Module 5 Fuses, Protection against Overvoltages, Modern Trends in Power System Protection

Course objective

To explain the principle of circuit interruption and different types of circuit breakers.

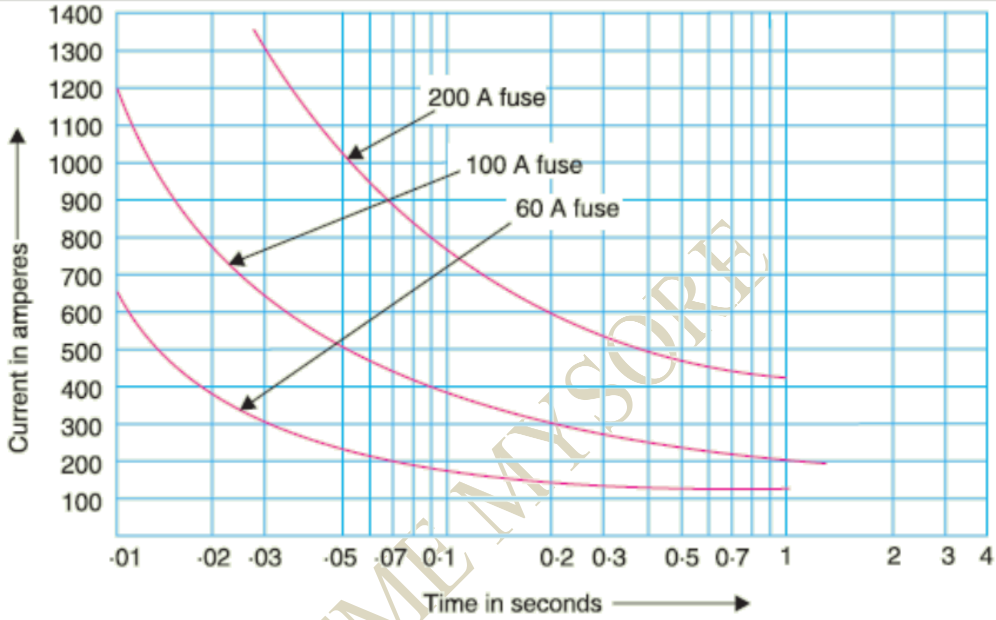
To describe the construction and operating principle of different types of fuses and to give the definitions of different terminologies related to a fuse.

To discuss protection Against Overvoltages and Gas Insulated Substation (GIS).

Module 5 Fuses

5.0 Introductions

Fuse is a short piece of metal, inserted in the circuit, which melts when excessive current flows through it and thus breaks the circuit. The fuse element is generally made of materials having low melting point, high conductivity and least deterioration due to oxidation e.g., silver, copper etc. It is inserted in series with the circuit to be protected. Under normal operating conditions, the fuse element is at a temperature below its melting point. Therefore, it carries the normal current without overheating. However, when a short-circuit or overload occurs, the current through the fuse increases beyond its rated value. This raises the temperature and fuse element melts (or blows out), disconnecting the circuit protected by it. In this way, a fuse protects the machines and equipment from damage due to excessive currents.



The time required to blow out the fuse depends upon the magnitude of excessive current. The greater the current, the smaller is the time taken by the fuse to blow out. In other words, a fuse has inverse time-current characteristics as above shown in Fig. Such a characteristic permits its use for overcurrent protection

Advantages

(i) It is the cheapest form of protection available.
(ii) It requires no maintenance.
(iii) Its operation is inherently completely automatic unlike a circuit breaker which requires an elaborate equipment for automatic action.
(iv) It can break heavy short-circuit currents without noise or smoke.
(v) The smaller sizes of fuse element impose a current limiting effect under short-circuit conditions.
(vi) The inverse time-current characteristic of a fuse makes it suitable for overcurrent protection.
(vii) The minimum time of operation can be made much shorter than with the circuit breakers.

Disadvantages

(i) Considerable time is lost in rewiring or replacing a fuse after operation.
(ii) On heavy short-circuits, *discrimination between fuses in series cannot be obtained unless there is sufficient difference in the sizes of the fuses concerned.
(iii) The current-time characteristic of a fuse cannot always be co-related with that of the protected Apparatus

Desirable Characteristics of Fuse Element

The function of a fuse is to carry the normal current without overheating but when the current exceeds its normal value, it rapidly heats up to melting point and disconnects the circuit protected by it. In order that it may perform this function satisfactorily, the fuse element should have the following desirable characteristics :
(i) low melting point e.g., tin, lead.
(ii) high conductivity e.g., silver, copper.
(iii) free from deterioration due to oxidation e.g., silver.
(iv) low cost e.g., lead, tin, copper.
The above discussion reveals that no material possesses all the characteristics. For instance, lead has low melting point but it has high specific resistance and is liable to oxidation. Similarly, copper has high conductivity and low cost but oxidises rapidly. Therefore, a compromise is made in the selection of material for a fuse

Fuse Element Materials

The most commonly used materials for fuse element are lead, tin, copper, zinc and silver. For small currents upto 10A, tin or an alloy of lead and tin (lead 37%, tin 63%) is used for making the fuse element. For larger currents, copper or silver is employed. It is a usual practice to tin the copper to protect it from oxidation. Zinc (in strip form only) is good if a fuse with considerable time-lag is required *i.e*., one which does not melt very quickly with a small overload.
The present trend is to use silver despite its high cost due to the following reasons:
(*i*) It is comparatively free from oxidation.
(*ii*) It does not deteriorate when used in dry air.
(*iii*) The coefficient of expansion of silver is so small that no critical fatigue occurs. Therefore, the fuse element can carry the rated current continuously for a long time.
(*iv*) The conductivity of silver is very high. Therefore, for a given rating of fuse element, the mass of silver metal required is smaller than that of other materials. This minimises the problem of clearing the mass of vapourised material set free on fusion and thus permits fast operating speed.
(*v*) Due to comparatively low specific heat, silver fusible elements can be raised from normal temperature to vapourisation quicker than other fusible elements. Moreover, the resistance of silver increases abruptly as the melting temperature is reached, thus making the transition from melting to vapourisation almost instantaneous. Consequently, operation becomes very much faster at higher currents.
(*vi*) Silver vapourises at a temperature much lower than the one at which its vapour will readily ionise. Therefore, when an arc is formed through the vapourised portion of the element, the arc path has high resistance. As a result, short-circuit current is quickly interrupted

5.1 DEFINITIONS
Operation of fuse-link. Process of pre-arcing and arcing resulting in blowing/melting of fuse-link.
Cut-off. The melting of fuse-element before the current reaches the prospective peak (fault current peak value). The value of current at which the cut-off (Melting) occurs is called cut-off current. Cut-off current measured as an instantaneous value.
Pre-arcing Time-Time between beginning of the prospective current loop and the cut-off
Arcing Time-Time between cut-off and final current zero.
Total Operating Time-Pre-arcing time plus acting time.
Fuse element-The part of the fuse which is designed to melt when the fuse operates.
Fuse link-The part of the fuse which needs replacement when the fuse blows out.

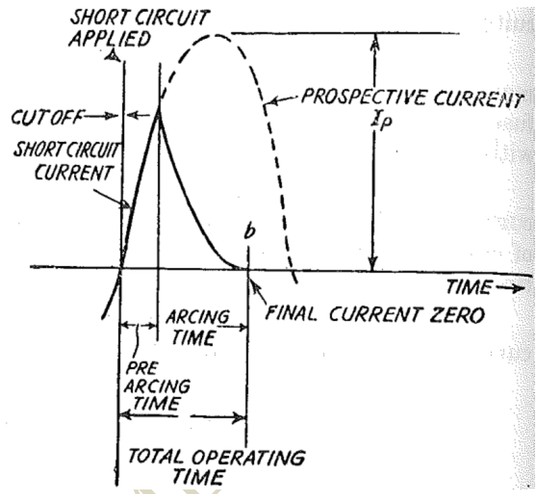
SPECIFICATION OF A FUSE LINK
Voltage Rating. This is specified by the manufacturer. The rated voltage of the fuse should be equal to or more than:

1. Voltage of the circuit in a single phase a.c. or two wire circuit.
2. Line voltage in case of three phase a.c. circuit.
3. Voltage between two outer wires in three wire d c circuits

Frequency. A fuse link suitable for 50 c/s may not have same rating for other frequencies of D.C. circuits
Current Rating. This rating is stated by the manufacturer. It is R.M.S. value of current which the fuse can carry continuously without melting.
Minimum Fusing Current. The minimum current at which the fuse will melt.
Fusing Factor. The ratio of minimum fusing current to the current rating,
Fusing factor = Minimum fusing current / current rating of fuse, this factor is more than 1
Prospective current of a circuit. The short circuit current that would flow in the circuit if the fuse were absent (replaced by a link of negligible impedance).
Prospective peak current of the circuit- Peak value of first current loop of short circuit current, It is measured in terms of the rms value of the A.C Component.

5.2 Fuse characteristic

Cut-off characteristic of fuse (HRC)

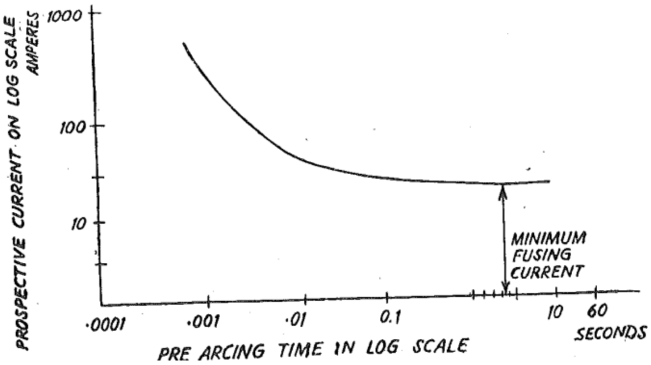


On occurrence of short circuit, the current starts increasing. It would have reached a peak of the prospective current (Ip), if no fuse were there to protect. But fuse does not allow current to reach Ip. Because of sufficient heat energy generated by the fault current, the fuse element is cut-off at Ic and arc is initiated and after a brief arcing time the current is interrupted. The cut-off value depends upon (1) normal current rating of the fuse; (2) prospective current (3) the asymmetry of circuit waveform.

Cut-off property has a great advantage that the short circuit current does not reach the prospective peak, Hence the circuit is not subjected to electrodynamic stresses corresponding to peak prospective current. Hence the bus bar design is considerably simplified because the maximum value of current for design purposes in cut-off value.

Time-current characteristics of fuse

A fuse being a Thermal device possesses inverse time-current characteristic, i.e. operating time decreases as fault current increases.



Typical Time-Current characteristic of a fuse

Normally the characteristics give pre-arcing time plotted against prospective currents upto the rupturing capacity rating of the fuse. Both the axis are plotted on logarithmic axis.

It is observed that as the prospective current increases, the pre-arcing time reduces. Further the characteristic becomes asymmetry and there is a minimum current below which the fuse does I not operate. For currents near the minimum fusing current, the operating time is long

Fuse Law

Fuse law determines the current carrying capacity of a fuse wire. The law can be established in the following way. At steady state condition, that is when fuse carry normal current without increasing its temperature to the melting limit. That means at this steady state condition, heat generated due to current through fuse wire is equal to heat dissipated from it, so there is an Equilibrium condition and fuse don't melt at normal rated current. But during abnormal condition as fault current increases the heat generate is not equal to heat dissipated

Heat generated = $I^2.R$
Where R is the resistance of the fuse wire

$$= I^2.\rho.\frac{l}{a}$$

Where ρ is the resistivity, l is the length and a is the cross sectional area of fuse wire

$$= I^2.\rho.\frac{L}{\pi d^2/4}$$

Where d is the diameter of fuse wire

$$= I^2.K_1.\frac{L}{d^2} \text{.............(i)}$$

Where K_1 is a constant

Heat lost ∝ surface area of fuse wire ∝ πd.l
Therefore, heat lost = K_2.d.l............. (ii)
Where K_2 is a constant

Now, equating (i) & (ii), we get,

$$I^2.K_1.\frac{l}{d^2} = K_2.d.l$$

$\Rightarrow I^2 = K.d^3$

Where $K = \frac{K_2}{K_1}$ is another constant

$\Rightarrow I = K.d^{3/2}$
$\Rightarrow I = K.d^{1.5}$

This is known as **fuse law, where '**I' is an approximate value of the minimum fusing current for a round fuse wire, given by $I = K.d^{3/2}$ where k is a constant depending upon the material of the fuse wire, and 'd' is the diameter of the wire.

5.3 Types of Fuses

In general, fuses may be classified into: (*i*) Low voltages fuses (*ii*) High voltage fuses

Low Voltage Fuses

Low voltage fuses can be subdivided into two classes viz., (i) semi-enclosed rewireable fuse (ii) high rupturing capacity (H.R.C.) cartridge fuse

Semi-enclosed rewireable fuse. Rewireable fuse (also known as kit-kat type) is used where low values of fault current are to be interrupted. It consists of (*i*) a base and (*ii*) a fuse carrier. The base is of porcelain and carries the fixed contacts to which the incoming and outgoing phase wires are connected. The fuse carrier is also of porcelain and holds the fuse element (tinned copper wire) between its terminals. The fuse carrier can be inserted in or taken out of the base when desired. When a fault occurs, the fuse element is blown out and the circuit is interrupted. The fuse carrier is taken out and the blown out fuse element is replaced by the new one. The fuse carrier is then reinserted in the base to restore the supply. This type of fuse has two advantages. Firstly, the detachable fuse carrier permits the replacement of fuse element without any danger of coming in contact with live parts. Secondly, the cost of replacement is negligible.

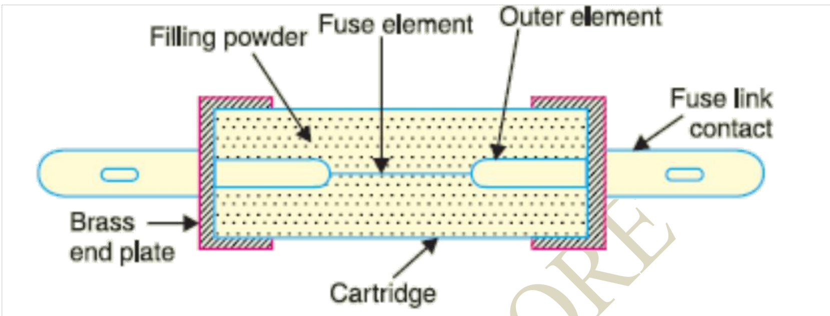
Disadvantages

(*i*) There is a possibility of renewal by the fuse wire of wrong size or by improper material.
(*ii*) This type of fuse has a low-breaking capacity and hence cannot be used in circuits of high fault level.
(*iii*) The fuse element is subjected to deterioration due to oxidation through the continuous heating up of the element. Therefore, after some time, the current rating of the fuse is decreased *i.e*., the fuse operates at a lower current than originally rated.
(*iv*) The protective capacity of such a fuse is uncertain as it is affected by the ambient conditions.
(*v*) Accurate calibration of the fuse wire is not possible because fusing current very much depends upon the length of the fuse element.

Semi-enclosed rewireable fuses are made upto 500 A rated current, but their breaking capacity is low *e.g*., on 400 V service, the breaking capacity is about 4000 A. Therefore, the use of this type of fuses is limited to domestic and lighting loads.

High-Rupturing capacity (H.R.C.) cartridge fuse. The primary objection of low and uncertain breaking capacity of semi-enclosed rewireable fuses is overcome in H.R.C. cartridge fuse. Fig. shows the essential parts of a typical H.R.C. cartridge fuse. It consists of a heat resisting ceramic body having metal end-caps to which is welded silver current-carrying element. The space within the body surrounding the element is completely packed with a filling powder. The filling material may be chalk, plaster of paris, quartz or marble dust and acts as an arc quenching and cooling medium.

Under normal load conditions, the fuse element is at a temperature below its melting point. Therefore, it carries the normal current without overheating. When a fault occurs, the current increases and the fuse element melts before the fault current reaches its first peak. The heat produced in the process vapourises the melted silver element. The chemical reaction between the silver vapour and the filling powder results in the formation of a high resistance substance which helps in quenching the arc.



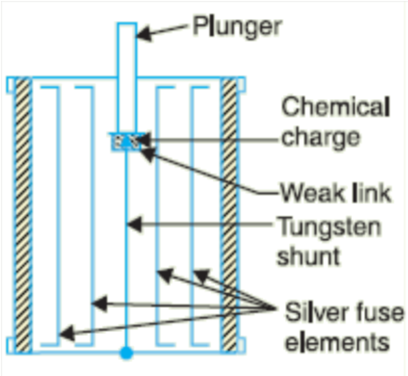
Advantages

(*i*) They are capable of clearing high as well as low fault currents.
(*ii*) They do not deteriorate with age.
(*iii*) They have high speed of operation.
(*iv*) They provide reliable discrimination.
(*v*) They require no maintenance.
(*vi*) They are cheaper than other circuit interrupting devices of equal breaking capacity.
(*vii*) They permit consistent performance.

Disadvantages

(*i*) They have to be replaced after each operation.
(*ii*) Heat produced by the arc may affect the associated switches.

H.R.C. fuse with tripping device. Sometime, H.R.C. cartridge fuse is provided with a tripping device. When the fuse blows out under fault conditions, the tripping device causes the circuit breaker to operate. Fig. shows the essential parts of a H.R.C. fuse with a tripping device. The body of the fuse is of ceramic material with a metallic cap rigidly fixed at each end. These are connected by a number of silver fuse elements. At one end is a plunger which under fault conditions hits the tripping mechanism of the circuit breaker and causes it to operate. The plunger is electrically connected through a fusible link, chemical charge and a tungsten wire to the other end of the cap as shown. When a fault occurs, the silver fuse elements are the first to be blown out and then current is transferred to the tungsten wire. The weak link in series with the tungsten wire gets fused and causes the chemical charge to be detonated. This forces the plunger outward to operate the circuit breaker. The travel of the plunger is so set that it is not ejected from the fuse body under fault conditions.



Advantages. H.R.C. fuse with a tripping device has the following advantages over a H.R.C. fuse without tripping device :

(*i*) In case of a single phase fault on a three-phase system, the plunger operates the tripping mechanism of circuit breaker to open all the three phases and thus prevents "single phasing".

(*ii*) The effects of full short circuit current need not be considered in the choice of circuit breaker. This permits the use of a relatively inexpensive circuit breaker.

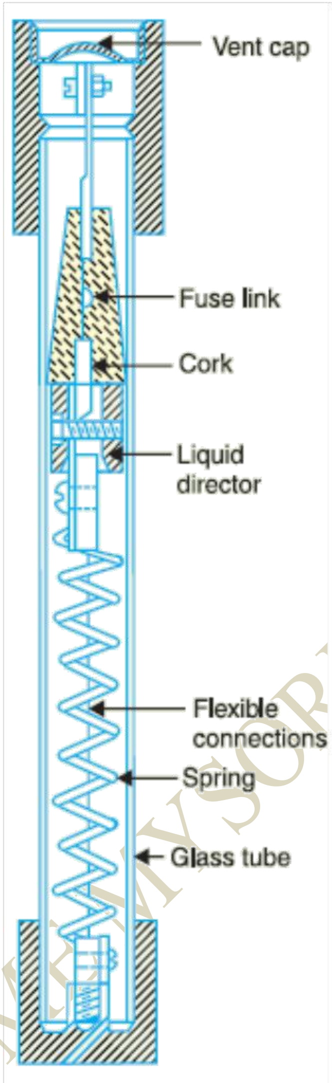
(*iii*) The fuse-tripped circuit breaker is generally capable of dealing with fairly small fault currents itself. This avoids the necessity for replacing the fuse except after highest currents for which it is intended. Low voltage H.R.C. fuses may be built with a breaking capacity of 16,000 A to 30,000 A at 440V. They are extensively used on low-voltage distribution system against over-load and shortcircuit conditions.

High Voltage Fuses

The low-voltage fuses discussed so far have low normal current rating and breaking capacity. Therefore, they cannot be successfully used on modern high voltage circuits. Intensive research by the manufacturers and supply engineers has led to the development of high voltage fuses. Some of the high voltage fuses are :

(i) Cartridge type. This is similar in general construction to the low voltage cartridge type except that special design features are incorporated. Some designs employ fuse elements wound in the form of a helix so as to avoid corona effects at higher voltages. On some designs, there are two fuse elements in parallel ; one of low resistance (silver wire) and the other of high resistance (tungsten wire). Under normal load conditions, the low resistance element carries the normal current. When a fault occurs, the low-resistance element is blown out and the high resistance element reduces the short-circuit current and finally breaks the circuit. High voltage cartridge fuses are used upto 33 kV with breaking capacity of about 8700 A at that voltage. Rating of the order of 200 A at 6·6 kV and 11 kV and 50 A at 33 kV are also available.

(ii) Liquid type. These fuses are filled with carbon tetrachloride and have the widest range of application to h.v. systems. They may be used for circuits upto about 100 A rated current on systems upto 132 kV and may have breaking capacities of the order of 6100 A. Fig. 20.5 shows the essential parts of the liquid fuse. It consists of a glass tube filled with carbon tetrachloride solution and sealed at both ends with brass caps. The fuse wire is sealed at one end of the tube and the other end of the wire is held by a strong phosphor bronze spiral spring fixed at the other end of the glass tube. When the current exceeds the prescribed limit, the fuse wire is blown out. As the fuse melts, the spring retracts part of it through a baffle (or liquid director) and draws it well into the liquid. The small quantity of gas generated at the point of fusion forces some part of liquid into the passage through baffle and there it effectively extinguishes the arc.



Difference Between a Fuse and Circuit Breaker

It is worthwhile to indicate the salient differences between a fuse and a circuit breaker in the tabular form.

S. No.	Particular	Fuse	Circuit breaker
1.	*Function*	It performs both detection and interruption functions.	It performs interruption function only. The detection of fault is made by relay system.
2.	*Operation*	Inherently completely automatic.	Requires elaborate equipment (*i.e.* relays) for automatic action.
3.	*Breaking capacity*	Small	Very large
4.	*Operating time*	Very small (0·002 sec or so)	Comparatively large (0·1 to 0·2 sec)
5.	*Replacement*	Requires replacement after every operation.	No replacement after operation.

5.4 Applications of HRC Fuse

Applications of High-voltage high rupturing capacity fuses are used for short circuit protection in high-voltage switchgear for the 50 to 60 Hz frequency range Distribution transformers up to 2000 kVA High-voltage motors up to 3 MW Capacitors up to1200 kvar MV voltage transformers Cable feeders

5.5 Discrimination: - Discrimination between two fuses is said to occur if on the occurrence of a short-circuit or overcurrent fault, only the desired fuse operates

Figure 15.34 shows a single –line diagram of a distribution network. It is very clear from the figure that a 60A fuse must operate for the fault at F. A 200A fuse should act as a back-up in case of failure of a 60Afuse. The characteristics of two fuses have to be coordinated as shown in fig 15.35

Discrimination between Two Fuses

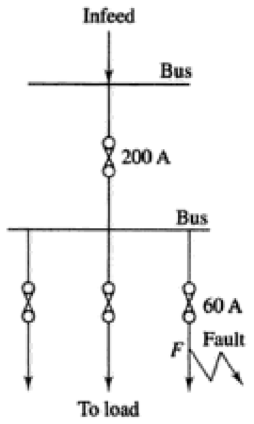


Fig. 15.34

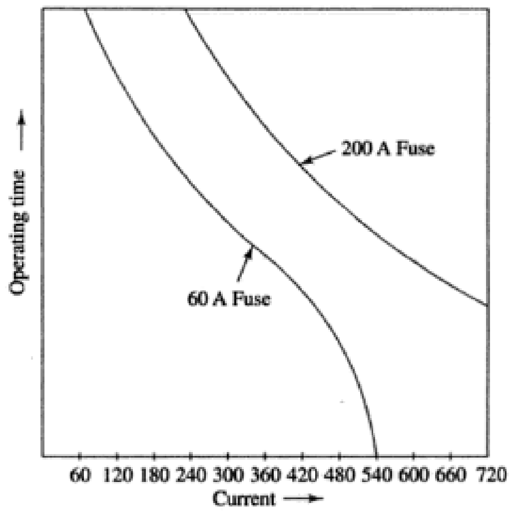


Fig. 15.35

Discrimination between a fuse and over current relay

Fig 15.36 shows a single line diagram of an 11kV feeder supplying a pole-mounted transformer. The drop-out fuse is for the protection of transformer only. Hence, the overcurrent relay has to be coordinated with kit-kat fuse. The characteristic of both the relay and fuse are plotted in fig 15.37 considering the transformer ratio.

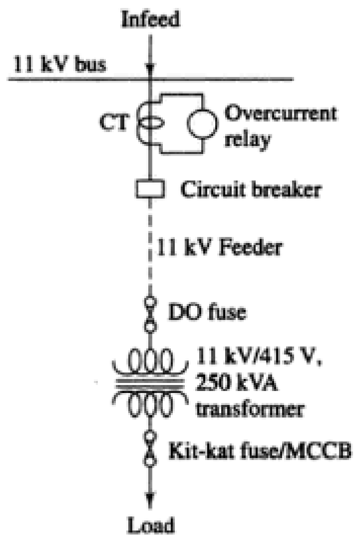


Fig. 15.36

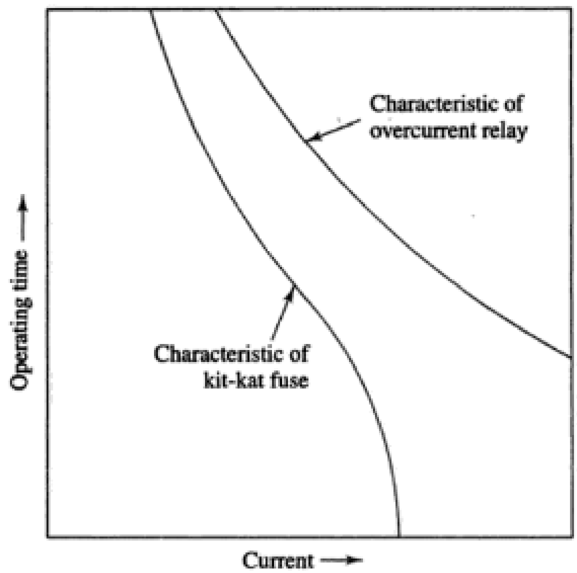


Fig. 15.37

5.6 Causes of Overvoltages

The Overvoltages on a power system may be broadly divided into two main categories *viz*.

1. Internal causes

(*i*) Switching surges **(*ii*)** Insulation failure **(*iii*)** Arcing ground **(*iv*)** Resonance

2. External causes *i.e*. lightning

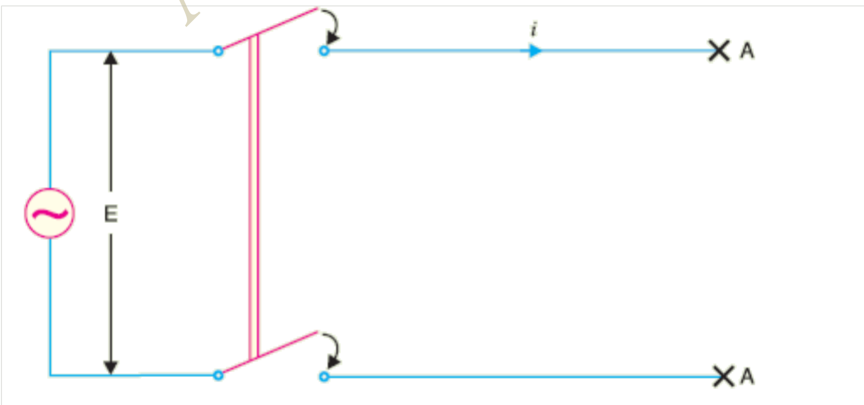
Internal causes do not produce surges of large magnitude. Experience shows that surges due to internal causes hardly increase the system voltage to twice the normal value. Generally, surges due to internal causes are taken care of by providing proper insulation to the equipment in the power system. However, surges due to lightning are very severe and may increase the system voltage to several times the normal value. If the equipment in the power system is not protected against lightning surges, these surges may cause considerable damage. In fact, in a power system, the protective devices provided against overvoltages mainly take care of lightning surges

Internal Causes of Overvoltages

Internal causes of overvoltages on the power system are primarily due to oscillations set up by the sudden changes in the circuit conditions. This circuit change may be a normal switching operation such as opening of a circuit breaker, or it may be the fault condition such as grounding of a line conductor. In practice, the normal system insulation is suitably designed to withstand such surges. We shall briefly discuss the internal causes of overvoltages.

1. Switching Surges. The overvoltages produced on the power system due to switching operations are known as switching surges. A few cases will be discussed by way of illustration:

(*i*) Case of an open line. During switching operations of an unloaded line, travelling waves are set up which produce overvoltages on the line. As an illustration, consider an unloaded line being connected to a voltage source as shown in Fig.

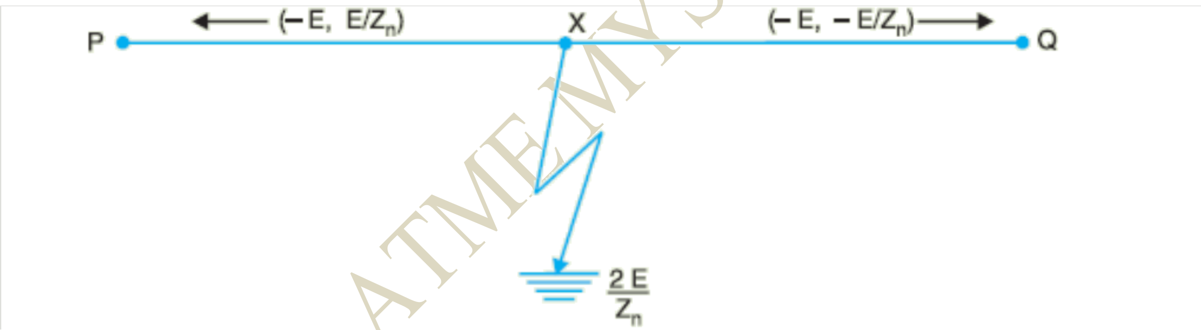


When the unloaded line is connected to the voltage source, a voltage wave is set up which travels along the line. On reaching the terminal point *A*, it is reflected back to the supply end without change of sign. This causes voltage doubling *i.e*. voltage on the line becomes twice the normal value. If $E_{r.m.s.}$ is the supply voltage, then instantaneous voltage which the line will have to withstand will be $2\sqrt{2}\,E$. This overvoltage is of temporary nature. It is because the line losses attenuate the wave and in a very short time, the line settles down to its normal supply voltage *E*. Similarly, if an unloaded line is switched off, the line will attain a voltage of 2√2 E for a moment before settling down to the normal value.

(ii) Case of a loaded line. Overvoltages will also be produced during the switching operations of a loaded line. Suppose a loaded line is suddenly interrupted. This will set up a voltage of 2 Zn i across the break (i.e. switch) where i is the instantaneous value of current at the time of opening of line and *Zn is the natural impedance of the line. For example, suppose the line having Zn = 1000ohm carries a current of 100 A (r.m.s.) and the break occurs at the moment when current is maximum. The voltage across the breaker (i.e. switch) = 2 √2 × 100*1000/1000 = 282·8 kV. If Vm is the peak value of voltage in kV, the maximum voltage to which the line may be subjected is = (Vm + 282·8) kV

(iii) Current chopping. Current chopping results in the production of high voltage transients across the contacts of the air blast circuit breaker as detailed in chapter 19. It is briefly discussed here. Unlike oil circuit breakers, which are independent for the effectiveness on the magnitude of the current being interrupted, air-blast circuit breakers retain the same extinguishing power irrespective of the magnitude of this current. When breaking low currents (e.g. transformer magnetising current) with air-blast breaker, the powerful de-ionising effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is called current chopping and produces high transient voltage across the breaker contacts. Overvoltages due to current chopping are prevented by resistance switching

Insulation failure. The most common case of insulation failure in a power system is the grounding of conductor (*i.e.* insulation failure between line and earth) which may cause overvoltages in the system. This is illustrated in Fig.



Suppose a line at potential *E* is earthed at point *X*. The earthing of the line causes two equal voltages of −*E* to travel along *XQ* and *XP* containing currents −*E*/*Zn* and +*E*/*Zn* respectively. Both these currents pass through *X* to earth so that current to earth is 2 *E*/*Zn*.

3. Arcing ground. In the early days of transmission, the neutral of three phase lines was not earthed to gain two advantages. Firstly, in case of line-to-ground fault, the line is not put out of action. Secondly, the zero sequence currents are eliminated, resulting in the decrease of interference with communication lines. Insulated neutrals give no problem with short lines and comparatively low voltages. However, when the lines are long and operate at high voltages, serious problem called arcing ground is often witnessed. The arcing ground produces severe oscillations of three to four times the normal voltage. The phenomenon of intermittent arc taking place in line-to-ground fault of a 3 phase system with consequent production of transients is known as **arcing ground.**
The transients produced due to arcing ground are cumulative and may cause serious damage to the equipment in the power system by causing breakdown of insulation. Arcing ground can be prevented by earthing the neutral

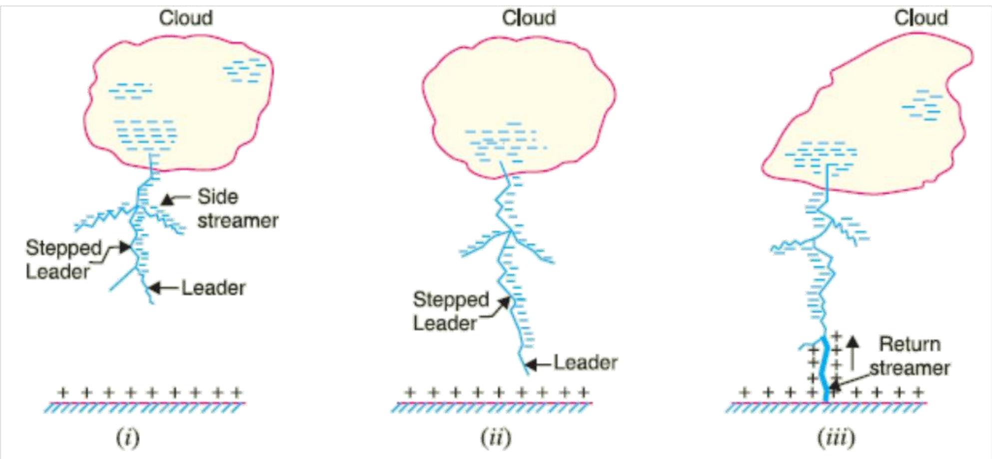
4. Resonance. Resonance in an electrical system occurs when inductive reactance of the circuit becomes equal to capacitive reactance. Under resonance, the impedance of the circuit is equal to resistance of the circuit and the p.f. is unity. Resonance causes high voltages in the electrical system. In the usual transmission lines, the capacitance is very small so that resonance rarely occurs at the fundamental supply frequency. However, if generator e.m.f. wave is distorted, the trouble of resonance may occur due to 5th or higher harmonics and in case of underground cables too

5.7 Lightning phenomena

An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as **lightning.** Lightning is a huge spark and takes place when clouds are charged to such a high potential (+ve or −ve) with respect to earth or a neighbouring cloud that the dielectric strength of neighbouring medium (air) is destroyed. There are several theories which exist to explain how the clouds acquire charge. The most accepted one is that during the uprush of warm moist air from earth, the friction between the air and the tiny particles of water causes the building up of charges. When drops of water are formed, the larger drops become positively charged and the smaller drops become negatively charged. When the drops of water accumulate, they form clouds, and hence cloud may possess either a positive or a negative charge, depending upon the charge of drops of water they contain. The charge on a cloud may become so great that it may discharge to another cloud or to earth and we call this discharge as lightning. The thunder which accompanies lightning is due to the fact that lightning suddenly heats up the air, thereby causing it to expand. The surrounding air pushes the expanded air back and forth causing the wave motion of air which we recognise as thunder.

Mechanism of Lightning Discharge

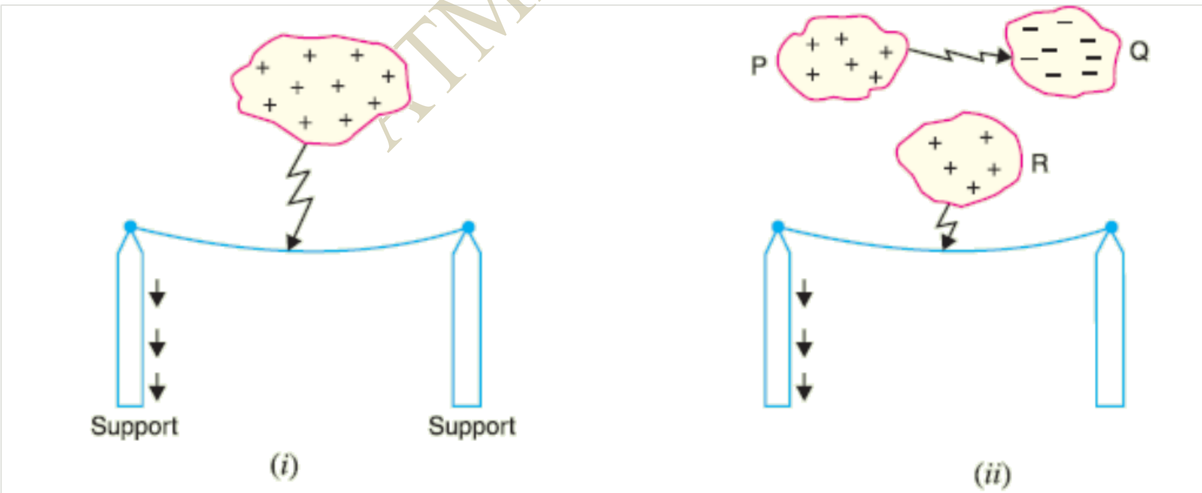
Let us now discuss the manner in which a lightning discharge occurs. When a charged cloud passes over the earth, it induces equal and opposite charge on the earth below. Fig. 24.4 shows a negatively charged cloud inducing a positive charge on the earth below it. As the charge acquired by the cloud increases, the potential between cloud and earth increases and, therefore, gradient in the air increases. When the potential gradient is sufficient (5 kV*/cm to 10 kV/cm) to break down the surrounding air, the lightning stroke starts. The stroke mechanism is as under: (i) As soon as the air near the cloud breaks down, a streamer called leader streamer or pilot streamer starts from the cloud towards the earth and carries charge with it as shown in Fig. (i). The leader streamer will continue its journey towards earth as long as the cloud, from which it originates feeds enough charge to it to maintain gradient at the tip of leader streamer above the strength of air. If this gradient is not maintained, the leader streamer stops and the charge is dissipated without the formation of a complete stroke. In other words, the leader streamer will not reach the earth. Fig.(i) shows the leader streamer being unable to reach the earth as gradient at its end cloud not be maintained above the strength of air. It may be noted that current in the leader streamer is low (<100 A) and its velocity of propagation is about 0·05% that of Velocity of light. Moreover, the luminosity of leader is also very low.



(ii) In many cases, the leader streamer continues its journey towards earth [(ii)] until it makes contact with earth or some object on the earth. As the leader streamer moves towards earth, it is accompanied by points of luminescence which travel in jumps giving rise to stepped leaders. The velocity of stepped leader exceeds one-sixth of that of light and distance travelled in one step is about 50 m. It may be noted that stepped leaders have sufficient luminosity and give rise to first visual phenomenon of discharge.
(iii) The path of leader streamer is a path of ionisation and, therefore, of complete breakdown of insulation. As the leader streamer reaches near the earth, a return streamer shoots up from the earth [(iii)] to the cloud, following the same path as the main channel of the downward leader. The action can be compared with the closing of a switch between the positive and negative terminals; the downward leader having negative charge and return streamer the positive charge. This phenomenon causes a sudden spark which we call lightning. With the resulting neutralisation of much of the negative charge on the cloud, any further discharge from the cloud may have to originate from some other portion of it. The following points may be noted about lightning ischarge :
(a) A lightning discharge which usually appears to the eye as a single flash is in reality made up of a number of separate strokes that travel down the same path. The interval between them varies from 0·0005 to 0·5 second. Each separate stroke starts as a downward leader from the cloud.
(b) It has been found that 87% of all lightning strokes result from negatively charged clouds and only 13% originate from positively charged clouds.
(c) It has been estimated that throughout the world, there occur about 100 lightning strokes per second.
(d) Lightning discharge may have currents in the range of 10 kA to 90 kA.

Types of Lightning Strokes

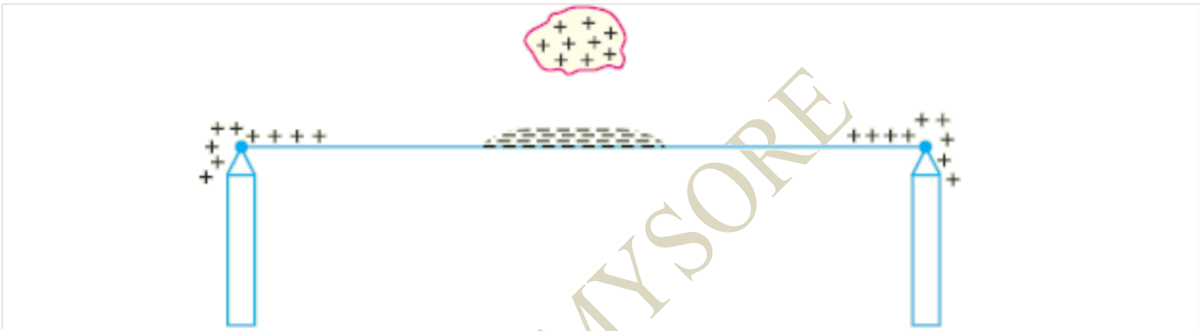
There are two main ways in which a lightning may strike the power system (e.g. overhead lines, towers, sub-stations etc.), namely; **1.** Direct stroke **2.** Indirect stroke
1. Direct stroke. In the direct stroke, the lightning discharge (i.e. current path) is directly from the cloud to the subject equipment e.g. an overhead line. From the line, the current path may be over the insulators down the pole to the ground. The overvoltages set up due to the stroke may be large enough to flashover this path directly to the ground. The direct strokes can be of two types viz. (i) Stroke A and (ii) stroke B



(i) In stroke *A*, the lightning discharge is from the cloud to the subject equipment *i.e.* an overhead line in this case as shown in Fig. (*i*). The cloud will induce a charge of opposite sign on the tall object (*e.g.* an overhead line in this case). When the potential between the cloud and line exceeds the breakdown value of air, the lightning discharge occurs between the cloud and the line.
(ii) In stroke *B*, the lightning discharge occurs on the overhead line as a result of stroke *A* between the clouds as shown in Fig. (*ii*). There are three clouds *P*, *Q* and *R* having positive, negative and positive charges respectively. The charge on the cloud *Q* is bound by the cloud *R*. If the cloud *P* shifts too near the cloud *Q*, then lightning

discharge will occur between them and charges on both these clouds disappear quickly. The result is that charge on cloud *R* suddenly becomes free and it then discharges rapidly to earth, ignoring tall objects.
Two points are worth noting about direct strokes. Firstly, direct strokes on the power system are very rare. Secondly, stroke *A* will always occur on tall objects and hence protection can be provided against it. However, stroke *B* completely ignores the height of the object and can even strike the ground. Therefore, it is not possible to provide protection against stroke *B*.

2. Indirect stroke. Indirect strokes result from the electrostatically induced charges on the conductors due to the presence of charged clouds. This is illustrated in Fig. A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. This negative charge, however, will be only on that portion of the line right under the cloud and the portions of the line away from it will be positively charged as shown in Fig. The induced positive charge leaks slowly to earth *via* the insulators. When the cloud discharges to earth or to another cloud, the negative charge on the wire is isolated as it cannot flow quickly to earth over the insulators. The result is that negative charge rushes along the line is both directions in the form of travelling waves. It may be worthwhile to mention here that majority of the surges in a transmission line are caused by indirect lightning strokes



Harmful Effects of Lightning
A direct or indirect lightning stroke on a transmission line produces a steep-fronted voltage wave on the line. The voltage of this wave may rise from zero to peak value (perhaps 2000 kV) in about 1 μs and decay to half the peak value in about 5μs. Such a steep-fronted voltage wave will initiate travelling waves along the line in both directions with the velocity dependent upon the *L* and *C* parameters of the line.
(*i*) The travelling waves produced due to lightning surges will shatter the insulators and mayeven wreck poles.
(*ii*) If the travelling waves produced due to lightning hit the windings of a transformer or generator, it may cause considerable damage. The inductance of the windings opposes any sudden passage of electric charge through it. Therefore, the electric charges "piles up" against the transformer (or generator). This induces such an excessive pressure between the windings that insulation may breakdown, resulting in the production of arc. While the normal voltage between the turns is never enough to *start* an arc, once the insulation has broken down and an arc has been started by a momentary overvoltage, the line voltage is usually sufficient to *maintain* the arc long enough to severely damage the machine.
(*iii*) If the arc is initiated in any part of the power system by the lightning stroke, this arc will set up very disturbing oscillations in the line. This may damage other equipment connected to the line.

5.8 Protection against Lightning

Transients or surges on the power system may originate from switching and from other causes but the most important and dangerous surges are those caused by lightning. The lightning surges may cause serious damage to the expensive equipment in the power system (*e.g*. generators, transformers etc.) either by direct strokes on the equipment or by strokes on the transmission lines that reach the equipment as travelling waves. It is necessary to provide protection against both kinds of surges. The most commonly used devices for protection against lightning surges are :

(*i*) Earthing screen
(*ii*) Overhead ground wires
(*iii*) Lightning arresters or surge diverters

Earthing screen provides protection to power stations and sub-stations against direct strokes whereas overhead ground wires protect the transmission lines against direct lightning strokes. However, lightning arresters or surge diverters protect the station apparatus against both direct strokes and the strokes that come into the apparatus as travelling waves. We shall briefly discuss these methods of protection.

Protection of Stations and Sub – Stations from Direct Strokes

The power stations and sub-stations generally house expensive equipment. These stations can be protected against direct lightning strokes by providing earthing screen. It consists of a network of copper conductors (generally called shield or screen) mounted all over the electrical equipment in the sub-station or power station. The shield is properly connected to earth on atleast two points through a low impedance. On the occurrence of direct stroke on the station, screen provides a low resistance path by which lightning surges are conducted to ground. In this way, station equipment is protected against damage. The limitation of this method is that it does not provide protection against the travelling waves which may reach the equipment in the station

Power stations are usually indoor while substations may be indoor or outdoor. For protection of a structure from direct strokes there are three requirements which are to be fulfilled. These requirements are interception, conduction and dissipation.

These requirements involve:

(i) An object in good electrical connection with the earth so that the leader stroke may get attracted,
(ii) A low impedance path joining this object to earth so that the discharge follows it in preference to any other path,
(iii) A low resistance connection with the earth body.

For 1, the upper portion of a metal structure may be employed. Alternatively a separate metallic system, often called the shield, either mounted on the structure or near to and above it may be provided. A particular shield configuration in the form of masts or overhead ground wires is considered to provide good shielding.

For 2, the requirements are:

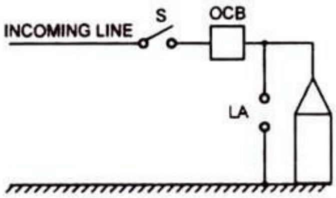
(i) Low resistance (i.e., adequate conductivity and cross- section, properly bounded joints, free from possible corrosion),
(ii) Low reactance (i.e., absence of sharp bends, or loops and short conductors),
(iii) And sufficient clearance from any other conducting objects that might provide separate uncontrolled path to ground.

Outdoor substations have much of equipment carried on metal gantries and the interconnection of the upper portion of these will screen the apparatus. Usually, there is suitable grounding provided.

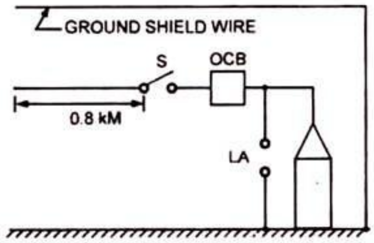
Shielding of the station and the incoming lines (about 0.8 km out from the station) to restrict the severity of the waves that can enter the station through the lines is a desirable supplement, particularly in the case of hv lines (66 kV and above) to the lightning arrester located in the station [below Fig. (b)].

Where overhead ground wires cannot be provided on the incoming lines due to existing structure/construction, additional protection of the station equipment against direct lightning strokes can be provided by equipping each line with protector tubes at the entrance to the structure of the station and at each tower for a distance of about 0.8 km out from the station, as illustrated in below Fig. c). However, shielding of the power station/substation is the only way of eliminating direct strokes to the station itself.

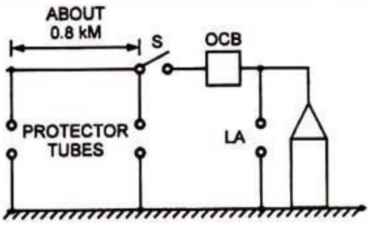
If sufficient supports are available for overhead groundwires, these may be run over the station in such a way that the station and all equipments will lie in the protected zone. Ground wire should be strong so that entire station is covered, including any apparatus outside the main structure as shown.



(a) Lightining Arrester at Station With No Direct Stroke Shielding



(b) Lightining Arrester At Station With Shielding Against Direct Lightning Strokes



(c) Lighning Arrester At Station With Protector Tube Extending Out 0.8 KM Station Protection Schemes

Protection of Overhead Transmission Lines from Direct Lightning Strokes by Ground Wires:

The two methods of protecting overhead transmission lines against lightning strokes are:
(i) Overhead ground wires and (ii) Expulsion protector tubes.

(i) Protection of Overhead Transmission Lines from Direct Lightning Strokes by Ground Wires:

A ground wire is a form of lightning protection employing a conductor or conductors, well-grounded at regular intervals, preferably at each support (pole or tower), and attached from support to support above the transmission line conductors.

No doubt the ground wire can be run below the line but running of ground wire above the line is considered better as it provides more effective shield. The ground wire shields the phase or line conductors by attracting itself the lightning strokes which, in the absence of ground wire, would strike the line conductors.

The elevation at which the ground wire is strong is likewise determined by calculation and selected so that the line conductors come within the zone of protection of the respective ground wire. For reliable protection the protective angle α is taken equal to 20-30 degrees. This is the angle between the vertical line through the ground wire axis and the line passing from the ground wire axis to the outermost line or phase conductor.

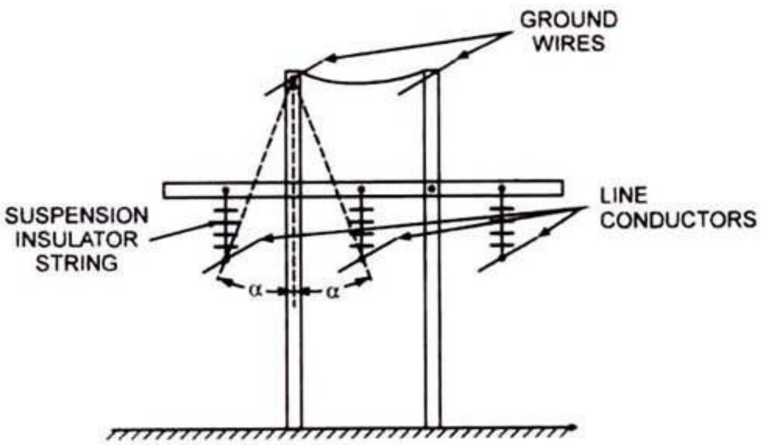


Fig. *Arrangement of Ground Wires on a Transmission Line For Direct Stroke Lightning Protection*

Coupling Factor:
The entire ground wire voltage does not show up across the line insulators as a voltage of the same polarity as the ground wire is also induced in the line conductors. The ratio of the induced voltage on the line to the potential of ground wire is called the coupling factor, i.e.,

$$\text{Coupling factor, } K = \frac{\text{Voltage induced in the line conductors}}{\text{Potential of ground wire}} = \frac{V_{Li}}{V_g}$$

The voltage across the line conductor and earth is the product of coupling factor and ground wire potential.
Consider an arrangement of line conductors and ground wire, as illustrated in Fig. When the ground wire is struck by a lightning stroke at point A, currents flow as indicated in the figure. Currents I_1 and I_2 flow in opposite directions from point A. Again at point B, the current subdivides and let I_4 flow, through earth connecting wire, to the ground.

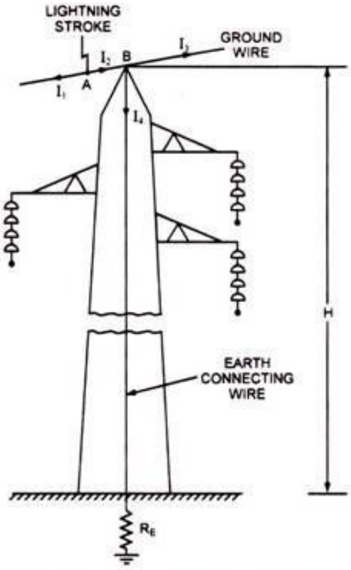


Fig. 9.12. ***Arrangement of Conductors and Earth Representing Lightning Current***

Suppose the ground resistance R_E is high. The currents in the down lead and into the earth (I_4) causes a voltage drop in the ground connection, thereby raising the potential of ground (or shield) wire above true earth potential. Let this be V_g –

$$\text{So } V_g = I_4 R_E$$

Potential between the line conductor and earth,

$$V_1 = K\ V_g$$

Where k is the coupling factor and is given as –

$$K = \frac{\log_e \dfrac{h}{h_1}}{\log_e \dfrac{2H}{r}}$$

where h is the distance from phase conductor to ground wire, h_1 is the distance between conductor image and ground, H is the height of ground wire above ground and r is the radius of ground wire.

In the absence of corona the electrostatic and electromagnetic coupling factors are equal.

In case of corona, electrostatic coupling increases while the electromagnetic coupling remains unaffected.

The electromagnetic coupling factor is determined as above using the actual diameter of the ground wire while the electrostatic coupling factor is determined by using the increased diameter of the ground wire due to corona as follows –

$$K_{fs} = \frac{\log_e \dfrac{h}{h_1}}{\log_e \dfrac{2H}{r_1}}$$

where r_1 is the increased radius of ground wire and K_{fs} is the electrostatic coupling factor,

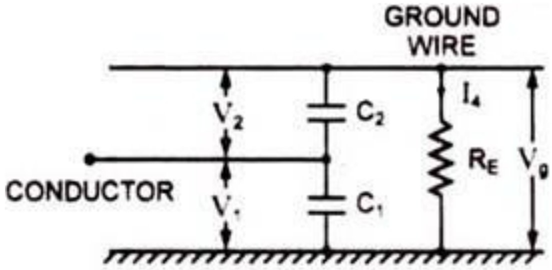


Fig. 9.13. *Equivalent Electrical Circuit*

The resultant coupling factor,

$$K_{fr} = \sqrt{K_{fs} \, K_{fm}}$$

where kf_m is the electromagnetic coupling factor.
Above Figure 9.13 represents the equivalent electrical circuit corresponding to arrangement shown in above Fig. 9.12. C_1 and C_2 are the capacitances between conductor and earth and between ground wire and conductor respectively. Let V_1 and V_2 be the potential drops across these capacitances. Also from the equivalent electrical circuit diagram shown in above Fig, we have –

$V_2 = V_g - V_1$

$V_2 = V_g - V_1 = V_g - K\,V_g = V_g\,(1 - K) = I_4\,R_E\,(1 - K)$

i.e., the potential difference between the ground wire and the line, V_2 may be high. If the clearance between the down lead and the line conductor is not sufficient or if the support is metallic and the insulator is small, a flashover will be caused from the ground wire to the line conductor.

This is just as bad as a direct hit on the line conductor with flashover from it to ground because either may cause a short circuit. Sometimes, special measures such as counterpoise rods (horizontal rods buried in ground) may be necessary to obtain reasonable ground resistance (about 5 – 10 Ω) and sometimes it may be necessary to offset the down leads so that adequate clearances are obtained.

Besides taking the brunt of a direct stroke, the ground wire reduces the voltage electrostatically or electromagnetically induced in the conductors by the discharge of a neighbouring cloud. For example, referring to below Fig. if C_1 is the capacitance of cloud to the line and C_2 the capacitance of the line to ground.

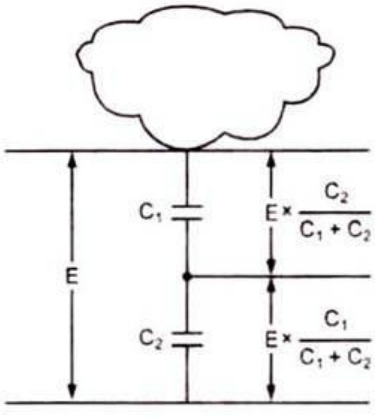


Fig. 9.14. *Reduction in Induced Voltage Due To Ground Wire*

The induced voltage on the line is $\frac{C_1}{C_1 + C_2}$ times the cloud voltage. The presence of the ground wire above the line causes a considerable increase in C_2 and therefore, a reduction of the induced voltage on the line.
The induced voltage could be very much reduced by an array of ground wires but this is too expensive to install in practice. Peak has made a laboratory study of the protective effect of ground wires and has found that a single ground wire reduces the induced lightning voltage to one-half of that without ground wire; for two ground wires the reduction is one-third, while for three ground wires it is to one- fourth. These results were obtained under the favourable conditions of good earths and low impedance for the earth connections.

The ground wire also affords an additional protective effect by causing an attenuation of any travelling waves that are set up in the lines by acting as a short-circuited secondary of the line conductors. For this reason its resistance should not be too large. Ground wire is usually made of steel, which has a high permeability and thus possesses a resistance which increases with frequency.

The objections to the ground wire are the additional cost, and the possibility of the wire breaking and falling across the line conductors, thus causing a direct short circuit. Failure due to the latter cause, however, is rare, as substantial galvanized stranded steel conductors are usually employed. Indeed, such a steel conductor joining the tops of the towers generally adds greatly to the mechanical strength and stability of the line, particularly if the line is of the flexible type.

Ground wires are extensively used for direct-stroke protection of transmission lines for voltages of 110 kV and upward (up to 500 kV). Ground wires are usually strung on all vital transmission lines and on all sections of transmission lines running through regions subject to frequent lightning storms.

The selection of size, number and arrangement of ground wires is of great importance in line design. The selection of size of ground wire is based on the consideration of mechanical strength rather than electrical considerations.

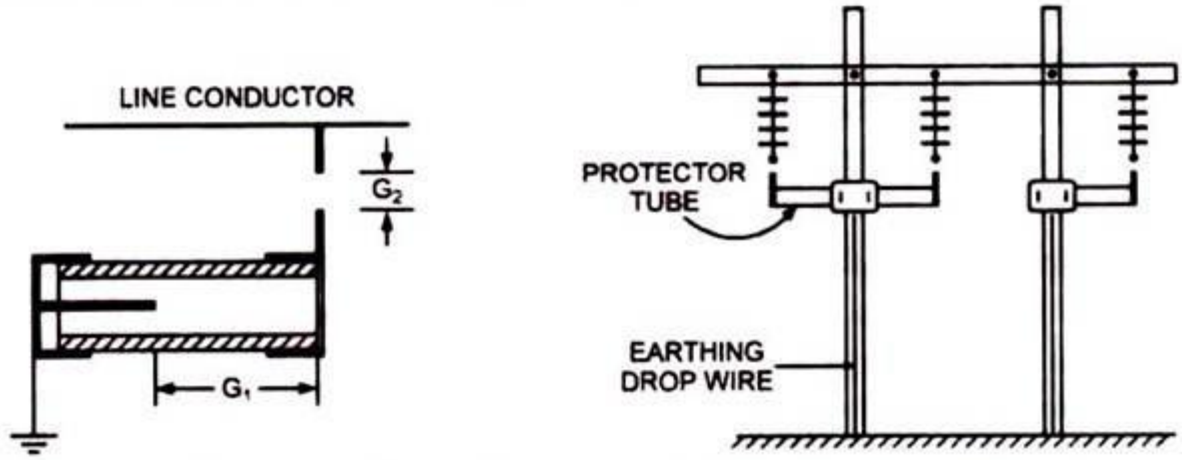
In practice, one ground wire is generally used, which allows the intensity of over-voltages to be considerably reduced, and lessens the work demanded from the lightning arresters connected to the system. In exposed situations, or lines subject to severe lightning disturbances, it would probably be good practice to install one or two additional wires. In case of horizontal spacing of conductors on the tower, two ground wires are run on the top portion of the tower.

On wood-pole transmission lines within the working voltage range of 33 to 110 kV, ground wires are provided only at the approaches to the power station and system substations. No special means of lightning protection is provided on the remaining sections of such lines as advantage can be taken of the insulation provided by the wood-pole supports. By installing the ground wires on the substation approaches of the lines the latter will be guarded against the possibility of lightning strokes close to the substations.

(ii) Protection of Overhead Transmission Lines from Direct Lightning Strokes by Protector Tube:
Even after reduction in the induced voltage by using a ground wire, there still exist over-voltages in the system which must be removed by using additional protective devices such as lightning arrester that bypasses the surges to the ground. Another device that is quite common in use is the protector tube.
Expulsion protector tube consists of a backlisted fibre tube containing two built-in electrodes between which an internal gap is provided. An outer electrode or arcing horn, made from steel wire 5 or 6 mm in dia is attached to the bolt at the upper end of the protector tube (below Fig 9.15) to provide an external spark gap between it and a line conductor.
The internal gap can be adjusted by turning the tube about the bolt which secures the tube to the bracket. The external gap is adjusted to templates made from wire 3 or 4 mm in diameter.

Fig. 9.15. ***Power Line Expulsion Protector Tube***

On a transmission tower one tube is often mounted below each line so that the upper electrode is connected to an arc-shaped horn located at the proper distance below the line, thus forming a series gap G_2 with it [below Fig. 9.16(a)], The lower electrode is solidly grounded.



(a) Schematic Diagram of Protector Tube Connections

(b) Protector Tube Mounted on 110 kV Wooden Pole

Fig. 9.16. ***Expulsion Protector Tube***

When a surge of sufficient voltage travels along the phase conductor and reaches the point where the expulsion tube is mounted, both of the series air gaps (internal air gap G_1 and external air gap G_2) breakdown and drain the surge current to ground through the tube and its earthing conductor; thereby reducing the crest value of surge voltage.

On breakdown of the tube gaps on two or three phases, or on one phase of solidly-grounded neutral circuits, the operating voltage simultaneously initiates a flow of short circuit or power current. This current must flow through the tubes and set up arcs between their spark gaps.

The high temperature of the arc across the gap in the tubes then produces a large amount of gases due to decomposition of some of the tube material. These gases flash out of the tube under pressures reaching from 100 to 500 atm and intensely deionize the arc. The latter is thus extinguished and the circuit insulation returned to its normal value with respect to earth.

Arc extinction duration will be only one or two half-periods. This interval is too short for the protective relays of the line to come into action, the circuit breaker remains closed and the line remains in operation. Immediately after the gases have been expelled and the arc suppressed, every tube is ready for a new operation.
The purpose of external air gap G_2 is to isolate the expulsion tube from the line conductor. Failure to provide the external gap would otherwise place the tube at the operating potential of the conductor and cause flow of

leakage currents over the tube surface and to eventual carbonizing of the tube material and final destruction of the tube.

3. Protection of Electrical Equipment from Travelling Waves:

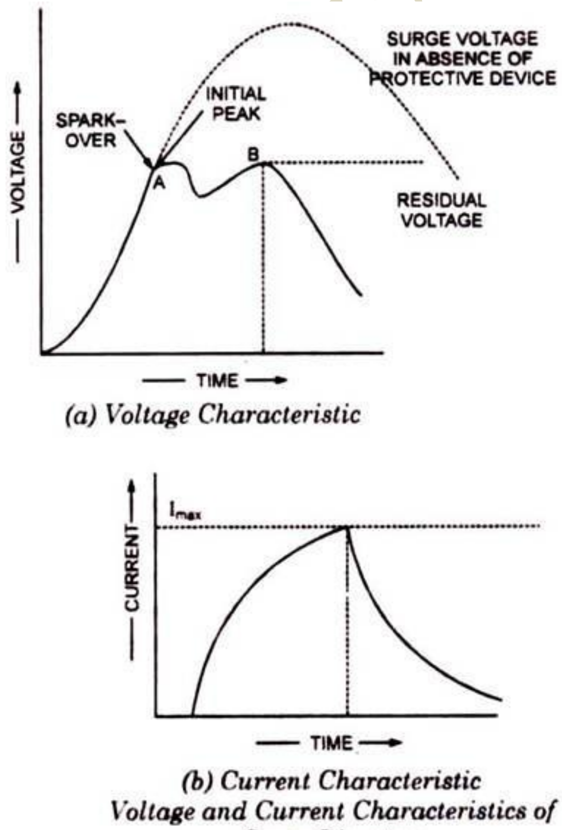
The ground wire or earthling screen used for the protection of overhead lines and power stations and substations not only provides an adequate protection against lightning but also reduces the over-voltages induced electrostatically or electromagnetically, but such shielding is inadequate in providing protection against travelling waves which may reach the terminal equipment and cause damage to it.

The damages that may be caused by travelling waves are:

i. The high peak or crest voltage of the surge may cause flashover in the internal winding thereby spoil the winding insulation.
ii. The steep wave front of the surge may cause internal flashover between inter-turns of the transformer.
iii. The high peak voltage of the surge may cause external flashover, between the terminals of the electrical equipment which may result in damage to insulators.
iv. The steep wave front resulting into resonance and high voltages may cause internal or external flashover of an un-predicable nature causing building up of the oscillation in the electrical apparatus.

Thus it is absolutely necessary to provide some protective device at the power stations or substations to prevent transformers and other equipment from being subjected to travelling surges reaching there. The most common devices used for protection of equipment at the substations against travelling waves are lightning arresters or surge diverters.

A surge diverter is a device that is connected between line and earth, i.e., in parallel with the equipment to be protected at the substation.



(a) Voltage Characteristic

(b) Current Characteristic
Voltage and Current Characteristics of Surge Diverters

Fig. 9.17

When a travelling wave reaches the diverter, it sparks-over at a certain prefixed voltage as illustrated by point A in the figure, and provides a conducting path of relatively low impedance between the line and ground.
The surge impedance of the line restricts the amplitude of current flowing to ground. This is necessary in order to protect the insulation of the equipment. Fig. 9.17 shows the shape of voltage and of current at the diverter terminals.
It should, however, be noted that the surge diverter should provide a path of low impedance only when the travelling surge reaches the surge diverter, neither before it nor after it.

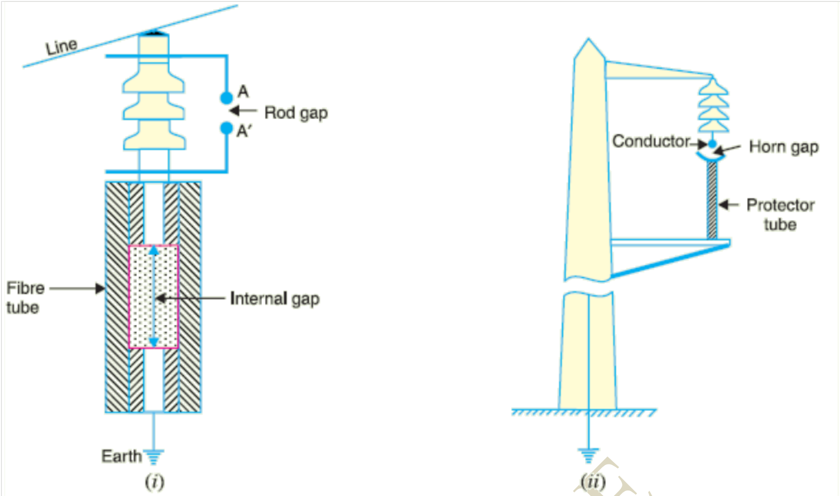
An ideal surge diverter should have the following characteristics:
i. It should not draw any current during normal operating conditions, i.e., its spark over voltage must be above the normal or abnormal power frequency that may occur in the system.
ii. Any abnormal transient voltage above the breakdown value must cause it to breakdown as quickly as possible so that it may provide a conducting path to ground.
iii. When the breakdown have taken place, it should be capable of carrying the resulting discharge current without getting damaged itself and without the voltage across it exceeding the breakdown value.
iv. The power frequency current following the breakdown must be interrupted as soon as the transient voltage has fallen below the breakdown value.
There are many types of surge diverters which are used to protect the power system.

The choice of lightning arrester depends upon the following factors:
(i) Voltage of the line.
(ii) Frequency of the lightning.
(iii) Cost.
(iv) Weather conditions.
(v) Reliability.

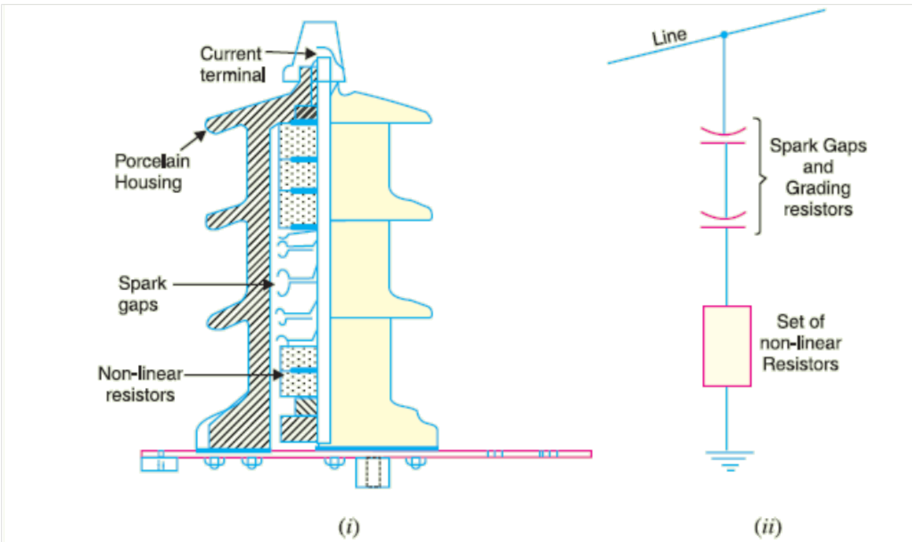
Types of Lightning Arresters
There are several types of lightning arresters in general use. They differ only in constructional details but operate on the same principle *viz*. providing low resistance path for the surges to the ground. We shall discuss the following types of lightning arresters :
1. Rod gap arrester **2.** Horn gap arrester **3.** Multigap arrester **4.** Expulsion type lightning arrester **5.** Valve type lightning arrester

Expulsion type arrester. This type of arrester is also called ‘protector tube’ and is commonly used on system operating at voltages upto 33 kV. Below Fig. (*i*) shows the essential parts of an expulsion type lightning arrester. It essentially consists of a rod gap *A A′* in series with a second gap enclosed within the fibre tube. The gap in the fibre tube is formed by two electrodes. The upper electrode is connected to rod gap and the lower electrode to the earth. One expulsion arrester is placed under each line conductor. Fig. (*ii*) shows the installation of expulsion arrester on an overhead line. On the occurrence of an overvoltage on the line, the series gap *A A′* is spanned and an arc is struck between the electrodes in the tube. The heat of the arc vaporises some of the fibre of tube walls, resulting in the production of a neutral gas*. In an extremely short time, the gas builds up high pressure and is expelled through the lower electrode which is hollow. As the gas leaves the tube violently, it carries away ionised air around the arc. This de-ionising effect is generally so strong that arc goes out at a current zero and will not be re-established.
Advantages
(*i*) They are not very expensive.
(*ii*) They are improved form of rod gap arresters as they block the flow of power frequency follow currents.
(*iii*) They can be easily installed.
Limitations
(*i*) An expulsion type arrester can perform only limited number of operations as during each operation some of the fibre material is used up.

(ii) This type of arrester cannot be mounted in an enclosed equipment due to the discharge of gases during operation.
(iii) Due to the poor volt/amp characteristic of the arrester, it is not suitable for the protection of expensive equipment



Valve type arrester. Valve type arresters incorporate non-linear resistors and are extensively used on systems operating at high voltages. Fig. 24.13 (*i*) shows the various parts of a valve type arrester. It consists of two assemblies (*i*) series spark gaps and (*ii*) non-linear resistor discs (made of material such as thyrite or metrosil) in series. The non-linear elements are connected in series with the spark gaps. Both the assemblies are accommodated in tight porcelain container. (*i*) The spark gap is a multiple assembly consisting of a number of identical spark gaps in series. Each gap consists of two electrodes with a fixed gap spacing. The voltage distribution across the gaps is linearised by means of additional resistance elements (called grading resistors) across the gaps. The spacing of the series gaps is such that it will withstand the normal circuit voltage. However, an overvoltage will cause the gap to breakdown, causing the surge current to ground via the non-linear resistors.
(*ii*) The non-linear resistor discs are made of an inorganic compound such as Thyrite or Metrosil. These discs are connected in series. The non-linear resistors have the property of offering a high resistance to current flow when normal system voltage is applied, but a low resistance to the flow of high-surge currents. In other words, the resistance of these non-linear elements decreases with the increase in current through them and *vice-versa*.



Working. Under normal conditions, the normal system voltage is insufficient to cause the breakdown of air gap assembly. On the occurrence of an overvoltage, the breakdown of the series spark gap takes place and the surge current is conducted to earth *via* the non-linear resistors. Since the magnitude of surge current is very large, the non-linear elements will offer a very low resistance to the passage of surge. The result is that the surge will rapidly go to earth instead of being sent back over the line. When the surge is over, the non-linear resistors assume high resistance to stop the flow of current.

Advantages

(*i*) They provide very effective protection (especially for transformers and cables) against surges.

(*ii*) They operate very rapidly taking less than a second.

(*iii*) The *impulse ratio is practically unity.

Limitations

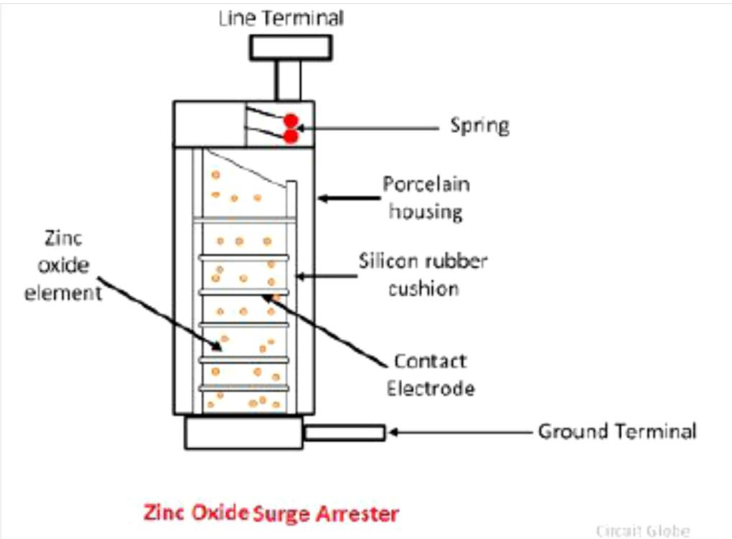
(*i*) They **may fail to check the surges of very steep wave front from reaching the terminal apparatus. This calls for additional steps to check steep-fronted waves.

(*ii*) Their performance is adversely affected by the entry of moisture into the enclosure. This necessitates effective sealing of the enclosure at all times.

Applications. According to their application, the valve type arresters are classified as (*i*) station type and (*ii*) line type. The station type arresters are generally used for the protection of important equipment in power stations operating on voltages upto 220 kV or higher. The line type arresters are also used for stations handling voltages upto 66 kV.

Metal Oxide Lightning Arrester

Such Types of diverter are also known as gapless surge diverters, or Zinc oxide diverter. The base material used for manufacturing metal oxide resistor is zinc oxide. It is a semiconducting N-type material. The material is doped by adding some fine power of insulating oxides. The powder is treated with some processes and then it is compressed into a disc-shaped. The disc is then enclosed in a porcelain housing filled with nitrogen gas or SF6. This arrester consists a potential barrier at the boundaries of each disc of ZNO. This potential barrier controls the flow of current. At normal operating condition, the potential barrier does not allow the current to flow. When an overvoltage occurs, the barrier collapse and sharp transition from insulating to conducting take place. The current start flowing and the surge is diverted to ground

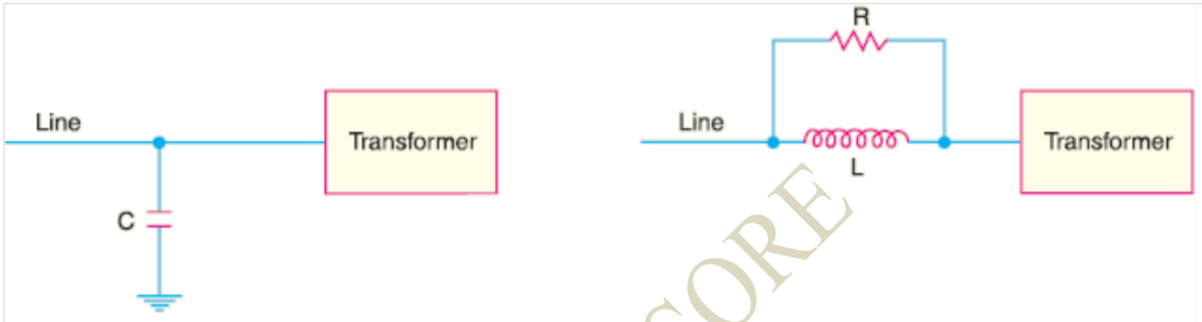


Zinc Oxide Surge Arrester

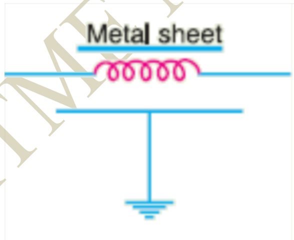
Surge Absorber

The travelling waves set up on the transmission lines by the surges may reach the terminals apparatus and cause damage to it. The amount of damage caused not only depends upon the amplitude of the surge but also upon the steepness of its wave front. The steeper the wave front of the surge, the more the damage caused to the equipment. In order to reduce the steepness of the wave front of a surge, we generally use surge absorber. A **surge absorber** is a protective device which reduces the steepness of wave front of a surge by absorbing surge energy. Although both surge diverter and surge absorber eliminate the surge, the manner in which it is done is different in the two devices. The surge diverter diverts the surge to earth but the surge absorber absorbs the surge energy. A few cases of surge absorption are discussed below :

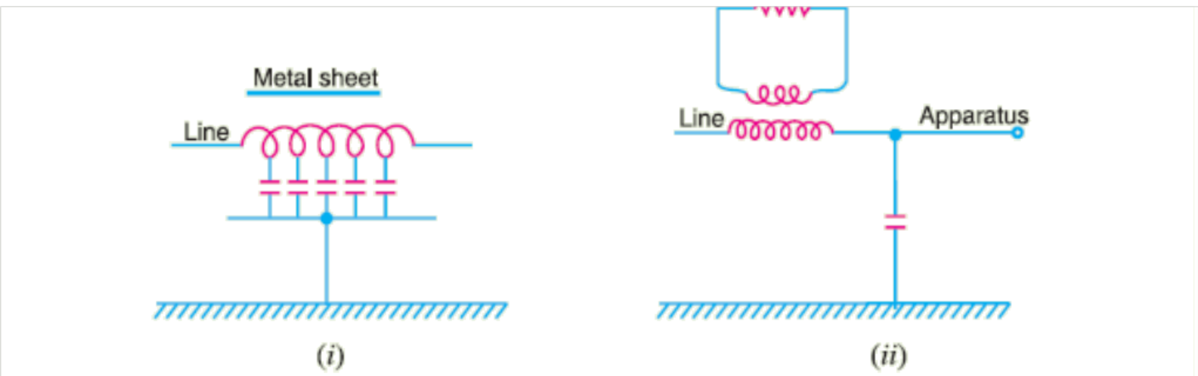
(i) A condenser connected between the line and earth can act as a surge absorber. Below Fig. shows how a capacitor acts as surge absorber to protect the transformer winding. Since the reactance of a condenser is inversely proportional to frequency, it will be low at high frequency and high at low frequency. Since the surges are of high frequency, the capacitor



(ii) Another type of surge absorber consists of a parallel combination of choke and resistance connected in series with the line as shown in below Fig.. The choke offers high reactance to surge frequencies (XL = 2 π f L). The surges are, therefore, forced to flow through the resistance R where they are dissipated.



(iii) Below Fig. shows the another type of surge absorber. It is called Ferranti surge absorber. It consists of an air cored inductor connected in series with the line. The inductor is surrounded by but insulated from an earthed metallic sheet called dissipator. This arrangement is equivalent to a transformer with short-circuited secondary. The inductor forms the primary whereas the dissipator forms the short-circuited secondary. The energy of the surge is used up in the form of heat generated in the dissipator due to transformer action. This type of surge absorber is mainly used, Fig. (*i*) shows the schematic diagram of 66 kV Ferranti surge absorber while Fig. (*ii*) shows its equivalent circuit



5.9 Insulation Coordination

Insulation Coordination is the process of determining the proper insulation levels of various components in a power system as well as their arrangements. It is the selection of an insulation structure that will withstand voltage stresses to which the system, or equipment will be subjected to, together with the proper surge arrester. The process is determined from the known characteristics of voltage surges and the characteristics of surge arresters.

Some common terms that must be known when performing an Insulation Coordination Study.

1. Basic Impulse Insulation Level (BIL)

This is the reference insulation level expressed as an impulse crest (or peak) voltage with a standard wave not longer than a **1.2 x 50 microsecond** wave.

A **1.2 x 50 microsecond** wave means that the impulse takes 1.2 microseconds to reach the peak and then decays to 50% of the peak in 50 microseconds.

2. Withstand Voltage

This is the BIL level that can repeatedly be applied to an equipment without flashover, disruptive charge or other electrical failure under test conditions.

3. Chopped Wave Insulation Level

This is determined by using impulse waves that are of the same shape as that of the BIL waveform, with the exception that the wave is chopped after 3 microseconds. Generally, it is assumed that the Chopped Wave Level is 1.15 times the BIL level for oil filled equipment such as transformers. However, for dry type equipment, it is assumed that the the Chopped Wave Level is equal to the BIL level.

4. Critical Flashover Voltage

This is the peak voltage for a 50% probability of flashover or disruptive charge.

5. Impulses Ratio

This is normally used for Flashover or puncture of insulation. It is the ratio of the impulse peak voltage to the value of the 60 Hz voltage that causes flashover or puncture. Or, it is the ratio of breakdown voltage at surge frequency to breakdown voltage at normal system frequency (60 Hz).

5.10 Basic Insulation Level Definition

When lightning impulse over voltage appears in the system, it is discharged through surge protecting devices before the equipments of the system gets damaged. Hence, the insulation of such equipment must be designed to withstand a certain minimum voltage before the lightning impulse over voltage gets discharged through surge protecting devices. Therefore, operating voltage level of surge protecting devices must be lower than the said minimum voltage withstanding level of the equipment. This minimum voltage rating is defined as BIL or basic insulation level of electrical equipment.

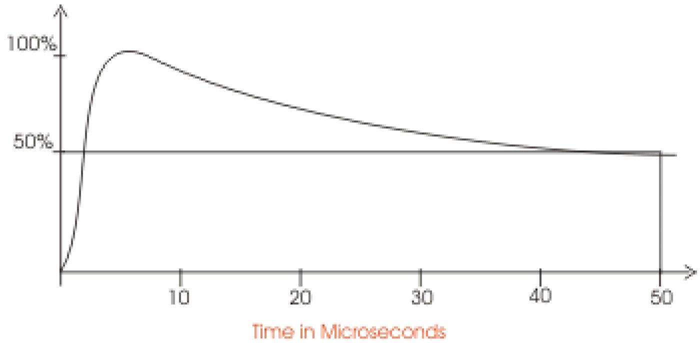
It is needless to say, that the voltage withstanding capacity of all equipments of an electrical substation or an electrical transmission system must be decided as per its operating system voltage. To ensure the stability of the system, during over voltage phenomenon, the breakdown or flash-over strength of all equipments connected to the system, should exceed a selected level. There may be different kind of over voltage tresses appeared on the system. These over voltages may differ in characteristics such as amplitude, duration, waveform and frequency etc. In the view of economy, an electrical power system must be designed for a basic insulation level or BIL depending upon the different characteristics of all possible over voltages appear on the system. Moreover there are different over voltage protecting devices installed in the system, which safely protect the system against different over voltage phenomenon. Due to these protecting devices the abnormal over voltages disappear from the system as fast as possible

Hence, this is unnecessary to design a system whose insulation can withstand all types of over voltages for all duration of time. For example, a lightning impulse voltage appears on the system for a period of microsecond rage and this is cleared from the system by lightning arrester as rapidly as possible. The insulation of an electrical equipment must be so designed that it should not be damaged before the lighting impulse voltage is cleared by lightning arrester. The basic insulation level or BIL of an electrical equipment determines the principle dielectric qualities of the apparatus and is expressed for impulse tested apparatus by peak value of the 1/50 microsecond full wave withstand voltage

The amount of insulation provided on any piece of apparatus and particularly the transformers constitutes quite an appreciable part of the cost. The standardizing bodies have had in mind to fix the basic insulation level or BIL as low as is commensurate with safety. The lightning impulse voltage is fully natural phenomena and hence it is highly uncertain in nature. So it is impossible to predict the shape and size of lightning surge. After studying and working lots on the nature of lightning surges, the standardizing bodies have decided and introduces a basic shape of impulse wave which is used for high voltage impulse testing purpose of electrical equipments. Although this created impulse voltage does not have any direct relation with natural lightning surges. Before going through details of basic insulation level of an electrical system, let's try to understand basic shape of standard impulse voltage

Impulse Voltage

As per American Standard the impulse wave shape is 1.5/40 microsecond. As per Indian Standard this is 1.2/50 microsecond. This representation of the wave has a special significance. Such as 1.2/50 microsecond impulse wave represents a unidirectional wave which rises to its peak value from zero in 1.2 microseconds and then falls to 50% of peak value in 50 microseconds. The represented wave shape is shown below,



The breakdown or flash-over voltage of the electrical equipment with this wave shape are required to be equal or higher than the basic insulation level fixed and the spark over voltage and discharge voltage of the protecting devices like lightning arresters, are definitely required to be lower than these values so that during lightning surges, the discharge occurs through the lightning arresters not through the equipment itself. There must be sufficient margin between the lightning arrestor and insulation level of the equipments.

Basic Insulation Level Table

Nominal System Voltage	Indian Standards BIL	British Standards BIL
11 KV	75 KV	-
33 KV	170 KV	200 KV
66 KV	325 KV	450 KV
132 KV	550/650 KV	650/750 KV
220 KV	900/1050 KV	900/1050 KV

Modern Trends in Power System Protection:

Gas insulated substations (GIS) have been used in power systems over the last three decades because of their high reliability, easy maintenance, small ground space requirement etc. In India also, a few GIS units are under various stages of installation**.** The basic insulation level (BIL) required for a gas insulated substation (GIS) is different from that of the conventional substation because of certain unique properties of the former. Gas insulated bus has a surge impedance (70Ω) more than that of the conventional oil filled cables, but much less than that of an over head line (300Ω - 400Ω). Further, the average bus run for a compact GIS is much less than that for the conventional station. In addition, the GIS is totally enclosed and therefore is free from any atmospheric contamination. Hence, in general the GIS permit lower BIL rating than the conventional one. However the life of GIS is affected by several factors such as: conductive particles, particle discharges and contamination (decomposition products, moisture, etc.). Conductive particles inside the enclosure are known to reduce the breakdown level of Gas insulated systems. Partial discharges can develop from conductive particles, contamination, and defects during the manufacturing process, etc.

The GIS require less number of lightning arresters than a conventional one. This is mainly because of its compactness. The basic consideration for insulation coordination is V-T characteristic. The V-T characteristic of SF6 is considerably flat compared to that of air. Air can withstand to very high voltages for very short time. However, as the duration of voltage increases, the withstand voltage falls off considerably. On the other hand, SF6 exhibits a flat characteristic, thus the ratio of basic lightning impulse level is close to unity for GIS, whereas for the conventional substations this ratio varies between 0.6 and 0.86. Although GIS has been in operation for several years, a lot of problems encountered in practice need further understanding. Some of the problems studied are:

a. Switching operations generate very fast transient overvoltages (VFTOS)

b. VFTOS may cause secondary breakdowns inside a GIS andTransient Enclosure Voltages (TEV) outside the GIS

c. Prolonged arcing may produce corrosive / toxic by productsd. Support spacers can be weak points when arc by products and metallic particles are present

e. From the reliability point of view, partial discharge detection is important. The methods of detection are of acoustic system and electric systems etc. These methods lack qualitycontrol.

5.10 GAS INSULATED SUBSTATIONS

SF6 gas insulated high voltage switchgear has been in commercial operation for more than 30 years. Continuous technological and design improvements of all the components during the course of the time are characterized by appreciable savings in area and volume occupied by the substation. Gas insulated substations are in service up to the highest voltage of 800 kV, meeting almost all the requirements in urban, industrial as well as rural areas. In the initial stages, the new SF6 gas insulated substations were almost exclusively used where space limitations, site restrictions or exponential ambient conditions made it difficult to use conventional air insulated substations. However, over the last 30 years, GIS at voltage up to 800 kV in various station configurations and with various performance requirements, have been installed in increasing numbers worldwide. The modular of design of GIS offers a high degree of flexibility to meet layout requirements of both substations, as well as power station switchgear, making efficient use of available space. GIS technology has reached a stage of application and a wide range of GIS equipment up to highest voltage of 800 kV is available with many unique features. They are:

1. Wide spread application of aluminum enclosure materials for standardized component models for all voltage ranges
2. The light weight enclosures have good conductivity, low eddy-current losses and a high resistance to corrosion
3. Easy handling, as well as reduced stresses on foundation and support structure are additional features
4. Standard arrangements can be easily modified and extended with good co-ordination between the manufacturer and the user.
5. A gas- tight barrier insulator in switchgear serve for the separation of gas compartments and prevents neighbouring switchgear parts from being affected during maintenance.

The Gas insulated substation comprises the following components:
1 Circuit breaker
2 Disconnector switch
3 Earthing switch
4 Current transformer
5 Voltage transformer
6 Bus bar & connectors
7 Power transformer
8 Surge arrester
9 Cable termination
10 SF6 / air or SF6 / oil bushing

Advantages of GIS over the conventional open air substation

The application of GIS during the last fifteen years has been very rapid. The rapid growth in GIS application is due to the following special advantages:

1. Area and volume saving in construction for over or underground applications. Therefore they offer saving in land area and construction costs.
2. Insensitivity to external influences because of grounded metal enclosures.
3. Greatly improved safety and reliability due to earthed metal housing of all high voltage parts and much higher intrinsic strength of SF6 gas as insulation.
4. Short on site erection times, based on large factory assembled and tested shipping units
5. Fulfillment of aesthetic requirements with indoor applications
6. High service reliability due to non-exposure of the use of high voltage parts to atmosphere influences
7. Reduction in radio interference with the use of earthed metal enclosures
8. Use as mobile substations for transportation to load centers on standard tracks. These substations can be located closer to load centers thereby reducing transmission losses and expenditure in the distribution network.
9. More optimal life cycle costs because of lesser maintenance, down time and repair costs.
10. It is not necessary that high voltage or extra high voltage switchgear has to be installed out doors

Disadvantages of GIS

Although GIS has been in operation for several years, a lot of problems encountered in practice need fuller understanding. Some of the problems being studied are:

1. Switching operation generate Very Fast Transients Over Voltages (VFTOS).
2. VFTOS may cause secondary breakdown inside a GIS and Transient Enclosure Voltages (TEV) outside the GIS.
3. Field non-uniformities reduce withstanding levels of a GIS.
4. Prolonged arcing may produce corrosive/toxic by-products.
5. Support spacers can be weak points when arc by-products and metallic particles are present

Course outcomes:

Interpret the construction and operating principle of different types of fuses and to give the definitions of different terminologies related to a fuse and Discuss protection against Overvoltages and Gas Insulated Substation