HIGH VOLTAGE ENGINEERING
8TH SEMESTER (EE)

UNIT I CONDUCTION AND BREAKDOWN

Recent trend in high voltage transmission, conduction and breakdown in solid, liquid and gasoeous dielectrics. Insulation breakdown, insulation characteristics of long air gap.

UNIT II METHODS OF HIGH VOLTAGE GENERATION

Methods of generation of power frequencies, high voltage: cascaded and resonance transformer, gigh voltage dc. Voltage multiplier circuit. Electrostatic generation: van de graff machine and its voltage stabilasations. Impulse voltage generations:basic impulse circuit, single stage and multiple stage impulse generator.

UNIT III PROTECTION SYSTEM AGAINST SURGE

Ground wire, protectective angle, tower footing resistance, surge diverters: gap type and gapless type. Insulation coordination. Basic impulse level, voltage time curve, impulse ratio.

UNIT IV LIGHTNING

Lightning phenomena, lightning stroke mechanism, principle of lightning stroke mechanism, tower footing resistance, insulation flashover voltage, lightning arresters and their characteristics, generation of direct voltage, measurement of high voltage, general layout of high voltage laboratory.

TEXT BOOKS:

1. S.Naidu and V. Kamaraju, _High Voltage Engineering‘, Tata McGraw Hill, Fifth Edition, 2013.
2. E. Kuffel and W.S. Zaengl, J.Kuffel, _High voltage Engineering fundamentals‘, Newnes Second Edition Elsevier , New Delhi, 2005.
3. Subir Ray,‘ An Introduction to High Voltage Engineering‘ PHI Learning Private Limited, New Delhi, Second Edition, 2013.

REFERENCES:

1. L.L. Alston, _High Voltage Technology‘, Oxford University Press, First Indian Edition, 2011.
2. C.L. Wadhwa, _High voltage Engineering‘, New Age International Publishers, Third Edition, 2010.

HIGH VOLTAGE ENGINEERING

1. Aim of the Subject

To design of the insulation, various surges induced in power system and protective systems

Objective of the Subject

- To understand the various types of over voltages in power system and protection methods.
- Generation of over voltages in laboratories.
- Measurement of over voltages.
- Nature of Breakdown mechanism in solid, liquid and gaseous dielectrics.

2. Need and Importance for Study of the Subject

- Study the materials used in the insulation (solid, liquid and gas) of power system
- Understand the problem in design of the insulation, various surges induced in power system and protective systems
- Confidently face the challenges regarding testing procedures in insulation system
- Ability of developing the insulation coordination system

3. Industry Connectivity and Latest Developments

Industry Connectivity

Power system Equipment like Transformers, circuit breaker etc.

Latest Developments

Testing Power system Equipments.

4. Industrial Visit (Planned if any)

Required

UNIT-1

Recent trend in high voltage transmission

During the latest 20 years, HVDC has become the dominating technology for long distance transmission of bulk power. The use of 800 kV HVAC that was introduced in several countries during the 1960´s and 1970´s has come to a halt . The rapid development and the increased confidence the HVDC technology have caused the transition from ac to dc.

This paper will cover the classic thyristor based HVDC technology. The newer HVDC LightTM technique will be covered in a companion paper. The development of HVDC systems in the last 10 years has three main avenues compared with the technology of 1990:

1. The traditional classic HVDC technology is still dominating but with improved equipment and sub-systems (e.g. valves, dc-bushings, AC-filters, DC-filters etc.)
2. The new circuit concept of CCC (capacitor commutated converter) in the classic HVDC technology, that significantly improves the performance of the traditional converter.
3. The new HVDC using VSC (voltage source converters) using IGBTs in place of thyristors.

In all of the three lines of development the industry has taken maximum benefit of the dramatic development that is taking part in the computer field. Today's development is to a significant extent directed to the VSC technology that presently is developed in the lower power range (below ≈300 MW), where it has found many interesting transmission uses besides the traditional HVDC applications. It is believed that VSC systems such as HVDC Light in a few years will take over a large portion of the traditional HVDC market, that presently covered by thyristor technology. This paper deals with the recent developments of the classic, thyristor based, HVDC technology that still is dominating the bulk power dc transmission.

Beginning with a brief historical perspective on the development of High Voltage Direct Current (HVDC) transmission systems, this paper presents an overview of the status of HVDC systems in the world today. It then reviews the underlying technology of HVDC systems, and discusses the HVDC systems from a design, construction, operation and maintenance points of view. The paper then discusses the recent developments in HVDC technologies. The paper also presents an economic and financial comparison of HVDC system with those of an AC system; and provides a brief review of reference installations of HVDC systems. The paper concludes with a brief set of guidelines for choosing HVDC systems in today's electricity system development. In today electricity industry, in view of the liberalisation and increased effects to conserve the environment, HVDC solutions have become more desirable for the following reasons:

- Environmental advantages
- Economical (cheapest solution)
- Asynchronous interconnections
- Power flow control
- Added benefits to the transmission (stability, power quality etc.)

Historical Perspective on HVDC Transmission It has been widely documented in the history of the electricity industry, that the first commercial electricity generated (by Thomas Alva Edison) was direct current (DC) electrical power. The first electricity transmission systems were also direct current systems. However, DC power at low voltage could not be transmitted over long distances, thus giving rise to high voltage alternating current (AC) electrical systems. Nevertheless, with the development of high voltage valves, it was possible to once again transmit DC power at high voltages and over long distances, giving rise to HVDC transmission systems. Some important milestones in the development of the DC transmission technology are presented in Box 1. Important Milestones in the Development of HVDC technology

- Hewitt´s mercury-vapour rectifier, which appeared in 1901.
- Experiments with thyratrons in America and mercury arc valves in Europe before 1940.
- First commercial HVDC transmission, Gotland 1 in Sweden in 1954.
- First solid state semiconductor valves in 1970. • First microcomputer based control equipment for HVDC in 1979.

• Highest DC transmission voltage (+/- 600 kV) in Itaipú, Brazil, 1984.
• First active DC filters for outstanding filtering performance in 1994.
• First Capacitor Commutated Converter (CCC) in Argentina-Brazil interconnection, 1998
• First Voltage Source Converter for transmission in Gotland, Sweden ,1999

HVDC Installations in the world today Since the first commercial installation in 1954 a huge amount of HVDC transmission systems have been installed around the world. Figure 1 shows, by region, the different HVDC transmissions around the world. Rationale for Choosing HVDC There are many different reasons as to why HVDC was chosen in the above projects. A few of the reasons in selected projects are:

• In Itaipu, Brazil, HVDC was chosen to supply 50Hz power into a 60 Hz system; and to economically transmit large amount of hydro power (6300 MW) over large distances (800 km)

• In Leyte-Luzon Project in Philippines, HVDC was chosen to enable supply of bulk geothermal power across an island interconnection, and to improve stability to the Manila AC network

• In Rihand-Delhi Project in India, HVDC was chosen to transmit bulk (thermal) power (1500 MW) to Delhi, to ensure: minimum losses, least amount right-of-way, and better stability and control.

• In Garabi, an independent transmission project (ITP) transferring power from Argentina to Brazil, HVDC back-to-back system was chosen to ensure supply of 50 Hz bulk (1000MW) power to a 60 Hz system under a 20-year power supply contract

. • In Gotland, Sweden, HVDC was chosen to connect a newly developed wind power site to the main city of Visby, in consideration of the environmental sensitivity of the project area (an archaeological and tourist area) and improve power quality.

• In Queensland, Australia, HVDC was chosen in an ITP to interconnect two independent grids (of New South Wales and Queensland) to: enable electricity trading between the two systems (including change of direction of power flow); ensure very low environmental impact and reduce construction time. The HVDC technology The fundamental process that occurs in an HVDC system is the conversion of electrical current from AC to DC (rectifier) at the transmitting end, and from DC to AC (inverter) at the receiving end. There are three ways of achieving conversion:

• Natural Commutated Converters. Natural commutated converters are most used in the HVDC systems as of today. The component that enables this conversion process is the thyristor, which is a controllable semiconductor that can carry very high currents (4000 A) and is able to block very high voltages (up to 10 kV). By means of connecting the thyristors in series it is possible to build up a thyristor valve, which is able to operate at very high voltages (several hundred of kV).The thyristor valve is operated at net frequency (50 hz or 60 hz) and by means of a control angle it is possible to change the DC voltage level of the bridge. This ability is the way by which the transmitted power is controlled rapidly and efficiently.

• Capacitor Commutated Converters (CCC). An improvement in the thyristor-based commutation, the CCC concept is characterised by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves. The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.

• Forced Commutated Converters. This type of converters introduces a spectrum of advantages, e.g. feed of passive networks (without generation), independent control of active and reactive power, power quality. The valves of these converters are built up with semiconductors with the ability not only to turn-on but also to turn-off. They are known as VSC (Voltage Source Converters). Two types of semiconductors are normally used in the voltage source converters: the GTO (Gate Turn-Off Thyristor) or the IGBT (Insulated Gate Bipolar Transistor). Both of them have been in frequent use in industrial applications since early eighties. The VSC commutates with high frequency (not with the net frequency). The operation of the converter is achieved by Pulse Width Modulation (PWM). With PWM it is possible to create any phase angle and/or amplitude (up to a certain limit) by changing the

PWM pattern, which can be done almost instantaneously. Thus, PWM offers the possibility to control both active and reactive power independently. This makes the PWM Voltage Source Converter a close to ideal component in the transmission network. From a transmission network viewpoint, it acts as a motor or generator without mass that can control active and reactive power almost instantaneously.

Advantages of HVDC Systems Modern HVDC systems combines the good experience of the old installations with recently developed technologies and materials. The result is a very competitive, flexible and efficient way of transmitting electrical energy with a very low environmental impact. It is important to remark that an HVDC system not only transmit electrical power from one point to another, but it also has a lot of value added which should have been necessary to solve by another means in the case of using a conventional AC transmission. Some of these aspects are:

• No limits in transmitted distance. This is valid for both OH lines and sea or under ground cables.

• Very fast control of power flow, which implies stability improvements, not only for the HVDC link but also for the surrounding AC system.

• Direction of power flow can be changed very quickly (bi-directionality).

• An HVDC link don´t increase the short-circuit power in the connecting point. This means that it will not be necessary to change the circuit breakers in the existing network.

• HVDC can carry more power for a given size of conductor

• The need for ROW (Right Of Way) is much smaller for HVDC than for HVAC, for the same transmitted power. The environmental impact is smaller with HVDC.

• VSC technology allows controlling active and reactive power independently without any needs for extra compensating equipment.

• VSC technology gives a good opportunity to alternative energy sources to be economically and technically efficient.
• HVDC transmissions have a high availability and reliability rate, shown by more than 30 years of operation. HVDC in the new Electricity Industry The question is often asked as to when should HVDC transmission be chosen over an AC system. In the past, conventions were that HVDC was chosen when :

• Large amounts of power (>500 MW) needed to be transmitted over long distances(>500 km); • Transmitting power under water; 18

• Interconnecting two AC networks in an asynchronous manner. HVDC systems remain the best economical and environmentally friendly option for the above conventional applications. However, three different dynamics - technology development, deregulation of electricity industry around the world, and a quantum leap in efforts to conserve the environment - are demanding a change in thinking that could make HVDC systems the preferred alternative to high voltage AC systems in many other situations as well. To elaborate:

• New technologies, such as the VSC based HVDC systems, and the new extruded polyethylene DC cables, have made it possible for HVDC to become economic at lower power levels (up to 200 MW) and over a transmission distance of just 60 km.

• Liberalization has brought other demands on the power infrastructure overall. Transmission is now a contracted service, and there is very little room for deviation from contracted technical and economic norms. HVDC provides much better control of the power link and is therefore a better way for providing contractual transmission services.

• Liberalization has brought on the phenomenon of trading to the electricity sector, which would mean bi-directional power transfers, depending on market conditions. HVDC systems enable the bi-directional power flows, which is not possible with AC systems (two parallel systems would be required).

• In the past, when the transmission service was part of a government owned, vertically integrated utility, the land acquisition and obtaining rightsof-way was relatively easier, and very often was done under the principle of "Eminent Domain" of the State. With liberalization, transmission service provision is by and large in the domain of corporatized, sometimes privatized, entities. Land acquisition and/or obtaining rights-ofway is now a significant portion of the project's costs. Once these costs are included in their entirety in the economical analysis of HVDC versus AC alternatives, it would be seen that HVDC is much more economical in this regard, since it requires much less land/right-of-way for a given level of power.

• In an environmentally sensitive areas, such as national parks and protected sanctuaries, the lower foot print of HVDC transmission systems becomes the only feasible way to build a power link. So how should power system planners, investors in power infrastructure (both public and private), and financiers of such infrastructure be guided with respect to choosing between an HVDC and an high voltage AC alternative? The answer is to let the "market" decide. In other words:

• the planners, investors and financiers should issue functional specifications for the transmission system to qualified contractors, as opposed to the practice of issuing technical specifications, which are often inflexible, and many times include older technologies and techniques) while inviting bids for a transmission system.

• The functional specifications could lay down the power capacity, distance, availability and reliability requirements; and last but not least, the environmental conditions.

• The bidders should be allowed to bid either an HVDC solution or an AC solution; and the best option chosen. It is quite conceivable that with changed circumstances in the electricity industry, the technological developments, and environmental considerations, HVDC would be the preferred alternative in many more transmission projects.

Conduction and breakdown in solid, liquid and gases dielectrics

Breakdown in solids

Solid insulation forms an integral part of high voltage structures. The solid materials provide the mechanical support for conducting parts and at the same time insulate the conductors from one another. Frequently practical insulation structures consist of combinations of solids with liquid and/or gaseous media. Therefore, the knowledge of failure mechanisms of solid dielectrics under electric stress is of great importance. In gases the transport of electricity is limited to positive and negative charge carriers, and the destruction of insulating properties involves a rapid growth of current through the formation of electron avalanches.

The mechanism of electrical failure in gases is now understood reasonably clearly. This is not the case for solid insulation. Although numerous investigators have studied the breakdown of solids for nearly a century now, and a number of detailed theories have been put forward which aimed to explain quantitatively the breakdown processes in solids, the state of knowledge in this area is still very crude and inconclusive. Electrical conduction studies in solids are obscured by the fact that the transport phenomena besides electronic and ionic carriers include also currents due to the slower polarization processes such as slow moving dipoles (orientation polarization) and interfacial polarization. Electrical methods are unable to distinguish between the conduction currents and the currents due to polarization having a longer time constant than the duration of a particular experiment. At low stresses and normal temperatures conduction by free electrons and ions in solids is exceptional. Examples in which the conduction is believed to be of the simple electrolytic type at room temperature and above are glasses. In this case the conduction–temperature relation is found to be of the form

$$\sigma = A \exp\left[-\frac{u}{kT}\right]$$

where A and u are empirical constants. Ceramics also develop a significant conductivity at higher temperatures that may be electronic or ionic.

Intrinsic breakdown

If the material under test is pure and homogeneous, the temperature and environmental conditions are carefully controlled, and the sample is so stressed that there are no external discharges. With under voltages applied for a short time the electric strength increases up to an upper limit which is called the intrinsic electric strength. The intrinsic strength is a property of the material and temperature only. Experimentally the intrinsic strength is rarely reached, but numerous attempts have been made to measure it for various materials. To achieve the highest strength the sample is so designed that there is a high

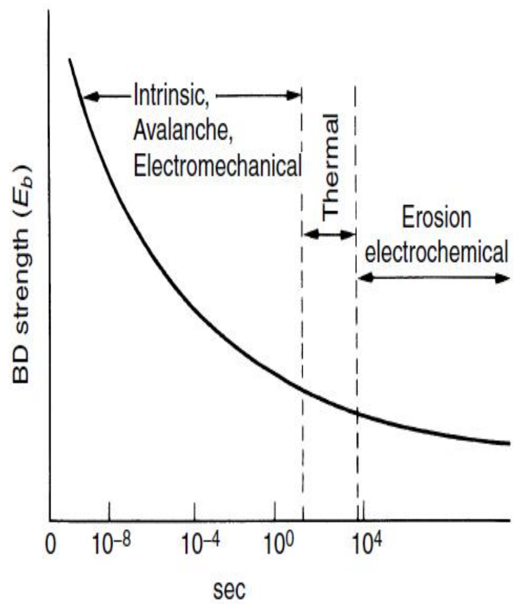

Figure 6.1 *Mechanisms of failure and variation of breakdown strength in solids with time of stressing*

Fig.1.1: Strength in solid w.r.t Time

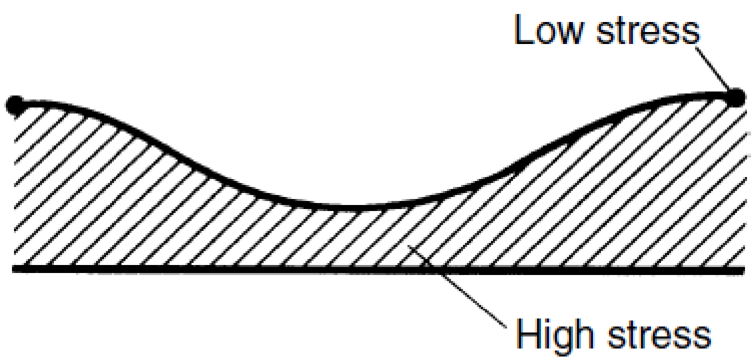

Fig.1.2: Arrangement used for Measuring intrinsic solid breakdown

stress in the centre of the solid under test and too low stress at the edges which cause discharge in the medium as shown in Fig. 6.2. The intrinsic breakdown is accomplished in times of the order of 108 sec and has therefore been postulated to be electronic in nature. The stresses required for an intrinsic breakdown are well in excess of 106 V/cm.

The intrinsic strength is generally assumed to be reached when electrons in the insulator gain sufficient energy from the applied field to cross the forbidden energy gap from the valence to the conduction band. The criterion condition is formulated by solving an equation for the energy balance between the gain of energy by conduction electrons from the applied field and its loss to the lattice. Several models have been proposed in an attempt to predict the critical value of the field which causes intrinsic breakdown, but no completely satisfactory solution has yet been obtained.

The models used by various workers differ from each other in the proposed mechanisms of energy transfer from conduction electrons to the lattice, and also by the assumptions made concerning the mywbut.com 3 distribution of conduction electrons. In pure homogeneous dielectric materials the conduction and the valence bands are separated by a large energy gap, and at room temperature the electrons cannot acquire sufficient thermal energy to make transitions from valence to conduction band. The conductivity in perfect dielectrics should therefore be zero.

In practice, however, all crystals contain some imperfections in their structures due to missing atoms, and more frequently due to the presence of foreign atoms (impurities). The impurity atoms may act as traps for free electrons in energy levels that lie just below the conduction band, as illustrated schematically in Fig. 6.3.

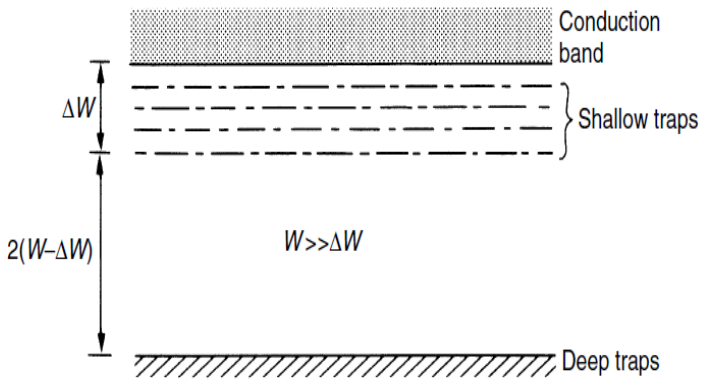

Figure 6.3 *Schematic energy level diagram for an amorphous dielectric*

Fig.1.3: Schematic energy level diagram for amorphous dielectrics.

At low temperatures the trap levels will be mostly filled with electrons caught there as the crystal was cooled down during its manufacture. At room temperature some of the trapped electrons will be excited thermally into the conduction band, because of the small energy gap between the trapping levels and the conduction level. An amorphous crystal will therefore have some free conduction electrons.

Tracking

Tracking is the formation of a permanent conducting path, usually carbon, across a surface of insulation and in most cases the conduction path results from degradation of the insulation.

For tracking to occur the insulation must contain some organic substance. In an outdoor environment insulation will in time become covered with contaminant which may be of industrial or coastal origin. In the presence of moisture the contamination layer gives rise to leakage current which heats the surface and causes interruption in the moisture film; small sparks are drawn between the separating moisture films.

This process acts effectively as an extension to the electrodes. The heat resulting from the small sparks causes carbonization and volatilization of the insulation and leads to formation of permanent 'carbon track' on the surface. The phenomenon of tracking severely limits the use of organic insulation in the outdoor environment. The rate of tracking depends upon the structure of the polymers and it can be drastically slowed down by adding appropriate fillers to the polymer which inhibit carbonization. Moisture is not essential to tracking. The conducting path may arise from metallic dust; for example, in oil-immersed equipment with moving parts which gradually wear and deposit on the surface.

Breakdown in liquids

The general state of knowledge on the electrical breakdown in liquids is less advanced than is in case of gases or even solids. Many aspects of liquid breakdown have been investigated over the last decades, but the findings and conclusions of the many workers cannot be reconciled and so produce mywbut.com 19 a general theory applicable to liquids, as the independent data are at variance and sometimes contradictory. The principal reason for this situation is the lack of comprehensive theory concerning the physical basis of the liquid state which would form the skeleton structure in which observations could be compared and related. Comprehensive reviews of the published data on the subject have been made periodically and the more recent ones include the reviews of Lewis,11
Sharbaugh and Watson,12
Swann,13
Kok,14
Krasucki,15
Zaky and Hawley,16
and Gallagher.17
The work falls broadly into two schools of thought. On the one hand there are those who attempt to explain the breakdown of liquids on a model which is an extension of gaseous breakdown, based on the avalanche ionization of the atoms caused by electron collision in the applied field. The electrons are assumed to be ejected from the cathode into the liquid by either a field emission, in which case they are assumed to tunnel out through the surface aided by the field, or by the field enhanced thermionic (Schottky's) effect. This type of breakdown mechanism has been considered to apply to homogeneous liquids of extreme purity, and does not apply to commercially exploited liquid insulation. Conduction studies in highly pure liquids showed that at low fields the conduction is largely ionic due to dissociation of impurities and increases linearly with the field strength.

This conduction saturates at intermediate fields. At high field, as we approach breakdown, the conduction increases more rapidly and tends to be unstable. It is believed that this increased current results from electron emission at the cathode by one or both of the above mechanisms, and possibly by field aided dissociation of molecules in the liquid. It has long been recognized that the presence of foreign particles in liquid insulation has a profound effect on the breakdown strength of liquids. In one approach it has been postulated14 that the suspended particles are polarizable and are of higher permittivity than the liquid. As a result they experience an electrical force directed towards the place of maximum stress. With uniform field electrodes the movement of particles is presumed to be initiated by surface irregularities on the electrodes, which give rise to local field gradients. The accumulation of particles continues and tends to form a bridge across the gap which leads to initiation of breakdown.

The impurities can also be gaseous bubbles of lower breakdown strength than the liquid, in which case on breakdown of the bubble the total breakdown of the liquid may be triggered. A mathematical model for bubble breakdown has been proposed by Kao.18

BREAKDOWN OF GASES

At normal temperature and pressure, the gases are excellent insulators. The current conduction is of the order of 10–10 A/cm2. This current conduction results from the ionisation of air by the cosmic radiation and the radioactive substances present in the atmosphere and the earth. At higher fields, charged particles may gain sufficient energy between collision to cause ionisation on impact with neutral molecules.

It is known that during an elastic collision, an electron loses little energy and rapidly builds up its kinetic energy which is supplied by an external electric field. On the other hand, during elastic collision, a large part of the kinetic energy is transformed into potential energy by ionising the molecule struck by the electron. Ionisation by electron impact under strong electric field is the most important process leading to breakdown of gases.

This ionisation by radiation or photons involves the interaction of radiation with matter. Photoionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionisation energy and is represented as $A + h\nu \rightarrow A+ + e$ where A represents a neutral atom or molecule in the gas and $h\nu$ the photon energy. Photoionization is a secondary ionization process and is essential in the streamer breakdown mechanism and in some corona discharges. If the photon energy is less than the ionization energy, it may still be absorbed thus raising the atom to a higher energy level.
This is known as *photoexcitation*.

The life time of certain elements in some of the excited electronic states extends to seconds. These are known as metastable states and these atoms are known as *metastables*. Metastables have a relatively high potential energy and are, therefore, able to ionize neutral particles. Let A be the atom to be ionized and Bm the metastable, when Bm collides with A, ionization may take place according to the reaction.

$$A + B^m \longrightarrow A^+ + B + e$$

Ionization by metastable interactions comes into operation long after excitation and it has been shown that these reactions are responsible for long-time lags observed in some gases.

Direct stroke:

When thunder cloud directly discharges on to a transmission line tower or line wires, it is called direct stroke. This is the most severe form and this occurs rarely.

Inducted Stroke:

When thunder storm generates negative charges at its ground end. The transmission line and Tower develop induced positive charges. Normally lines are unaffected, because they are insulated by string insulators. However, because of the high field gradients involved, the positive charge leak from the Tower along the insulator surfaces to the live conductors, after a few micro seconds, (say). When the cloud discharges through some earthed objects other than the transmission line, huge concentration of positive charge is left with. The transmission line and earth act as a huge capacitor. This may result in a stroke and hence the name inducted lightning stroke.

Explain the various theories of charge formation in clouds

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 th range of300 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 potentialof a cloud lies approximately within the range of 10 MV to 100 MV.The energy in a lightningstroke may be of the order of 250 kWhr.

Raindrops:

Raindrops elongate and become unstable under an electric field, the limiting diameter Being 0.3 cm in a field of 100 kV/cm. 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 . 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 spacecharge, 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

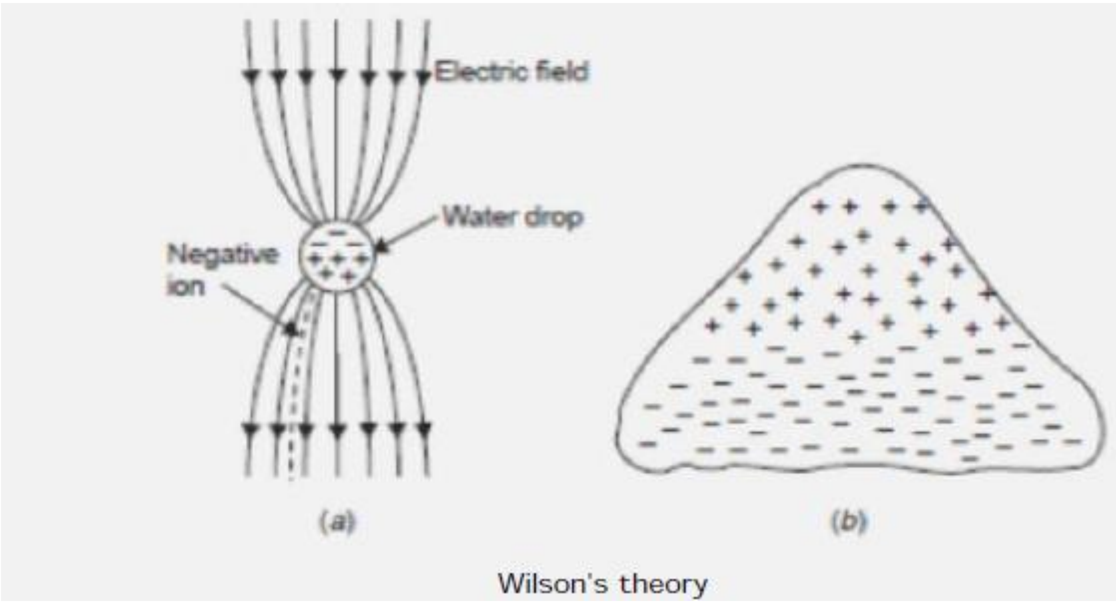

Fig.1.4: Atmospheric collision

Simpson's and Scarse Theory

Simpsons 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:

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 aircurrents 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.

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 positivel ycharged by induction. Lightning discharge will require the puncture of the air between the cloudand 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. After agradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets ionized. At this a streamer starts from the cloud towards the earth which cannot be detected with the naked eye; only a spot travelling is detected.

The current in the streamer is of the order of 100 amperes and the speed of the streamer is 0.16 m/μ sec. This streamer is known as pilot streamer because this leads to the lightning phenomenon. Depending upon the state of ionization of the air surrounding the streamer, it is branched to several paths and this is known as stepped leader. The leader steps are of the order of 50 m in length and are accomplished in about a microsecond. The charge is brought from the cloud through the already ionized path to these pauses. The air surrounding these pauses is again ionized and the leader in this way reaches the earth Once the stepped leader has made contact with the earth it is believed that a power return stroke moves very fast up towards the cloud through the already ionized path by the leader.

This streamer is very intense where the current varies between 1000 amps and 200,000 amps and the speed is about10% that of light. It is here where the –ve charge of the cloud is being neutralized by the positive induced charge on the earth . It is this instant which gives rise to lightning flash which we observe with our naked eye. There may be another cell of charges in the cloud near the neutralized charged cell. This charged cell will try to neutralize through this ionized path. This streamers known as dart leader. The velocity of the dart leader is about 3% of the velocity of light. The effect of the dart leader is much more severe than that of the return stroke.

The discharge current in the return streamer is relatively very large but as it lasts only for a few microseconds the energy contained in the streamer is small and hence this streamer is known as cold lightning stroke 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.

Explain various causes of switching surges

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).

Temporary over voltages

For temporary over voltages, 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

ECHANISM research of long air gap discharge is rel-

Explain various types of over voltage protection

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 again 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 No shielding methods and then the shielding methods. However, the non shielding methods can also be used for external over voltages. 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 over voltage 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.

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, with or without aseries resistance. The choke connected between the equipment to be protected and the horn gapserves two purposes:

(i) The steepness of the wave incident on the equipment to be protected is reduced.
(ii) (ii) It reflects the voltage surge back on to the horn.

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.

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 normalvoltage) 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 surgecurrent without damaging itself.It should interrupt the power frequency follow current after the surge is discharged toground.There are mainly three types of surge diverters:
(*i*) Rod gap, (*ii*) Protector tube orexpulsion type of lightning arrester, (*iii*) Valve type of lightning arrester.

Rod gap

This type of surge diverter is perhaps the simplest, cheapest and most rugged one. For a given gap and wave shape of the voltage, the time for breakdown varies approximately inversely with the applied voltage.

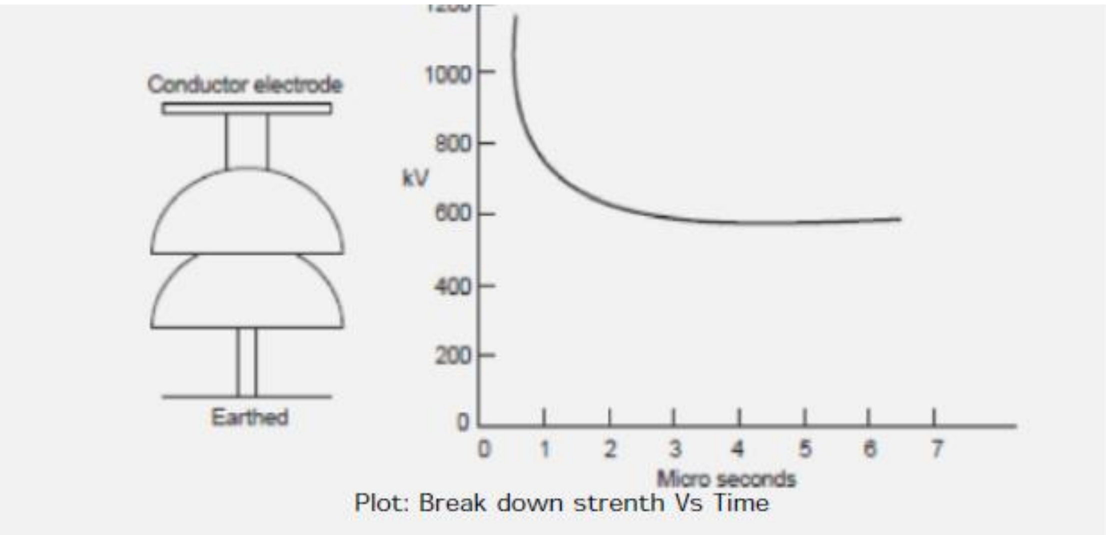

Fig.1.5: plot of Break down v/s Time.

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. 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.

Expulsion type of lightning arrester

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) (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) (iv) an open vent at the lower end for the gases to be expelled .It is desired that the breakdown voltage of a tube must be lower than that of the insulation for which it is used.

UNIT-2

HALF-WAVE RECTIFIER CIRCUIT

The simplest circuit for generation of high direct voltage is the half wave rectifier shown in Fig. 2.1
Here *RL* is the load resistance and *C* the capacitance to smoothen the d.c. output voltage.

GENERATION OF HIGH D.C. AND A.C. VOLTAGES

If the capacitor is not connected, pulsating d.c. voltage is obtained at the output terminals whereas with the capacitance *C*, the pulsation at the output terminal are reduced. Assuming the ideal transformer and small internal resistance of the diode during conduction the capacitor *C* is charged to the maximum voltage *Vmax* during conduction of the diode *D*. Assuming that there is no load connected, the d.c. voltage across capacitance remains constant at *Vmax* whereas the supply voltage oscillates between *Vmax* and during negative half cycle the potential of point *A* becomes – *Vmax* and hence the diode must be rated for 2*Vmax*. This would also be the case if the transformer is grounded at *A* instead of *B* as shown in Fig. 2.1 (*a*). Such a circuit is known as *voltage doubler* due to Villard for which the output voltage would be taken across *D*. This d.c. voltage, however, oscillates between zero and 2*Vmax* and is needed for the Cascade circuit.

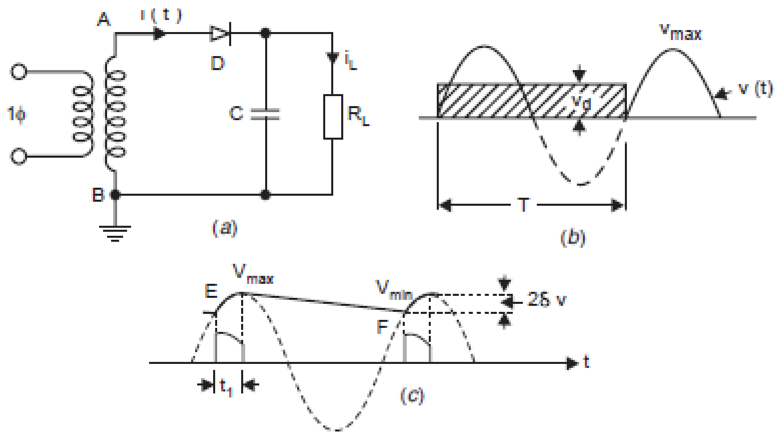

Fig. 2.1 (*a*) Single Phase rectifier (*b*) Output voltage without *C* (*c*) Output voltage with *C*

If the circuit is loaded, the output voltage does not remain constant at *Vmax*. After point *E* (Fig.2.1 (*c*)), the supply voltage becomes less than the capacitor voltage, diode stops conducting. The capacitor can not discharge back into the a.c. system because of one way action of the diode. Instead, the current now flows out of *C* to furnish the current *iL* through the load. While giving up this energy, the capacitor voltage also decreases at a rate depending on the time constant *CR* of the circuit and it reaches the point *F* corresponding to *Vmin*. Beyond *F*, the supply voltage is greater than the capacitor voltage and hence
the diode *D* starts conducting charging the capacitor *C* again to *Vmax* and also during this period it supplies current to the load also. This second pulse of *ip*(*ic* + *il*) is of shorter

duration than the initial charging pulse as it serve mainly to restore into *C* the energy that *C* meanwhile had supplied to load. Thus, while each pulse of diode current lasts much less than a half cycle, the load receives current more continuously from *C*.

Assuming the charge Assuming the charge supplied by the transformer to the load during the conduction period *t*, which is very small to be negligible, the charge supplied by the transformer to the capacitor during conduction equals the charge supplied by the capacitor to the load. Note that *ic*>> *iL*. During one period *T* = 1/*f* of the a.c voltage, a charge *Q* is transferred to the load *RL* and is given as

$$Q = \int_T i_L(t)\,dt = \int_T \frac{V_{RL}(t)}{R_L}dt = IT = \frac{I}{f}$$

where *I* is the mean value of the d.c output *iL*(*t*) and *VRL*(*t*) the d.c. voltage which includes a ripple as shown in Fig. 2.1 (*c*).

This charge is supplied by the capacitor over the period *T* when the voltage changes from *Vmax* to *Vmin* over approximately period *T* neglecting the conduction period of the diode. Suppose at any time the voltage of the capacitor is *V* and it decreases by an amount of *dV* over the time *dt* then charge delivered by the capacitor during this time is

$$dQ = CdV$$

Therefore, if voltage changes from *Vmax* to *Vmin*, the charge delivered by the capacitor.

$$\int dQ = \int_{V_{max}}^{V_{min}} CdV = -C(V_{max} - V_{min})$$

Or the magnitude of charge delivered by the capacitor

$$Q = C\,(V_{max} - V_{min}) \tag{2.3}$$

Using equation (2.2)

$$Q = 2\delta VC \tag{2.4}$$

Therefore, $2\delta VC = IT$

or

$$\delta V = \frac{IT}{2C} = \frac{I}{2fC} \tag{2.5}$$

Equation (2.5) shows that the ripple in a rectifier output depends upon the load current and the circuit parameter like *f* and *C*. The product *fC* is, therefore, an important design factor for the rectifiers. The higher the frequency of supply and larger the value of filtering capacitor the smaller will be the ripplein the d.c. output.

The single phase half-wave rectifier circuits have the following disadvantages:

(*i*) The size of the circuits is very large if high and pure d.c. output voltages are desired.

(*ii*) The h.t. transformer may get saturated if the amplitude of direct current is comparable with the nominal alternating current of the transformer.

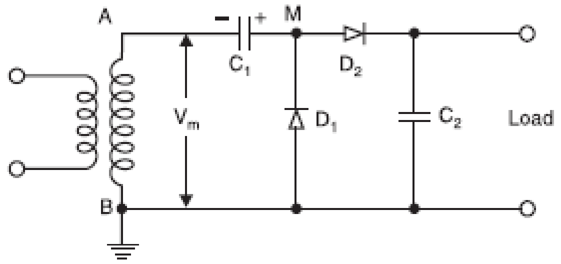

Fig. 2.2 Greinacher voltage doubler circuit

COCKROFT-WALTON VOLTAGE MULTIPLIER CIRCUIT

In 1932, Cockroft and Walton suggested an improvement over the circuit developed by Greinacher for producing high D.C. voltages. Fig. 2.3. shows a multistage single phase cascade circuit of the Cockroft-Walton type.

No Load Operation: The portion ABM′MA is exactly indentical to Greinarcher voltage doubler circuit and the voltage across *C* becomes 2*Vmax* when *M* attains a voltage 2*Vmax*.

During the next half cycle when *B* becomes positive with respect to *A*, potential of *M* falls and, therefore, potential of *N* also falls becoming less than potential at *M*′ hence *C*2 is charged through *D*2. Next half cycle *A* becomes more positive and potential of *M* and *N* rise thus charging *C*′2 through *D*′2. Finally all the capacitors *C*′1, *C*′2, *C*′3, *C*1, *C*2, and C3 are charged. The voltage across the column of capacitors consisting of *C*1, *C*2, *C*3, keeps on oscillating as the supply voltage alternates. This column, therefore, is known as *oscillating column*. However, the voltage across the capacitances *C*′1, *C*′2, *C*′3, remains constant and is known as *smoothening column*. The voltages at *M*′, *N*′, and *O*′ are 2 *Vmax* 4 *Vmax* and 6 *Vmax*. Therefore, voltage across all the capacitors is 2 *Vmax* except for *C*1 where it is *Vmax* only. The total output voltage is 2*n* Vmax where *n* is the number of stages. Thus, the use of multistages arranged in the manner shown enables very high voltage to be obtained. The equal stress of the elements (both capacitors and diodes) used is very helpful and promotes a modular design of such generators.

Generator Loaded: When the generator is loaded, the output voltage will never reach the value 2*n Vmax*. Also, the output wave will consist of ripples on the voltage. Thus, we have to deal with two quantities, the voltage drop Δ*V* and the ripple δ*V*.

Suppose a charge *q* is transferred to the load per cycle. This charge is *q* = *I*/*f* = *IT*. The charge comes from the smoothening column, the series connection of *C*′1, *C*′2, *C*′3,. If no charge were transferred during *T* from this stack via *D*1, *D*2, *D*3, to the oscillating column, the peak to peak ripple would merely be

$$2\delta V = IT \sum_{n=0}^{n} \frac{1}{C'_i} \qquad (2.6)$$

But in practice charges are transferred. The process is explained with the help of circuits in Fig. 2.3 (*a*) and (*b*).

Fig. 2.3 (*a*) shows arrangement when point *A* is more positive with reference to *B* and charging of smoothing column takes place and Fig. 2.4 (*b*) shows the arrangement when in the next half cycle *B* becomes positive with reference to *A* and charging of oscillating column takes place. Refer to Fig. 2.3 (*a*). Say the potential of point *O′* is now 6 *Vmax*. This discharges through the load resistance and say the charge lost is $q = IT$ over the cycle. This must be regained during the charging cycle (Fig. 2.3 (*a*)) for stable operation of the generator. *C*3 is, therefore supplied a charge *q* from *C*3. For this *C*2 must acquire a charge of 2*q* so that it can supply *q* charge to the load and *q* to *C*3, in the next half cycle termed by cockroft and Walton as the transfer cycle (Fig. 2.3 (*b*)). Similarly *C′*1 must acquire for stability reasons a charge 3*q* so that it can supply a charge *q* to the load and 2*q* to the capacitor *C*2 in the next half cycle(transfer half cycle).

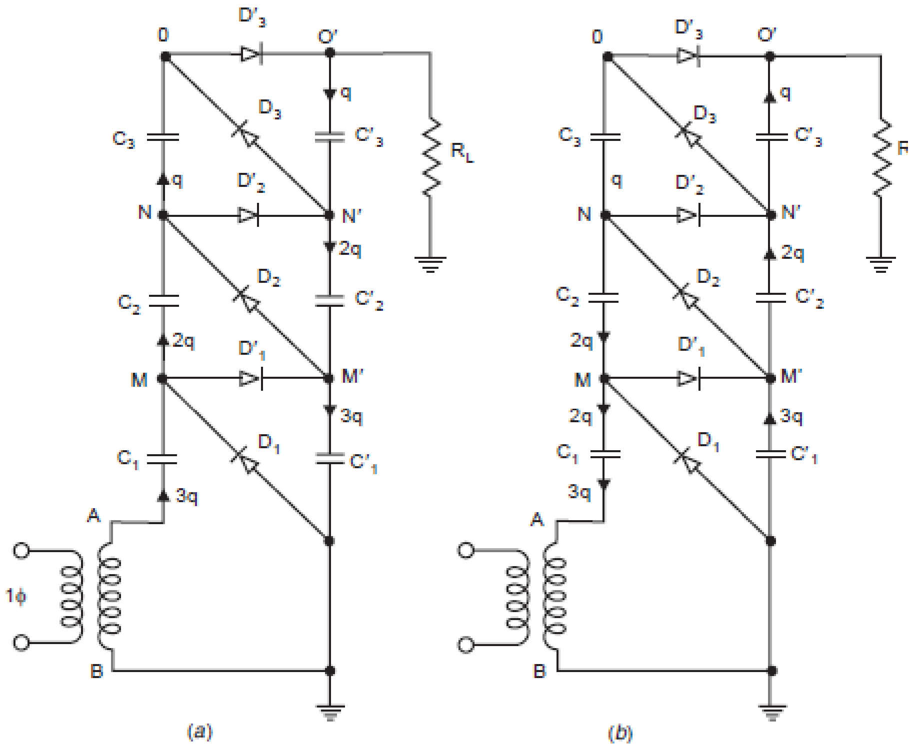

Fig. 2.4 (*a*) Charging of smoothening Column (*b*) Charging of oscillating column

Fig.2.3: (a) Charging of smoothing column (b) charging of oscillating column

During the transfer cycle shown in Fig. 2.3 (*b*), the diodes *D*1, *D*2, *D*3, conduct when *B* is positive with reference to *A*. Here *C′*2 transfers *q* charge to *C*3, *C*1 transfers charge 2*q* to *C*2 and the transformer provides change 3*q*.

For *n*-stage circuit, the total ripple will be

$$2\delta V = \frac{I}{f}\left(\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right)$$

$$\delta V = \frac{I}{2f}\left(\frac{1}{C'_n} + \frac{2}{C'_{n-1}} + \frac{3}{C'_{n-2}} + \ldots + \frac{n}{C'_1}\right) \qquad (2.7)$$

From equation (2.7), it is clear that in a multistage circuit the lowest capacitors are responsible for most
ripple and it is, therefore, desirable to increase the capacitance in the lower stages. However, this is objectionable from the view point of High Voltage Circuit where if the load is large and the load voltage goes down, the smaller capacitors (within the column) would be overstressed. Therefore, capacitors of equal value are used in practical circuits *i.e.*, $C'n = C'n - 1 = ...\ C'1 = C$ and the ripple is given as

$$\delta V = \frac{I}{2fC}\frac{n(n+1)}{2} = \frac{In(n+1)}{4fC} \qquad (2.8)$$

The second quantity to be evaluated is the voltage drop ΔV which is the difference between the theoretical no load voltage $2nVmax$ and the onload voltage. In order to obtain the voltage drop ΔV refer to Fig. 2.4 (*a*).
Here $C'1$ is not charged upto full voltage $2Vmax$ but only to $2Vmax - 3q/C$ because of the charge given up through $C1$ in one cycle which gives a voltage drop of $3q/C = 3I/fC$ .The voltage drop in the transformer is assumed to be negligible. Thus, $C2$ is charged to the Voltage

$$\left(2V_{max} - \frac{3I}{fC}\right) - \frac{3I}{fC}$$

since the reduction in voltage across C'_3 again is $3I/fC$. Therefore, C'_2 attains the voltage

$$2V_{max} - \left(\frac{3I + 3I + 2I}{fC}\right)$$

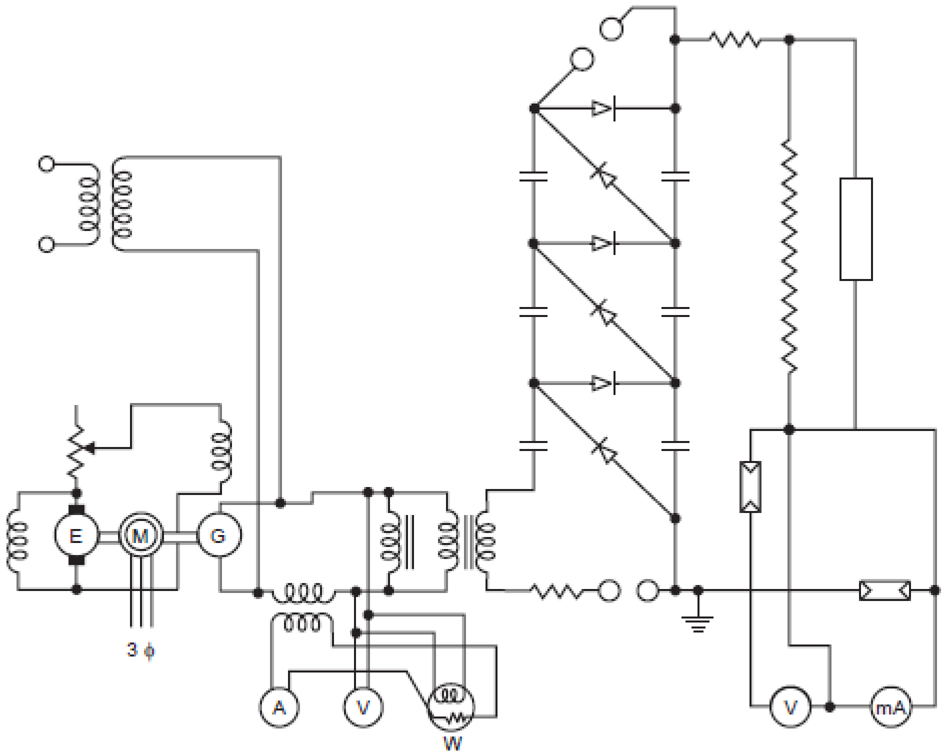

Fig. 2.5 A typical Cockroft circuit

Fig.2.4: Cockroft Circuit

ELECTROSTATIC GENERATOR

In electromagnetic generators, current carrying conductors are moved against the electromagnetic forces acting upon them. In contrast to the generator, electrostatic generators convert mechanical energy into electric energy directly. The electric charges are moved against the force of electric fields, thereby higher potential energy is gained at the cost of mechanical energy. The basic principle of operation is explained with the help of Fig. 2.4.
An insulated belt is moving with uniform velocity ν in an electric field of strength E (x). Suppose the width of the belt is b and the charge density σ consider a length dx of the belt, the charge $dq = \sigma\, bdx$. The force experienced by this charge (or the force experienced by the belt).

$$dF = Edq = E\,\sigma\, bdx$$

or
$$F = \sigma b \int Edx$$

Normally the electric field is uniform

$\therefore$
$$F = \sigma bV$$

The power required to move the belt

$$= \text{Force} \times \text{Velocity}$$
$$= Fv = \sigma bVv \qquad (2.15)$$

Now current
$$I = \frac{dq}{dt}\sigma b\frac{dx}{dt} = \sigma bv \qquad (2.16)$$

$\therefore$ The power required to move the belt

$$P = Fv = \sigma bVv = VI \qquad (2.17)$$

Assuming no losses, the power output is also equal to VI.

Fig. 2.4 shows belt driven electrostatic generator developed by Van deGraaf in 1931. An insulating belt is run over pulleys. The belt, the width of which may vary from a few cms to metres is driven at a speed of about 15 to 30 m/sec, by means of a motor connected to the lower pulley. The belt near the lower pully is charged electrostatically by an excitation arrangement. The lower charge spray unit consists of a number of needles connected to the controllable d.c. source (10 kV–100 kV) so that the discharge between the points and the belt is maintained. The charge is conveyed to the upper end where it is collected from the belt by discharging points connected to the inside of an insulated metal electrode through which the belt passes.

The entire equipment is enclosed in an earthed metal tank filled with insulating gases of good dielectric strength viz. SF6 etc. So that the potential of the electrode could be raised to relatively higher voltage without corona discharges or for a certain voltage a smaller size of the equipment will result. Also, the shape of the h.t., electrode should be such that the surface gradient of electric field is made uniform to reduce again corona discharges, even though it is desirable to avoid corona entirely. An isolated sphere is the most favourable electrode shape and will maintain a uniform field E with a voltage of Er where r is the radius of the sphere.

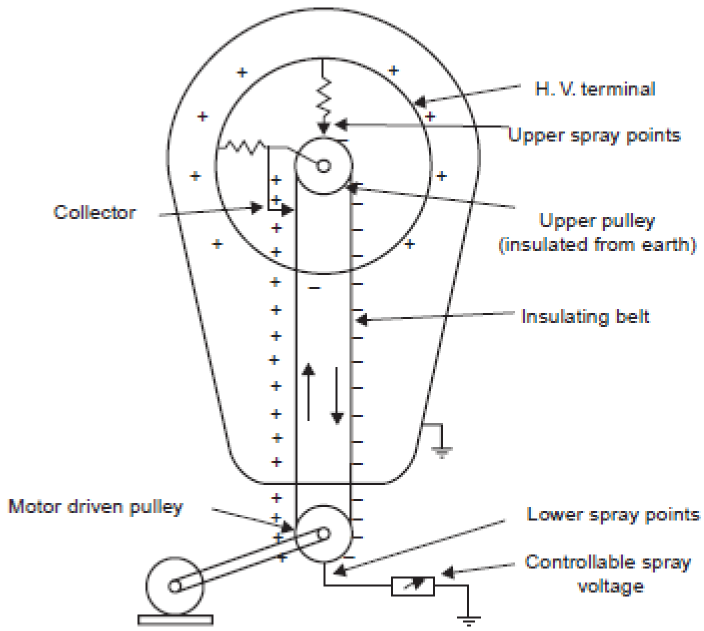

Fig. 2.8 Van de Graaf generator

Fig.2.5: Van de Graff Generator

As the h.t. electrode collects charges its potential rises. The potential at any instant is given as $V = q/C$ where q is the charge collected at that instant. It appears as though if the charge were collected for a long time any amount of voltage could be generated. However, as the potential of electrode rises, the field set up by the electrode increases and that may ionise the surrounding medium and, therefore, this would be the limiting value of the voltage. In practice, equilibrium is established at a terminal voltage which is such that the charging current.

$$\left(I = C\frac{dV}{dt}\right)$$

Equals the discharge current which will include the load current and the leakage and corona loss currents. The moving belt system also distorts the electric field and, therefore, it is placed within properly shaped field grading rings. The grading is provided by resistors and additional corona discharge elements.

The collector needle system is placed near the point where the belt enters the h.t. terminal. A second point system excited by a self-inducing arrangement enables the down going belt to be charged to the polarity opposite to that of the terminal and thus the rate of charging of the latter, for a given speed, is doubled. The self inducing arrangement requires insulating the upper pulley and maintaining it at a potential higher than that of the h.t. terminal by connecting the pulley to the collector needle system. The arrangement also consists of a row of points (shown as upper spray points in Fig. 2.8)
connected to the inside of the h.t. terminal and directed towards the pulley above its points of entry into the terminal. As the pulley is at a higher potential (positive), the negative charges due to corona discharge at the upper spray points are collected by the belt. This neutralises

any remaining positive charge on the belt and leaves an excess of negative charges on the down going belt to be neutralised by the lower spray points. Since these negative charges leave the h.t. terminal, the potential of the h.t. terminal is raised by the corresponding amount.

IMPULSE GENERATOR CIRCUITS

Fig. 3.3 represents an exact equivalent circuit of a single stage impulse generator along with a typical load. *C*1 is the capacitance of the generator charged from a d.c. source to a suitable voltage which causes discharge through the sphere gap. The capacitance *C*1 may consist of a single capacitance, in which case the generator is known as a single stage generator or alternatively if *C*1 is the total capacitance of a group of capacitors charged in parallel and then discharged in series, it is then known as a multistage generator.

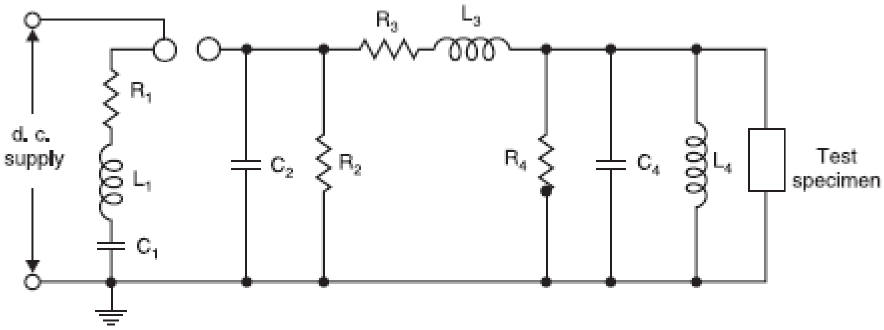

Fig. 3.3 Exact equivalent circuit of a single stage impulse generator with a typical load

Fig.2.6: Impulse Generator

*L*1 is the inductance of the generator and the leads connecting the generator to the discharge circuit and is usually kept as small as possible. The resistance *R*1 consists of the inherent series resistance of the capacitances and leads and often includes additional lumped resistance inserted within the generator for damping purposes and for output waveform control. *L*3, *R*3 are the external elements which may be connected at the generator terminal for waveform control. *R*2 and *R*4 control the duration of the wave.

However, *R*4 also serves as a potential divider when a CRO is used for measurement purposes. *C*2 and *C*4 represent the capacitances to earth of the high voltage components and leads. *C*4 also includes the capacitance of the test object and of any other load capacitance required for producing the required wave shape. *L*4 represents the inductance of the test object and may also affect the wave shape appreciably.
Usually for practical reasons, one terminal of the impulse generator is solidly grounded. The polarity of the output voltage can be changed by changing the polarity of the d.c. charging voltage.

For the evaluation of the various impulse circuit elements, the analysis using the equivalent circuit of Fig. 3.3 is quite rigorous and complex. Two simplified but more practical forms of impulse generator circuits are shown in Fig. 3.4 (*a*) and (*b*).

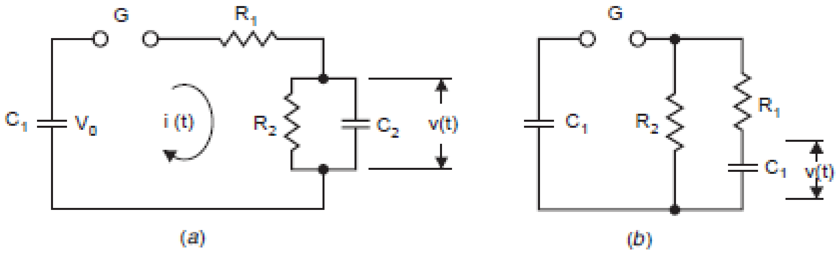

Fig. 3.4 Simplified equivalent circuit of an impulse generator

Fig.2.6: Equivalent Circuit of Impulse Generator.

The two circuits are widely used and differ only in the position of the wave tail control resistance *R*2. When *R*2 is on the load side of *R*1 (Fig. *a*) the two resistances form a potential divider which reduces the output voltage but when *R*2 is on the generator side of *R*1 (Fig. *b*) this particular loss of output voltage is absent.

The impulse capacitor *C*1 is charged through a charging resistance (not shown) to a d.c. voltage *V*0 and then discharged by flashing over the switching gap with a pulse of suitable value. The desired impulse voltage appears across the load capacitance *C*2. The value of the circuit elements determines the shape of the output impulse voltage. The following analysis will help us in evaluating the circuit parameters for achieving a particular wave shape of the impulse voltage.

MULTISTAGE IMPULSE GENERATOR CIRCUIT

In order to obtain higher and higher impulse voltage, a single stage circuit is inconvenient for the following reasons:
(*i*) The physical size of the circuit elements becomes very large.
(*ii*) High d.c. charging voltage is required.
(*iii*) Suppression of corona discharges from the structure and leads during the charging period is difficult.
(*iv*) Switching of vary high voltages with spark gaps is difficult.

In 1923 E. Marx suggested a multiplier circuit which is commonly used to obtain impulse voltages with as high a peak value as possible for a given d.c. charging voltage. Depending upon the charging voltage available and the output voltage required a number of identical impulse capacitors are charged in parallel and then discharged in series, thus obtaining a multiplied total charging voltage corresponding to the number of stages. Fig. 3.7 shows a 3-stage impulse generator circuit due to Marx employing '*b*' circuit connections. The impulse capacitors *C*1 are charged to the charging voltage *V*0 through the high charging resistors *Rc* in parallel. When all the gaps *G* break down, the *C*1′ capacitances are connected in series so that *C*2 is charged through the series connection of all the wave front resistances *R*1′ and finally all *C*1′ and *C*2 will discharge through the resistors *R*2′ and *R*1′. Usually *Rc* >> *R*2 >> *R*1.

If in Fig. 3.7 the wave tail resistors *R*2′ in each stage are connected in parallel to the series combination of $R1'$, G and $C1'$, an impulse generator of type circuit '*a*' is obtained. In order that the Marx circuit operates consistently it is essential to adjust the distances between various sphere gaps such that the first gap $G1$ is only slightly less than that of $G2$ and so on. If is also necessary that the axes of the gaps G be in the same vertical plane so that the ultraviolet radiations due to spark in the first gap G, will irradiate the other gaps. This ensures a supply of electrons released from the gap electrons to initiate breakdown during the short period when the gaps are subjected to over voltages.

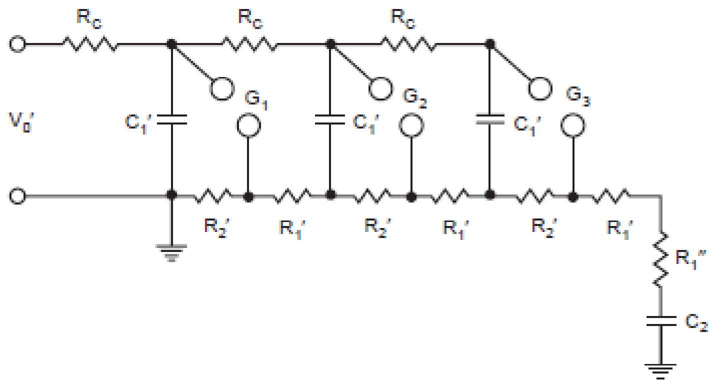

Fig. 3.7 A 3-stage Marx impulse generator in circuit '*b*' connections.

Fig.2.7: Three stage impulse generator.

The wave front control resistance can have three possible locations (*i*) entirely within the generator (*ii*) entirely outside the generator (*iii*) partly within and partly outside the generator. The first arrangement is unsatisfactory as the inductance and capacitance of the external leads and the load form an oscillatory circuit which requires to be damped by an external resistance.

The second arrangement is also unsatisfactory as a single external front resistance will have to withstand, even though for a very short time, the full rated voltage and therefore, will turn out to be inconveniently long and would occupy much space. A compromise between the two is the third arrangement as shown in Fig. 2.7 and thus both the "space economy" and damping of oscillations are taken care of. It can be seen that Fig. 3.7 can be reduced to the single stage impulse generator of Fig. 2.4 (*b*). After the generator has fired, the total discharge capacitance $C1$ may be given as

$$\frac{1}{C_1} \sum^{n} \frac{1}{C_1'}$$

the equivalent front resistance

$$R_1 = \sum^{n} R_1' + R_1''$$

where n is the number of stages. Goodlet has suggested another circuit shown in Fig. 3.8, for generation of impulse voltage where the load is earthed during the charging period, without the necessity for an isolating gap. The impulse output voltage has the same polarity as the charging voltage is case of Marx circuit, it is reversed in case of Goodlet circuit. Also, on discharge, both sides of the first spark gap are raised to the charging voltage in the Marx circuit but in case of Goodlet circuit they attain earth potential.

UNIT-3

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 transformers, circuit breakers, bus supports etc. have different breakdown voltages and hence the volt-time characteristics.

In order that all the equipments should be properly protected it is desired that the insulation of the various protective devices must be properly coordinated. The basic concept of insulation coordination is illustrated in Fig. 7.27. Curve *A* is the volt-time curve of the protective device and *B* the volt-time curve of the equipment to be protected. Fig. 7.27 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 voltage 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

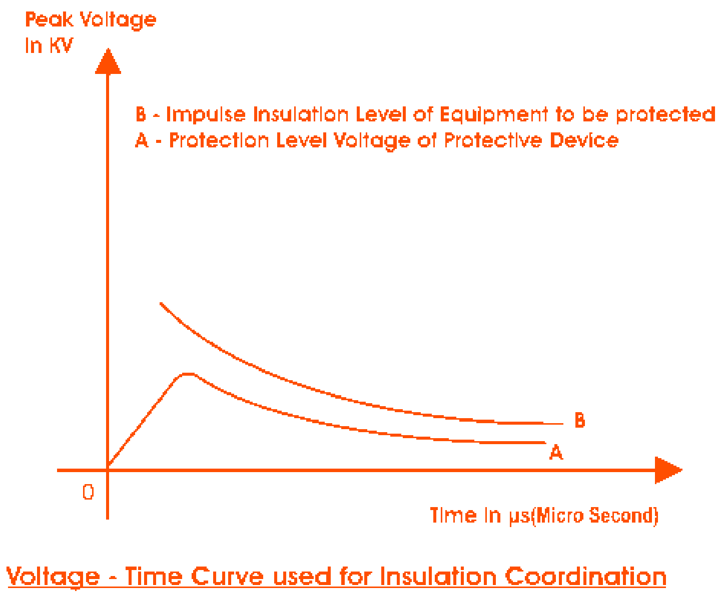

Fig.7.27: Voltage Time Curve

Voltage-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 **Fig. 7.27** Volt-time curve A 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 flashover 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. 7.28.

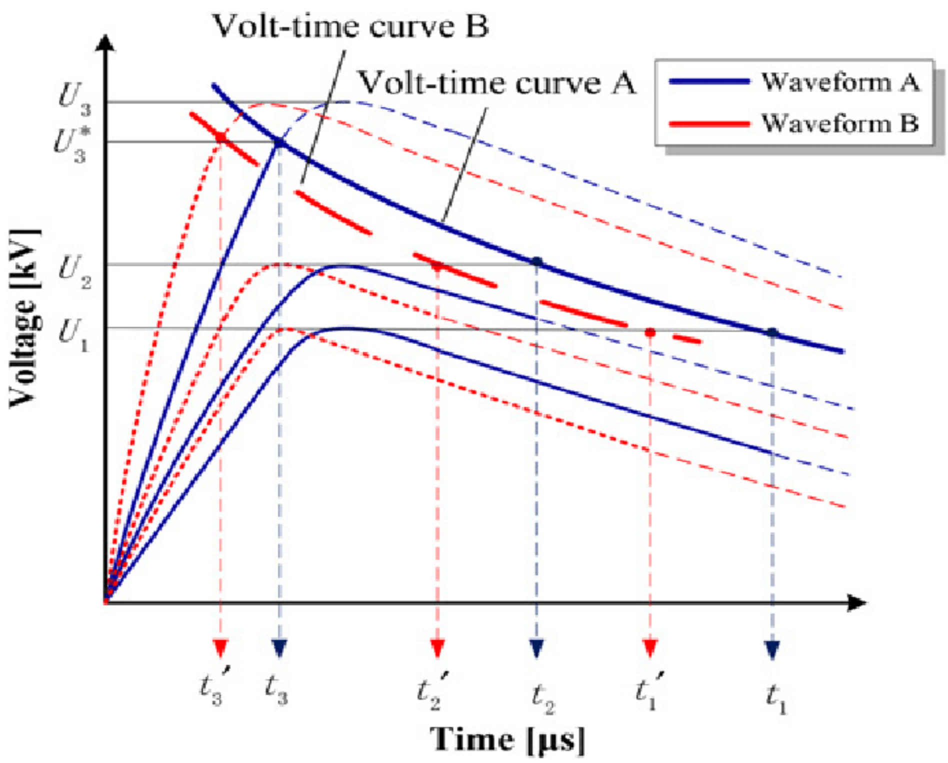

Fig.7.28: High Voltage Testing Insulation Curve

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 upto 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 where as 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.

OVERVOLTAGE PROTECTION

The causes of overvoltages in the system have been studied extensively in previous sections. Basically, there are two sources: (*i*) external overvoltages due to mainly lightning, and (*ii*) internal overvoltages 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.

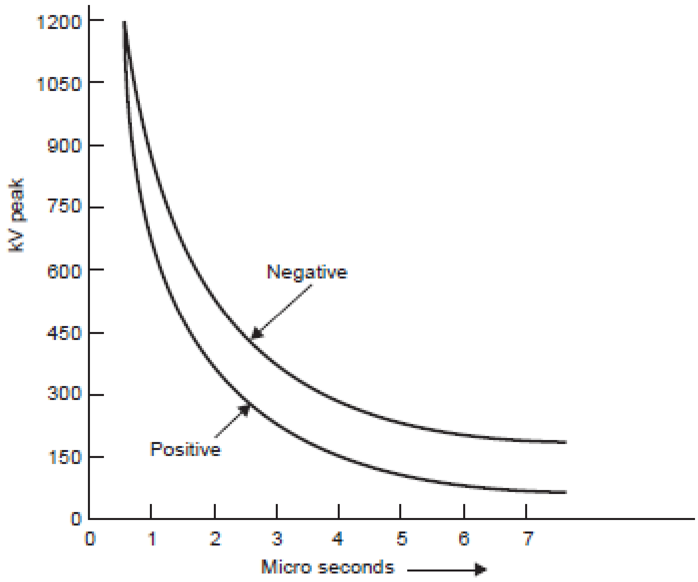

Fig. 7.34 Volt-time curves of gaps for positive and negative polarity

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. 7.34 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.

GROUND WIRES

The ground wire is a conductor running parallel to the power conductors of the transmission line and is placed at the top of the tower structure supporting the power conductors (Fig. 7.44 (*a*)). For horizontal configuration of the power line conductors, there are two ground wires to provide effective shielding to power conductors from direct lightning stroke whereas in vertical configuration there is one ground wire. The ground wire is made of galvanized steel wire or in the modern high voltage transmission lines ACSR conductor of the same size as the power conductor is used. The material and size of the conductor are more from mechanical consideration rather than electrical. A reduction in the effective ground resistance can be achieved by other relatively simpler and cheaper means. The ground wire serves the following purposes:

(i) It shields the power conductors from direct lightning strokes.

(ii) Whenever a transmission in power system and insulation coordination lightning stroke falls on the tower, the ground wires on both sides of the tower provide parallel paths for the stroke, thereby the effective impedance (surge impedance) is reduced and the tower top potentialis relatively less.

(*iii*) There is electric and magnetic coupling between the ground wire and the power conductors, thereby the changes of insulation failure are reduced.

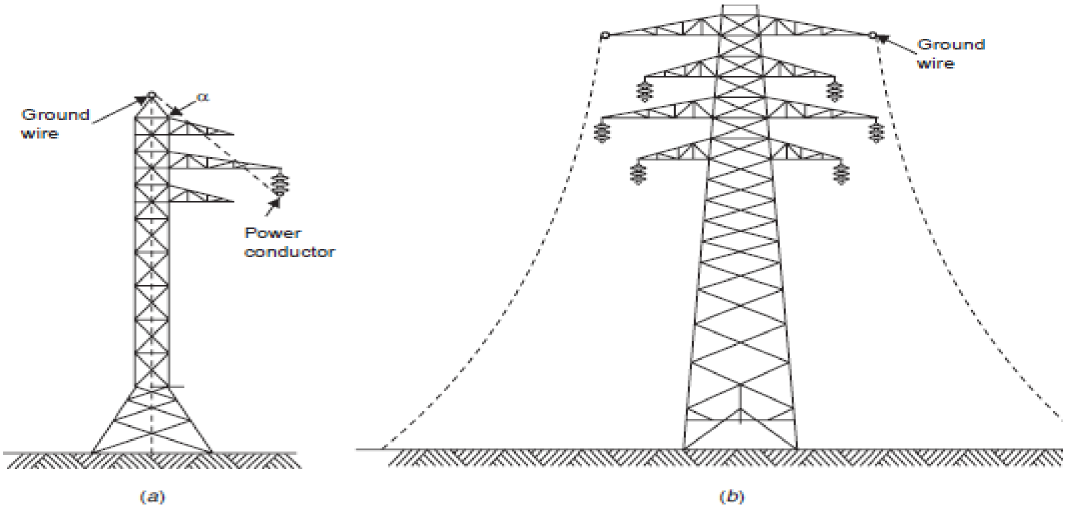

Fig. 7.44 (*a*) Protective angle; (*b*) Protection afforded by two ground wires

Protective angle of the ground wire is defined as the angle between the vertical line passing through the ground wire and the line passing through the outermost power conductor (Fig. 7.44 (*a*)) and the protective zone is the zone which is a cone with apex at the location of the ground wire and surface generated by line passing through the outermost conductor. According to Lacy, a ground wire
provides adequate shielding to any power conductor that lies below a quarter circle drawn with its centre at the height of ground wire and with its radius equal to the height of the ground wire above the ground. If two or more ground wires are used, the protective zone between the two adjacent wires can be taken as a semi-circle having as its diameter a line connecting the two ground wires (Fig. 7.44 (*b*)).

The field experience along with laboratory investigation has proved that the protective angle should be almost 30° on plain areas whereas the angle decreases on hilly areas by an amount equal to the slope of the hill. The voltage to which a transmission tower is raised when a lightning strikes the tower, is independent of the operating voltage of the system and hence the design of transmission line against lightning for a desired performance is independent of the operating voltage. The basic requirement for the design of a line based on direct stroke are:
(*i*) The ground wires used for shielding the line should be
Mechanically strong and should be so located that they provide sufficient shield.
(*ii*) There should be sufficient clearance between the power conductors themselves and between the power conductors and the ground or the tower structure for a particular operating voltage.
(*iii*) The tower footing resistance should be as low as can be justified economically.

UNIT-4

LIGHTNING PHENOMENON

Lightning has been a source of wonder to mankind for thousands of years. Schonland 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 cloud and the associated phenomenon.
1. The height of the cloud base above the surrounding ground level may vary from 160 to 9,500
m. The charged centres which are responsible for lightning are in the range of 300 to 1500 m.
2. 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.
3. The maximum potential of a cloud lies approximately within the range of 10 MV to 100 MV.
4. The energy in a lightning stroke may be of the order of 250 kWhr.
5. Raindrops:
(*a*) Raindrops elongate and become unstable under an electric field, the limiting diameter being 0.3 cm in a field of 100 kV/cm.
(*b*) 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.
(*c*) Falling raindrops greater than 0.5 cm in dia become unstable and break up into smaller drops.
(*d*) When a drop is broken up by air currents, the water particles become positively charged and the air negatively charged.
(*e*) When an ice crystal strikes with air currents, the ice crystal is negatively charged and the air positively charged.

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. 7.24.

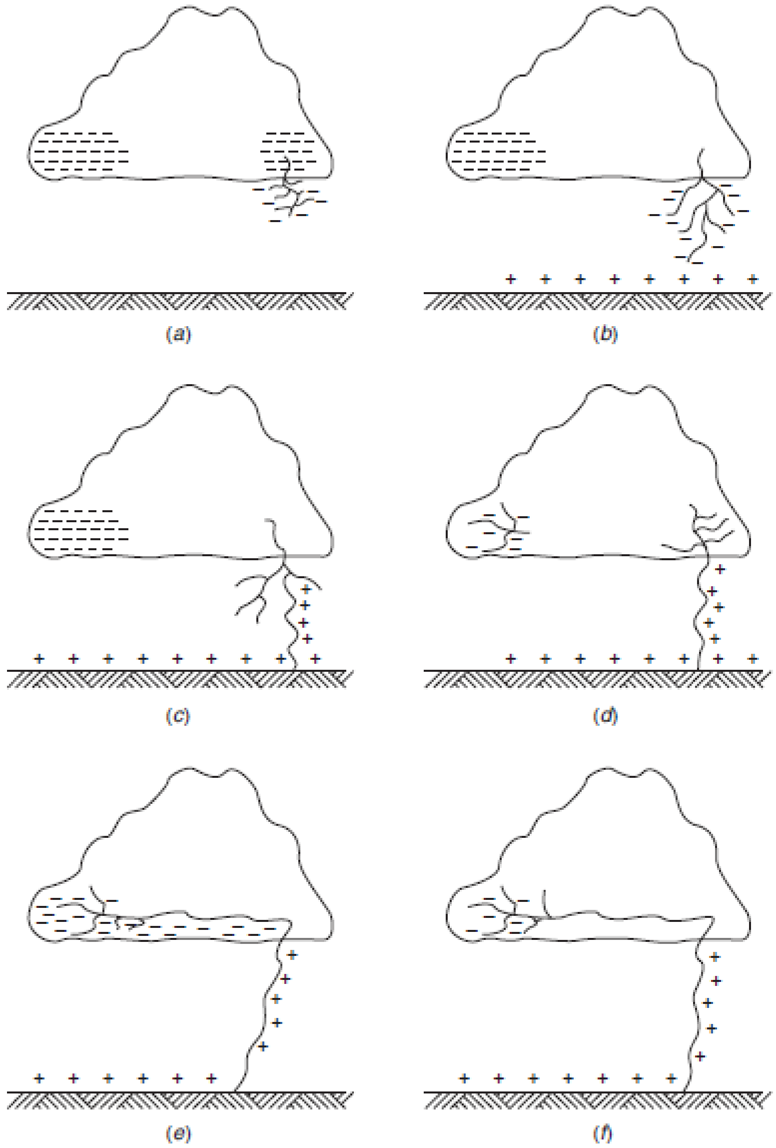

Fig. 7.24 Lightning mechanism

After a gradient of approximately 10 kV/cm is set up in the cloud, the air surrounding gets ionized. At this a streamer (Fig. 7.24(*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. 7.24(*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. 7.24(*c*)). Once the stepped leader has made contact with the earth it is believed that a power return stroke (Fig. 7.24(*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. 7.24(*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 ionised path. This streamer is known as dart leader (Fig. 7.24(*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 energycontained 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.

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 (Fig. 7.22(*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

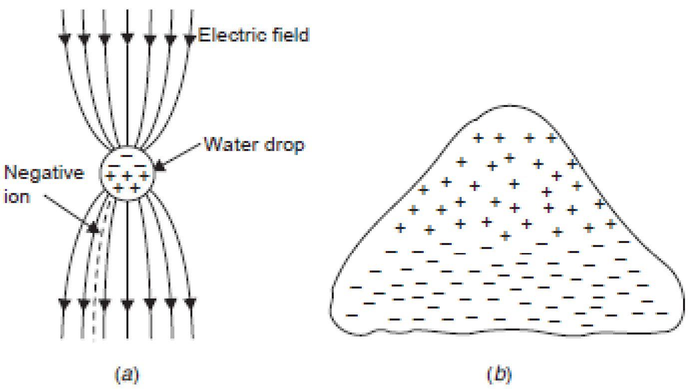

Fig. 7.22(*a*) Capture of negative ions by large falling drop; (*b*) Charge separation in a thunder cloud according to Wilson's theory.

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 uper positions of the cloud, the lower base of the cloud is negatively charged and the upper region is positively charged.

Surge Diverters

The following are the basic requirements of a surge diverter:
(*i*) It should not pass any current at normal or abnormal (normally 5% more than the normal voltage) power frequency voltage.
(*ii*) It should breakdown as quickly as possible after the abnormal high frequency voltage arrives.
(*iii*) It should not only protect the equipment for which it is used but should discharge the surge current without damaging itself.
(*iv*) 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.
Rod gap. This type of surge diverter is perhaps the simplest, cheapest and most rugged one. Fig. 7.36 shows one such gap for a breaker bushing. This may take the form of arcing ring. Fig. 7.37 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.

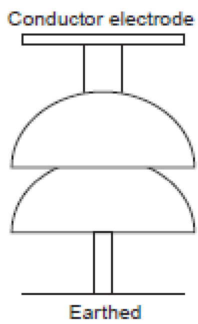

Fig. 7.36 A rod gap

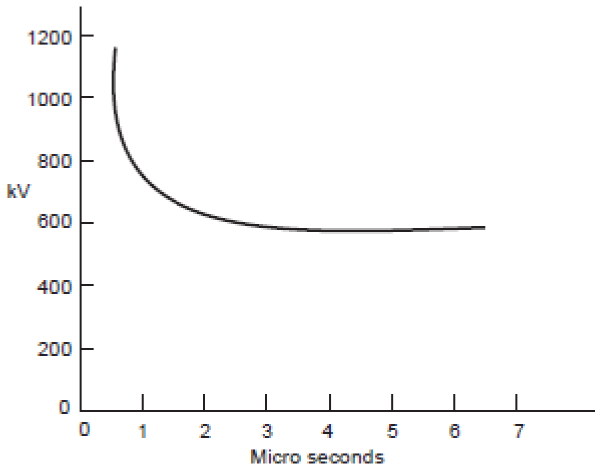

Fig. 7.37 Volt-time characteristic of rod gap

The time to flashover for positive polarity are 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.

Expulsion type of lightning arrester

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) (*ii*) a tube which has a fibre 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 forthe gases to be expelled (Fig. 7.38).

It is desired that the breakdown voltage of a tube must be lower than that of the insulation for which it is used. When a surge voltage is incident on the expulsion tube the series gap is spanned and an arc is formed between the electrodes within the tube. The heat of the arc vaporizes some of the organic material of the tube wall causing a high gas pressure to build up in the tube. The resulting neutral gas creates lot of turbulence within the tube and is expelled out from the open bottom vent of the tube and it extinguishes the arc at the first current zero. At this instant the rate of build up of insulation strength is greater than the RRRV.

Very high currents have been interrupted using these tubes. The breakdown voltage of expulsion tubes is slightly lower than for plain rod gaps for the same spacing. With each operation of the tube the diameter of the tube (fibre lining) increases; thereby the insulation characteristics of the tube will lower down even though not materially. The volt-time characteristics (Fig. 7.39) of the expulsion tube are somewhat better than the rod gap and have the ability to interrupt power voltage after flashover.

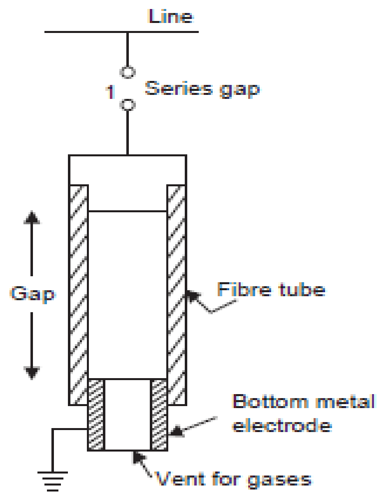

Fig. 7.38 Expulsion type lightning arrester