measured at 0.5, 1.0, 1.66, and 2.0 times the rated voltage (phase to ground) of the cable. The maximum value of the power factor and the difference in power factor between the rated voltage and 1.66 times the rated voltage, as well as, between the rated voltage and two times the rated voltage are specified. Sometimes, difficulty is felt in supplying the charging voltamperes of the cable from the available source. In such cases, a choke is used or a suitably rated transformer winding is used in series with the cable to form a resonant circuit. This improves the power factor and raises the test voltage between the cable core and the sheath to the required value, when a source of high voltage and high capacity is used. The Schering bridge has to be given protection against overvoltages, in case breakdown occurs in the cables.

10.3.3 High Voltage Tests on Cables

Cables are tested for withstand voltages using the power frequency a.c., d.c., and impulse voltages. At the time of manufacture, the entire cable is passed through a high voltage test at the rated voltage to check the continuity of the cable. As a routine test, the cable is tested applying an a.c. voltage of 2.5 times the rated value for 10 min. No damage to the cable insulation should occur. Type tests are done on cable samples using both high voltage d.c. and impulse voltages. The d.c. test consists of applying 1.8 times the rated d.c. voltage of negative polarity for 30 min., and the cable system is said to be fit, if it withstands the test. For impulse tests, impulse voltage of the prescribed magnitude as per specifications is applied, and the cable has to withstand five applications without any damage. Usually, after the impulse test, the power frequency dielectric power factor test is done to ensure that no failure occurred during the impulse test.

10.3.4 Partial Discharges

(a) Discharge Measurement

Partial discharge measurements and the discharge locations are important for cables, since the life of the insulation at a given voltage stress depends on the internal discharges. Also, the weakness of the insulation or faults can be detected with the help of these tests; the portion of the cable if weak may be removed, if necessary. The general arrangement for partial discharge tests is the same as described in Sec.9.4.

The equivalent circuit of the cable for discharges is shown in Fig. 10.6, and the cable connection to the discharge detector through the coupling condenser is shown in Figs. 10.7a and b. If the detector is connected through a coupling capacitor to one end of the cable as in Fig. 10.7a, it will receive the transient travelling wave directly from the cavity towards the nearer end, and after a short time, a second travelling wave pulse reflected from the far end is observed. Thus, the detected response is the combination of the above two transient pulses. But, if the connections are made as in Fig. 107b, no severe reflection is involved except as a second order effect of negligible magnitude. Now two transients will arrive at both the ends of the cable, and the superposition of the two pulses is detected. This can be obtained by adding the responses of the two transients. The superpositions of the two responses may give rise to a serious error in the measurement of the discharge magnitude. The magnitude of the possible error may be determined mainly by the shape of the response of the discharge detector.

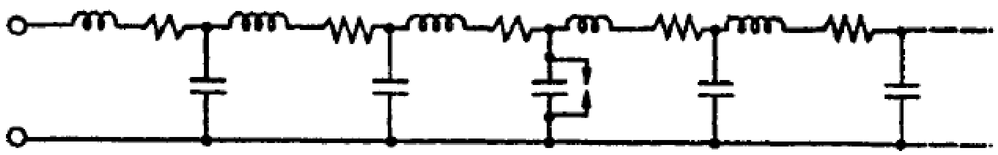


Fig. 10.6 Equivalent circuit of the cable for discharges

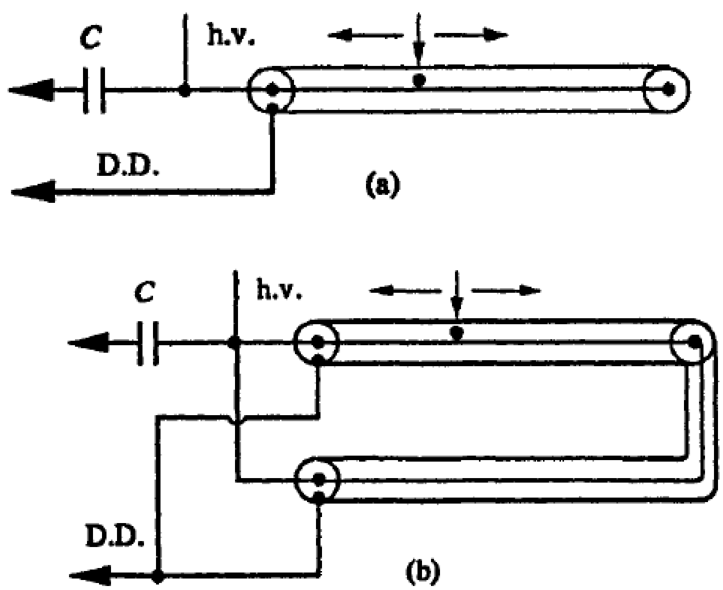


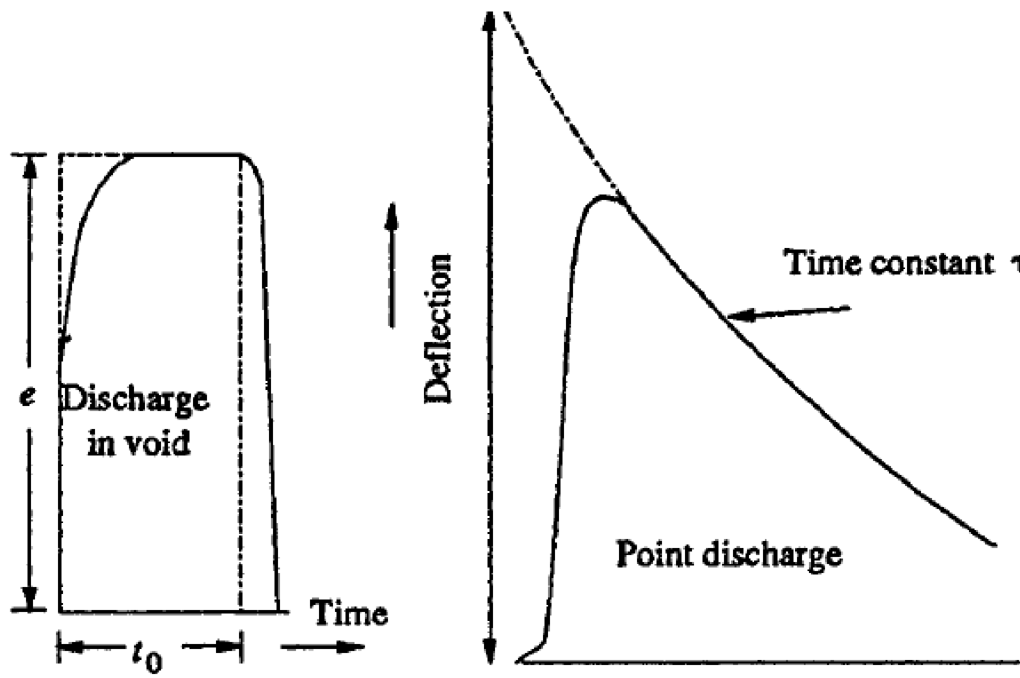
Fig. 10.7 Discharge detector connection to long length of cable
D.D.—Discharge detector

(b) Location of Discharges

The voltage dip caused by a discharge at a fault or a void is propagated as a travelling wave along the cable. This wave is detected as a voltage pulse across the terminals of the cable ends. By measuring the time duration between the pulses, the distance at which the discharge is taking place from the cable end can be determined. The shapes of the voltage pulses depend on the nature of the discharges. Typical waveshapes are given in Fig. 10.8. The detection circuits for the pulses are shown in Fig. 10.9, and the attenuation of the travelling wave in cables is given in Fig. 10.10. Usually, the pulses detected across the resistor are distorted after passing through the amplifier of the discharge detector.

(c) Scanning Method

In order to scan the entire cable length for voids or imperfections in manufacture, the bare core of the cable is passed through a high electric field and the discharge location is done. The core of the material is passed through a tube of insulating material filled with distilled water. Four electrodes in the form of rings are mounted at both ends of tube as well as at the middle, such that they have electrical contact with the water. The middle electrodes are energized with a high voltage, and the other two electrodes and



(a) Internal discharge
$t_0 = 20 - 40$ ns

(b) Corona discharge
$\tau = 50 - 500$ ns

------- Hypothetical waveshape
____ Waveshape observed with oscilloscope

Fig. 10.8 Typical waveshapes of pulses at the cable ends

cable conductor are grounded. If a discharge occurs in the portion between the middle electrodes, as the cable is passed between the middle electrodes' portion, the discharge is detected and is located at that length of cable.

This test is very convenient for isolating the defective insulation at the factory site. The manufactured cable, before being rolled on to its former, can be conveniently passed through the test apparatus. "The defective part" can be isolated and cut off from the cable reel before it is sent from the factory.

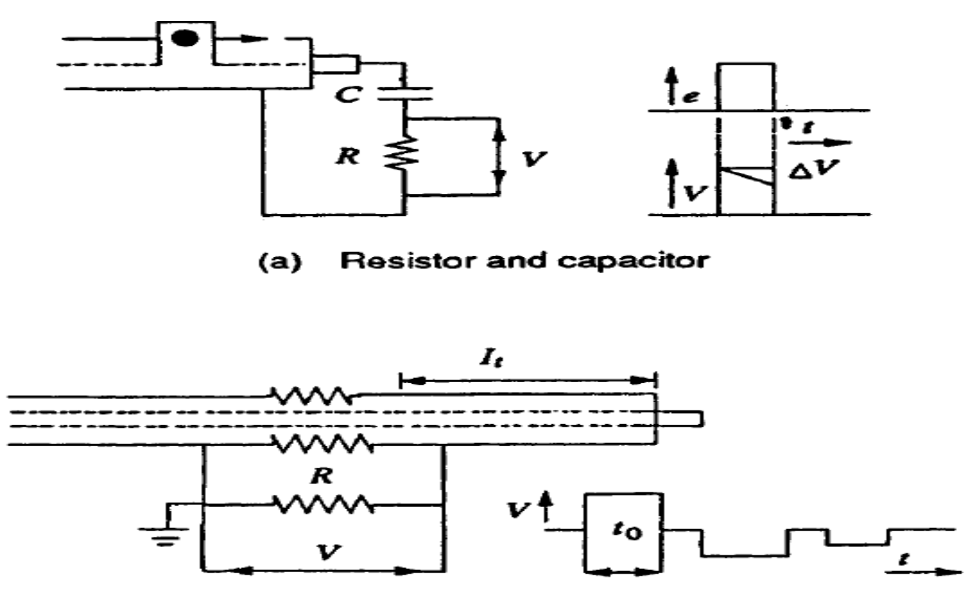
(d) Life Tests

Life tests are intended for reliability studies in service. In order to determine the expected life to the cable under normal stress, accelerated life tests using increased voltages are performed on actual cable lengths. It is established that the relation between the maximum electrical stress E_m and the life of the cable insulation in hours t approximately follows the relationship

$$E_m = K t^{-(1/n)}$$

where, K = constant which depends on the field conditions and the material, and

n = life index depending on the material.



(b) Without capacitor

Fig. 10.9 Detection circuits for long cables

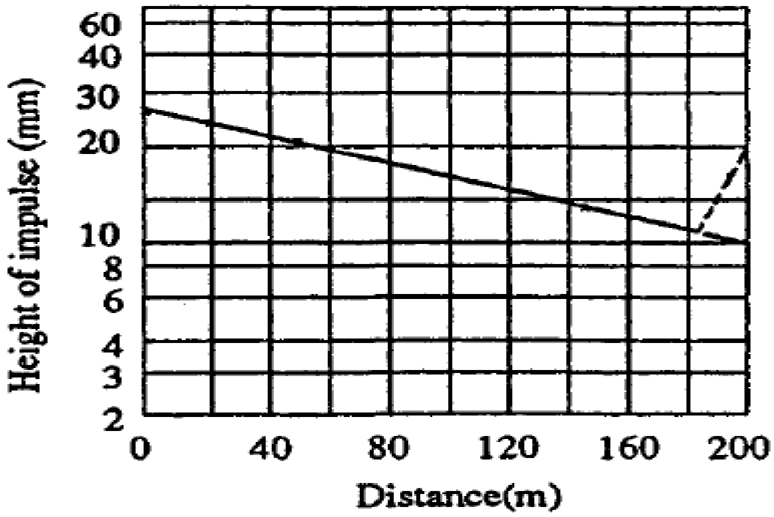


Fig. 10.10 Attenuation of travelling waves

By conducting long duration life tests at increased stress (1 hr to about 1000 hr) the expected life at the rated stress may be determined.

10.4 TESTING OF TRANSFORMERS

Transformers are very important and costly apparatus in power systems. Great care has to be exercised to see that the transformers are not damaged due to transient overvoltages of either lightning or power frequency. Hence, overvoltage tests become very important in the testing of transformers. Here, only the overvoltage tests are discussed, and other routine tests like the temperature rise tests, short circuit tests, etc. are not included and can be found in the relevent specifications.

(a) Induced Overvoltage Test

Transformers are tested for overvoltages by exciting the secondary of the transformer from a high frequency a.c. source (100 to 400 Hz) to about twice the rated voltage. This reduces the core saturation and also limits the charging current necessary in large power transformers. The insulation withstand strength can also be checked.

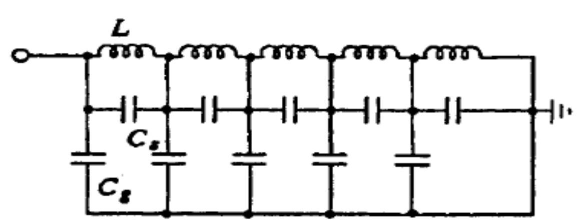
(b) Partial Discharge Tests

Partial discharge tests on the windings are done to assess the discharge magnitudes and the radio interference levels (see also Sec. 10.6). The transformer is connected in a manner similar to any other equipment (see Sec. 9.4) and the discharge measurements are made. The location of the fault or void is sometimes done by using the travelling wave technique similar to that for cables. So far, no method has been standardized as to where the discharge is to be measured. Multi-terminal partial discharge measurements are recommended. Under the application of power frequency voltage, the discharge magnitudes greater than 10^4 pico coulomb are considered to be severe, and the transformer insulation should be such that the discharge magnitude will be far below this value.

10.4.1 Impulse Testing of Transformers

The purpose of the impulse tests is to determine the ability of the insulation of the transformers to withstand the transient voltages due to lightning, etc. Since the transients are impulses of short rise time, the voltage distribution along the transformer winding will not be uniform. The equivalent circuit of a transfomer winding for impulses is shown in Fig. 10.11. If an impulse wave is applied to such a network (shown in Fig. 10.11) the voltage distribution along the element will be uneven, and oscillations will be set in producing voltages much higher than the applied voltage.

Impulse testing of transformers is done using both the full wave and the chopped wave of the standard impulse, produced by a rod gap with a chopping time of 3 to 6 μs. To prevent large overvoltages being induced in the windings not under test, they are short circuited and connected to ground. But the short circuiting reduces the impedance of the transformer and hence poses problems in adjusting the standard waveshape of the impulse generators. It also reduces the sensitivity of detection.



L — Inductance (series)
C_s — Series capacitance
C_g — Shunt capacitance to ground

Fig. 10.11 Equivalent circuit of transformer winding for impulses

(a) Procedure for Impulse Testing

The schematic diagram of the transformer connection for impulse testing is shown in Fig. 10.12, and the waveshapes of the full and chopped waves are shown in Fig. 10.13. In transformer testing it is essential to record the

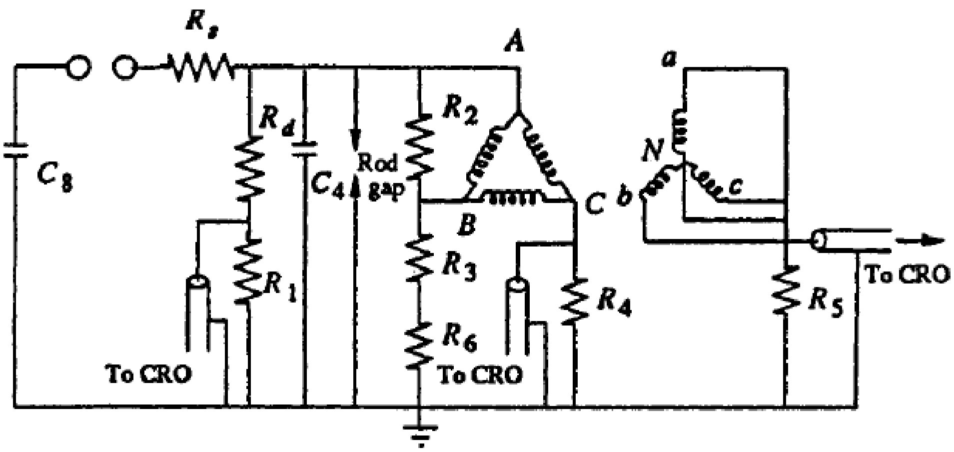


Fig. 10.12 Arrangement of transformer for impulse testing

waveforms of the applied voltage and current through the windings under test. Sometimes, the transferred voltage in the secondary and the neutral current are also recorded.

Impulse testing is done in the following sequence:

(*i*) applying impulse voltage of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test,
(*ii*) one full wave ovltage of 100% BIL,
(*iii*) two chopped waves of 100% BIL,
(*iv*) one full wave of 100% BIL, and
(*v*) one full wave of 75% BIL.

It is very important to see that the grounding is proper and the windings not under test are suitably terminated.

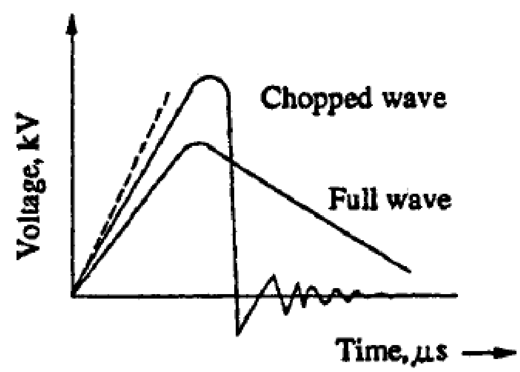
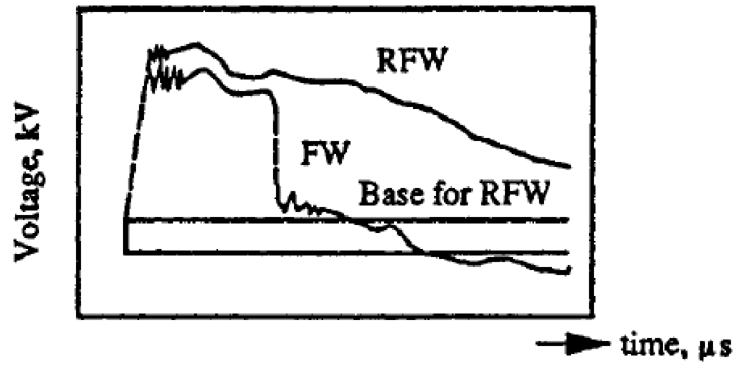
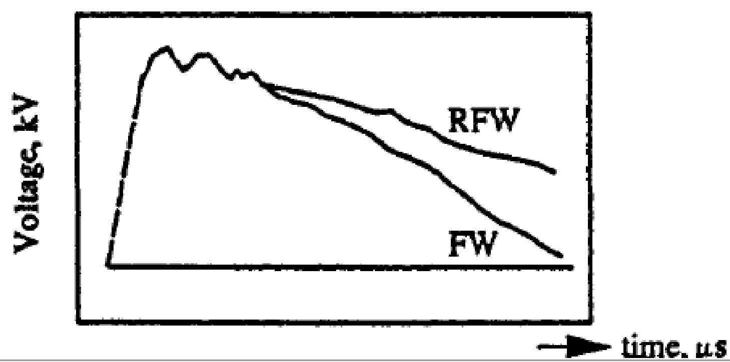


Fig. 10.13 Full wave and chopped wave



(a) Failure from the line lead to ground through oil



(b) 8.5% of winding failed

Fig. 10.14 Voltage oscillograms of transformer winding with a fault
RFW—Reduced full wave
FW—Full wave

(b) Detection and Location of Fault During Impulse Testing

The fault in a transformer insulation is located in impulse tests by any one of the following methods.

General observations : The fault can be located by general observations like noise in the tank or smoke or bubbles in breather.

Voltage oscillogram method : Fault or failure appears as a partial or complete collapse of the applied voltage wave. Figure 10.14 gives the typical waveform. The sensitivity of this method is low and does not detect faults which occur on less than 5% of the winding.

Neutral current method : In the neutral current method, a record of the impulse current flowing through a resistive shunt between the neutral and ground point is used for detecting the fault. The neutral current oscillogram consists of a high frequency oscillation, a low frequency disturbance, and a current rise due to reflections from the ground end of the windings. When a fault occurs such as arcing between the turns or from turn to the ground, a train of high frequency pulses similar to that in the front of the impulse current wave are observed in the oscillogram and the waveshape changes.

If the fault is local, like a partial discharge, only high frequency oscillations are observed without a change of waveshape. The sensitivity of the method decreases, if other windings not under test are grounded.

Transferred surge current method : In this method, the voltage across a resistive shunt connected between the low voltage winding and the ground is used for fault location. A short high frequency discharge oscillation is capacitively transferred at the event of failure and is recorded. Hence, faults at a further distance from the neutral are also clearly located. The waveshape is distorted depending on the location and type of fault, and hence can be more clearly detected.

After the location of the fault, the type of fault can be observed by dismantling the winding and looking for charred insulation or melted parts on the copper winding. This is successful in the case of major faults. Local faults or partial discharges are self healing and escape observation.

10.5 TESTING OF SURGE DIVERTERS

10.5.1 Introduction

In modern practices, surge diverters or lightning arresters are the most reliable apparatus to project the power system against transient voltages due to lightning and switching surges. They are invariably used from distribution voltages (400 V) to highest system transmission voltages of 765 kV or above. Hence, testing them precisely in standard laboratories with standard test procedures are of great importance in modern power system practice.

A surge diverter has to be a non-conductor for operating power frequency voltages. It should behave as a short circuit for transient overvoltages of impulse character, discharge the heavy current, and recover its insulation without allowing the follow-up of the power frequency current.

In Table 10.1, the impulse current ratings of the surge diverters in relation to their voltage are given, and the testing is usually done at these current ratings.

Table 10.1 Surge Diverter Voltage and Current Ratings

Diverter class	Diverter rating	Impulse current rating (8/20 μ s) (Amperes)	High current rating (4/10 μ s) (Amperes)	Long duration rating—duration is given in μ s (Amperes)
A	Low voltage (230 V to 600 V)	1500 2500	10,000 25,000	50 (500 μ s)
B	Distribution voltages (400 V to 33 kV)	5000	65,000	75 (1000 μ s)
C	Station type lightn-ing arresters (11 kV and above)	10,000	100,000	150 (2000 μ s)

10.5.2 Tests on Surge Diverters

(i) Power Frequency Sparkover Test

This is routine test. The test is conducted using a series resistance to limit the current in case a sparkover occurs. The arrester has to withstand at least 1.5 times the rated value of the voltage for five successive applications. The test is generally done also under dry and wet conditions.

(ii) Hundred per cent Standard Impulse Sparkover Test

This test is conducted to ensure that the diverter operates positively when over-voltages of impulse nature occur. The impulse generator is adjusted to give the standard impulse voltage of a preset magnitude specified in the specifications. The arrester has to sparkover every time in each of the ten successive applications. The test is done with both positive and negative polarity waveforms. Sometimes, the test is done by starting at a voltage level that does not give flashover at all, and is repeated in increasing steps of voltage till hundred per cent flashover occurs. The magnitude of the voltage at which hundred per cent flashover occurs is the required sparkover voltage.

(iii) Front of Wave Sparkover Test

In order to ensure that the surge diverter flashes over for very steep fronted waves of high peaks, this test is conducted using an overvoltage having a rate of rise of 100 kV/ μs, per 12 kV of the rating. The estimated maximum steepness of the waves are specified in standards and specifications. The test is done by conducting hundred per cent sparkover voltage test for increasing magnitudes of the standard impulse wave. The time to sparkover is measured. The volt-time characteristic of the diverter is plotted, and the intersection of the V–t characteristic and the line with slope of the virtual steepness of the front gives the front of a wave sparkover voltage.

(iv) Residual Voltage Test

This test is conducted on pro-rated diverters of ratings in the range 3 to 12 kV only. The voltage developed across the Non-Linear Resistor units (NLR) during the flow of surge currents through the arrester is called the 'residual voltage'. A pro-rated arrester is a complete, suitably housed section of an arrester including series gaps and non-linear series resistors in the same proportion as in the complete arrester.) Standard impulse currents of the rated magnitudes are applied, and the voltage developed across the diverter is recorded using a suitable voltage divider and a CRO. The magnitudes of the currents are approximately 0.5, 1.0, and 2.0 times the rated currents. From the oscillogram, a graph is drawn between the current magnitudes and the voltage developed across the diverter pro-rated unit. From the graph, the residual voltage corresponding to the exact rated current is obtained.

Let $V_1 =$ rating of the complete unit,

$V_2 =$ rating of the pro-rated unit tested,

$V_{R_1} =$ residual voltage of the complete unit, and

$V_{R_2} =$ residual voltage of the pro-rated unit.

Then, it is assumed that

$$\frac{V_1}{V_2} = \frac{V_{R1}}{V_{R_2}}$$

Let V_{RM} be the maximum permissible residual voltage for the complete unit. The ratio $V_{RM}/V_1 = r$, is defined as a multiplying factor of the rating for the residual voltage test, which depends on V_1. The "diverter" is said to pass the test, if

$$V_{R_2} < rV_2$$

10.5.3 High Current Impulse Test on Surge Diverters

This test is also done on pro-rated diverter units in the range of 3 to 12 kV. A high current impulse wave of 4/10 μs of peak value mentioned in the specifications is applied to a spare unit of identical characteristics. Two such applications are done on the units under test, allowing sufficient time for the cooling of the unit to the room temperature. The unit is said to pass the test, if (*i*) the power frequency sparkover voltage before and after the test does not differ by more than 10%,

(*ii*) the voltage and current waveforms of the diverter do not differ significantly in the two applications, and

(*iii*) the non-linear resistance elements in the diverter do not show any sign of puncture or external flashover.

(a) Long Duration Impulse Current Test

This test is also done on pro-rated units of 3 to 12 kV. The circuit used for generating a rectangular impulse wave consists of an artificial transmission line with lumped inductances and capacitances. The duration of the current pulse t is given by $2(n-1)\sqrt{LC}$, where n is the number of stages or sections used, and L and C are the inductance and capacitance of each unit. Rectangular wave is generated, if the surge impedance of the diverter is equal to $\sqrt{L/C}$ at the test current. As per the specifications, 20 applications are made with specified current in five groups. The interval between the successive applications is about 1 min. It is usual to record the waveforms in the first two and the last two applications of the current wave. The diverter is said to have passed the test, if

(*i*) the power frequency sparkover voltage before and after the application of the current wave does not differ by 10%,

(*ii*) the voltage across the diverter at the first and the last application does not differ by more than 8%, and

(*iii*) there is no sign of puncture or other damage.

(b) Operating Duty Cycle Test

This test is conducted on pro-rated units of diverters and gives better closeness to actual conditions. The diverter is kept energized at its rated power frequency supply voltage. The rated impulse current wave is applied first at a phase angle of about 30° from the a.c. voltage zero. If the power frequency follow-on current is not established, the angle at which current wave is applied is advanced in steps of 10° up to 90° or the peak position of the supply voltage wave till the follow-on current is established. In the course of application of the current wave, if the power frequency voltage is reduced during the flow of current, it can be compensated up to a maximum of 10% of the overvoltage. During the follow-on current period, the peak voltage across the diverter should be less than or equal to the rated peak voltage. Twenty applications of the impulse current at the selected points on the voltage wave are made in four groups. The time interval between each application is about 1 min, and between successive groups it is about half an hour. The arrester is said to have passed the test, if

(*i*) the average power frequency sparkover voltage before and after the test does not differ by more than 10%.
(*ii*) the residual voltage at the rated current does not vary by more than 10%,
(*iii*) the follow-on power frequency current is interrupted each time, and
(*iv*) no significant change, signs of flashover, or puncture occurs to the pro-rated unit.

(c) Other Tests

The other tests that are normally conducted on surge diverters are

(*i*) mechanical tests like porosity test, temperature cycle tests, and others,
(*ii*) pressure relief test,
(*iii*) the voltage withstand test on the insulator housing of the diverter,
(*iv*) the switching surge flashover test, and
(*v*) the pollution tests.

These tests are usually done on diverters used on Extra High Voltage (EHV) systems.

10.6 RADIO INTERFERENCE MEASUREMENTS

10.6.1 Introduction

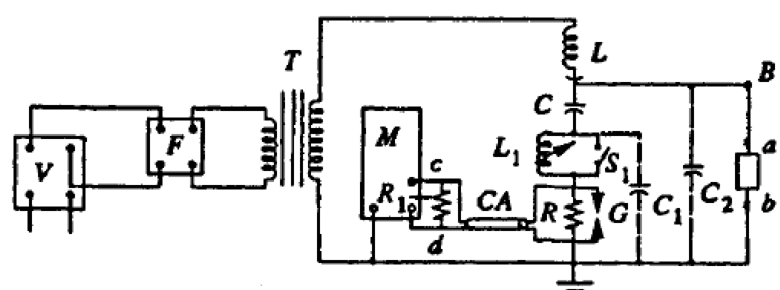
Many electrical apparatuses like transformers, line conductors, rotating machines, etc. produce unwanted electrical signals in the radio and high frequency (television band, microwave bands, etc.) ranges. These signals arise due to corona discharges in air, internal or partial discharges in the insulation, sparking at commutators and brush gear in rotating machines, etc. It is important to see that the noise voltages generated in the radio and other transmission bands are limited to acceptable levels, and hence the radio interference voltage measurements are of importance. It has been found that the surface conditions of the overhead conductors subjected to high voltage stresses and varying atmospheric conditions greatly influence the magnitude of the noise voltage produced. In case of solid insulators, the bonding between the porcelain and the metal pin, the binding of high voltage conductor and the insulator surface, and the surface pollution were found to be the sources of this noise.

10.6.2 Measurements of Radio Interference Voltage

The noise generated in the radio frequency band as a result of corona or partial discharges in high voltage power apparatus may be measured

(*i*) by the radio frequency line to ground voltage known as the radio influence voltage or RIV, and
(*ii*) as an interfering field by means of an antenna known as the radiated radio interference voltage or RI.

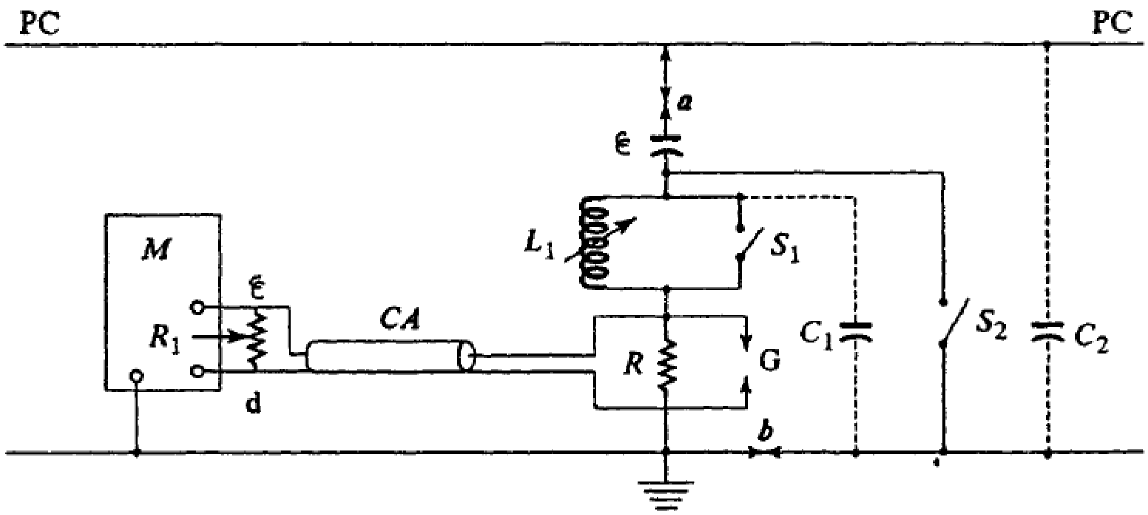
Normally, the tests and measurements done in the laboratories are RIV measurements, whereas field investigations with portable radio receivers are RI measurements.



F — Voltage control unit; V — Voltmeter; T — High voltage transformer; L — Radio frequency choke; C — Coupling condenser; R_1 — Meter input impedance; M — Radio noise meter; a-b — Test apparatus; CA — Coaxial cable; G — Protective gap; S_1 — Shorting switch, C_1, C_2 — Stray capacitances; L_1 — Tuning choke; R — Measuring impedance

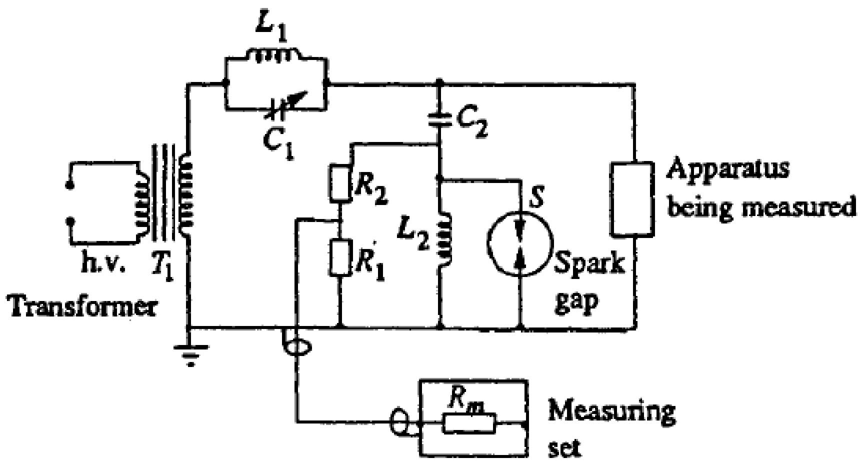
Fig. 10.15 Schematic diagram of circuit for the measurement of RIV of a high voltage appratus in 150 kHz to 30 MHz frequency range

A radio noise meter used in the laboratory consists of a portable radio receiver with a local oscillator, a radio frequency amplifier, a mixer, an intermediate frequency amplifier, and a detector similar to that of a standard radio receiver and operates in the frequency range 150 kHz to 30 MHz. In addition, the radio noise meter has multi-input circuits to accommodate a number of pick-up devices, attenuators, calibrators, and output circuits containing special detectors and meters. The detector circuit consists of a diode detector in series with a series resistance R_s, charging a parallel R-C circuit. The detector circuit is provided with a measuring device to measure either (a) the average value, (b) the peak value, or (c) quasi-peak value (the quasi-peak value of the impulse noise is equal to the rms value of the sine wave at the centre frequency of the pass band which produces the same deflection in the meter scale as that of the impulse). The voltmeter provided at the end of the detector has an input impedance of 50 to 75 Ω.



Є — Coupling condenser; M — Radio noise meter; a-b — Test apparatus; CA — Coaxial cable; O — Protective gap; S_1 — Shorting switch; C_1, C_2 — Stray capacitances; L_1 — Tuning choke; R — Measuring impedance; R_1 — Meter input impedance; P.C. — Power system conductor

Fig. 10.16 Circuit for measurement of RIV from the conductors of an energized system



T_1 — High voltage transformers; L_1, C_1 — Filter; C_2 — Coupling condenser; L_2 — Measuring choke; R_1, R_2 — Potential divider; S — Protective spark gap; R_m — Input impedance of the meter

Fig. 10.17 Circuit for RIV measurement as given by British standards

10.6.3 Test Circuits for the Measurements

The schematic circuits used for RIV measurements are shown in Figs. 10.15, 10.16 and 10.17. The RIV meter is first calibrated as per standards. The important components of the circuits are:

(*i*) The radio frequency choke to limit the loss of the RIV voltage and to conduct energy from the sample. The choke itself should be free from noise, and its impedance should be less than 1500 Ω.

(*ii*) The coupling capacitor C (< 0.001 μ F); it should be free from noise in the operating range and the resistance of R should be equal to 800 Ω. The value indicated by the meter gives the conducted radio noise from the test sample.

(*iii*) Coaxial cable (CA): A coaxial cable of characteristic impedance 185 Ω shall be connected between the resistance R and the radio noise meter.

When the radio noise meter measurements are stated, the information regarding the specifications of the meter used, the frequency range of measurements, the band pass characteristics, and the open circuit and the detector characteristics have to be mentioned.

Now-a-days, for transmission systems of 400 kV and above, radio noise voltages are of importance, and corrective measures are to be adopted for various apparatus and hardware to minimize the radio and television band noise.

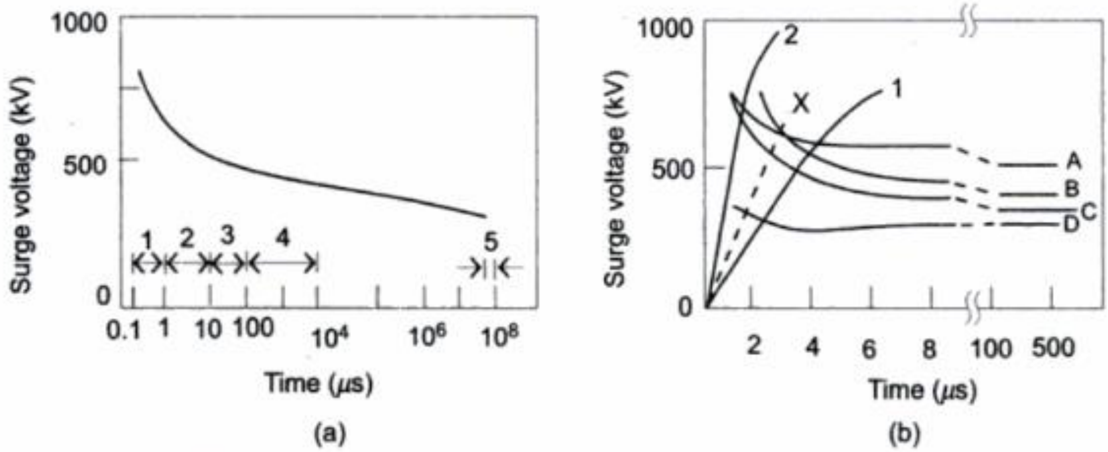
8.3 PRINCIPLES OF INSULATION COORDINATION ON HIGH VOLTAGE AND EXTRA HIGH VOLTAGE POWER SYSTEMS

Electric power supply should ensure reliability and continuity to the utility concerns. Hence, the power lines and sub-stations are to be operated and protected against overvoltages such that the number of failures are as few as possible. At the same time, the cost involved in the design, installation, and operation of the protective devices should not be too high. Hence, a gradation of system insulation and protective device operation is to be followed, keeping in view the importance of the various equipment involved.

Generally, sub-stations contain transformers, switchgear, and other valuable equipment with non-self restoring insulation, which have to be protected against failures and internal destruction. For other apparatus, which contain self-restoring insulation, like string insulators, they may be allowed to flashover in air. But the flashovers should be kept to a minimum so that the system disturbances are the least. Hence, lightning and switching surge protection requires establishment of protective voltage levels called shunt protection levels, by means of protective devices like lightning arresters.

The behaviour of shunt connected protective devices like rod gaps and surge diverters along with transformer insulation is given in Fig. 8.23.

In Fig. 8.23a the transformer insulation strength is given as a volt-time characteristic. Figure 8.23b gives the relative insulation strengths of the transformer (curve *A*), rod gaps (curves *B* and *C*), and that of a lightning arrester (curve *D*).



Typical transformer characteristic

1. For steep fronted lightning surge
2. Slow fronted lightning surge
3. Fast switching surge
4. Slow switching surge
5. Power frequency (1 minute withstand voltage)

Transformer—A
Rod gaps — B and C
Surge diverter— D
Critical slope — X

Fig. 8.23 *Volt-time characteristics of transformer rod gaps and surge diverters*

A lightning arrester protects the transformer insulation in the entire time region. The rod gap protects the transformer insulation, only if the rate of rise of surge is less than the critical slope (curve *X*). Thus, if the surge voltage rise is as shown by curve 1, rod gap flashes and protects the transformer, if the surge voltage rise follows curve 2, only the surge diverter can protect the transformer insulation.

Rod gaps are simple and cheap devices but do not meet all the requirements of a protective device. Moreover, their flashover characteristics depend on the atmospheric conditions, polarity of the wave, and waveshape. Also, it may give rise to very steep impulse waves on the transformer windings as chopped waves, because no current limiting resistance is used. Chopped impulse waves may lead to the destruction of the transformer turn to turn insulation. But still, rod gaps provide reasonable protection where lightning surge levels are low, and steep fronted surges are controlled by overhead ground wires.

Table 8.2 *Characteristics of 100–200 kV Surge Arresters 10 kA and Heavy Duty Type (ref. 14)*

	Characteristics	*Per unit values (referred to the rated values of the diverter)*
1.	Maximum 1.2/50 μs surge sparkover voltage	2.2 to 2.8
2.	Maximum front of wave sparkover voltage	2.9 to 3.1
3.	Maximum switching impulse sparkover voltage	2.3 to 3.0
4.	Maximum discharge voltage (V_d) for 8/20 μs current wave	
	5 kA	2.0 to 2.7
	10 kA	2.2 to 3.0
	20 kA	2.5 to 3.3

TEXT / REFERENCE BOOKS

1. M. S. Naidu and V. Kamaraju, 'High Voltage Engineering', 5thEdition Tata McGraw Hill Publishing Co. Ltd., New Delhi, 2013.
2. E.Kuffel and M.Abdullah, "High Voltage Engineering" -Per gammon Press, Oxford, 1970.
3. C.L.WADHWA, "High Voltage Engineering" -New Age International (P) Ltd, Publishers, 2007
4. E.Kuffel and W.s. Zaengal, "High Voltage Engineering Fundamentals",2nd Edition, Butterworth Heinemann, 2000.
5. H.M.Ryam, "High voltage Engineering and testing", 2nd Edition, 2001, IEEE power and energy series 32.