UNIT–V

Neutral Grounding and Protection Against Over Voltages

Ungrounded Neutral System:

In an ungrounded neutral system, the neutral is not connected to the ground i.e. the neutral is isolated from the ground. Therefore, this system is also called isolated neutral system or free neutral system. The line conductors have capacitances between one another and to ground.

Circuit behaviour under normal conditions:

Let us discuss the behaviour of ungrounded neutral system under normal conditions (i.e. under steady state and balanced conditions). The line is assumed to be perfectly transposed so that each conductor has the same capacitance to ground.

Therefore, $C_R=C_Y=C_B=C$ (say). Since the phase voltages V_{RN}, V_{YN} and V_{BN} have the same magnitude (of course, displaced 120° from one another), the capacitive currents I_R, I_Y and I_B will have the same value i.e.

$$I_R = I_Y = I_B = \frac{V_{ph}}{X_c}$$

where

V_{ph} = Phase voltage (i.e. line-to-neutral voltage)

X_C = Capacitive reactance of the line to ground.

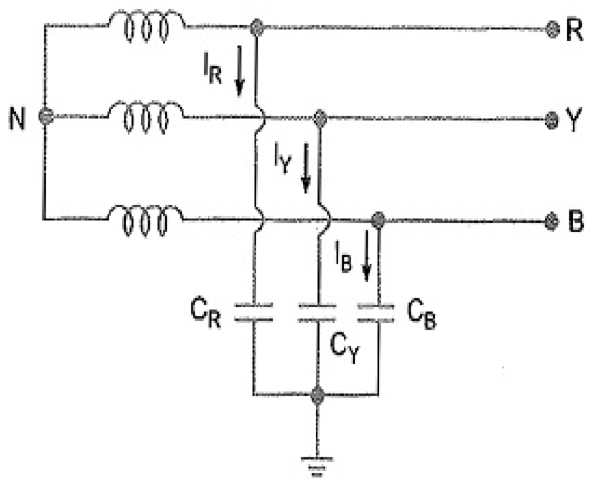


Figure (i) ungrounded neutral system

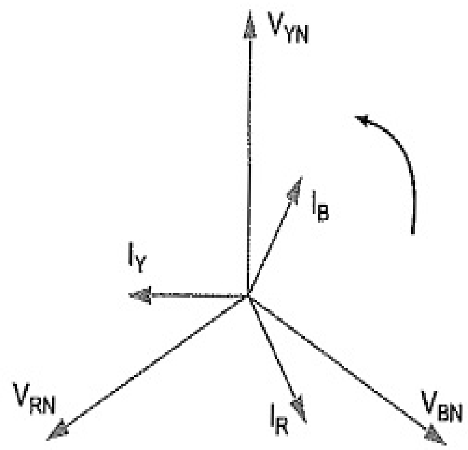


Figure (ii) Phasor diagram

The capacitive currents I_R, I_Y and I_B lead their respective phase voltages V_{RN},V_{YN} and V_{BN} by 90° as shown in the phasor diagram in Figure(ii). The three capacitive currents are equal in magnitude and are displaced 120° from each other. Therefore, their phasor sum is zero. As a result, no current flows to ground and the potential of neutral is the same as the ground potential. There-fore, ungrounded neutral system poses no problems under normal conditions. However, as we shall see, currents and voltages are greatly influenced during fault conditions.

Circuit behaviour under single line to ground-fault:

Let us discuss the behaviour of ungrounded neutral system when single line to ground fault occurs. Suppose line to ground fault occurs in line B at some point F. The circuit then becomes as shown in figure (i). The capacitive currents I_R and I_Y flow through the lines R and Y respectively. The voltages driving I_R and I_Y are V_{BR} and V_{BY} respectively. Note that V_{BR} and V_{BY} are the line voltages are shown in figure (ii). The paths of I_R and I_Y are essentially capacitive. Therefore, I_R leads V_{BR} by 90° and I_Y leads V_{BY} by 90° as shown in figure (ii). The capacitive fault current I_C in line B is the phasor sum of I_R and I_Y.

Fault current in line B:

$$I_C = I_R + I_Y$$

$$I_R = \frac{V_{BR}}{X_C} = \frac{\sqrt{3}V_{ph}}{X_C}$$

$$I_Y = \frac{V_{BY}}{X_C} = \frac{\sqrt{3}V_{ph}}{X_C}$$

$$I_R = I_Y = \frac{\sqrt{3}V_{ph}}{X_C}$$

$= \sqrt{3}$XPer phase capacitive current under normal conditions

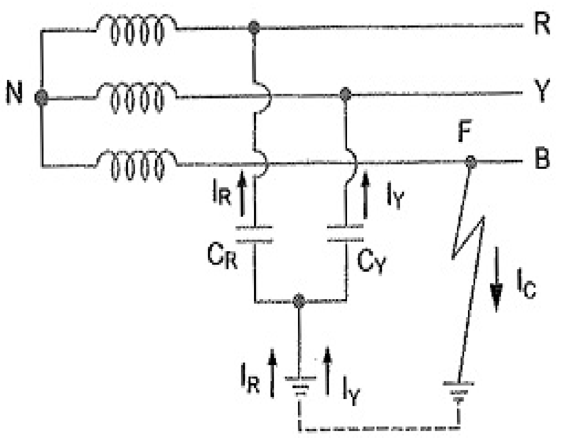


Figure (i) Line to ground fault occurs in line B

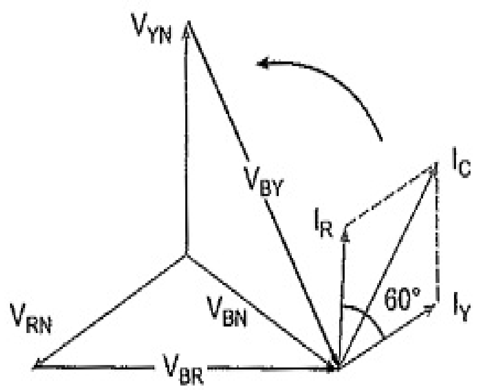


Figure (ii) Phasor Diagram

Capacitive fault current in line B is

$$I_C = \text{Phasor sum of } I_R \text{ and } I_Y$$

$$= \sqrt{3} I_R \quad \text{(from parallelgram principle if } I_R \text{ \& } I_Y\text{)}$$

$$= \sqrt{3} X \frac{\sqrt{3} V_{ph}}{X_C}$$

$$I_C = \frac{3V_{ph}}{X_C}$$

$$I_C = 3\text{xPer phase capacitive current under normal conditions}$$

Therefore, when single line to ground fault occurs on an ungrounded neutral system, the follow-ing effects are produced in the system:

i. The potential of the faulty phase becomes equal to ground potential. However, the voltages of the two remaining healthy phases rise from their normal phase voltages to full line value. This may result in insulation breakdown.
ii. The capacitive current in the two healthy phases increase to √3 times the normal value.
iii. The capacitive fault current (I_C) becomes 3 times the normal per phase capacitive current.
iv. The presence of inductance and capacitance in the system leads to what is known as Arcing Grounds and the voltage of the system may rise to dangerously high values.
v. The capacitive fault current I_C flows into earth. If this current is once maintained, it may exist even after the earth fault is cleared. This phenomenon of persistent arc is called arcing ground. Due to arcing ground, the system capacity is charged and discharged in a cyclic order. This system cannot provide adequate protection against earth faults. It is because the capacitive fault current is small in magnitude and cannot operate protective devices.

Due to above disadvantages, ungrounded neutral system is not used these days: The modern high-voltage 3-phase systems employ grounded neutral owing to a number of advantages.

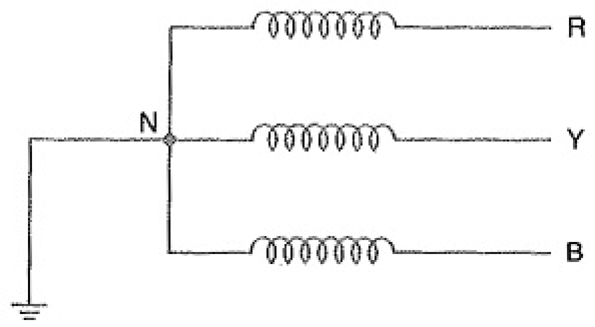
Methods of Neutral Grounding:

i. Solid grounding
ii. Resistance grounding
iii. Reactance grounding
iv. Resonant Grounding or Peterson coil or Arc Suppression Coil Grounding

Solid Grounding or Effective Grounding:

When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.) is directly connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called Solid Grounding or Effective Grounding.

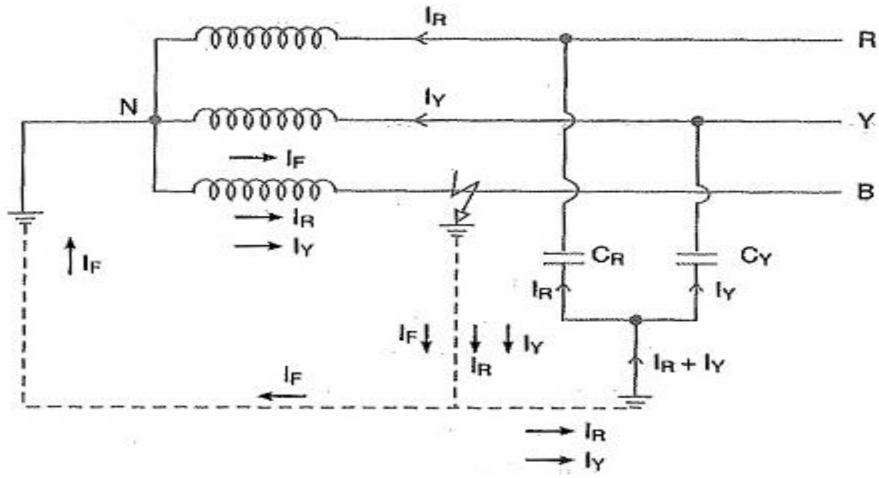
Figure shows the solid grounding of the neutral point. Since the neutral point is directly connected to earth through a wire, the neutral point is held at earth potential under all conditions. Therefore, under fault conditions, the voltage of any conductor to earth will not exceed the normal phase voltage of the system.



Solid grounding of the neutral point

The solid grounding of neutral point has explained below:

1. The neutral is effectively held at earth potential.
2. When earth fault occurs on any phase, the resultant capacitive current I_C is in phase opposition to the fault current I_F. The two currents completely cancel each other. Therefore, no arcing ground or overvoltage conditions can occur.



Line to ground fault in line B

3. Consider a line to ground fault in line B as shown in below figure. The capacitive currents flowing in the healthy phases R and Y are I_R and I_Y respectively. The resultant capacitive current I_C is the phasor sum of I_R and I_Y. In addition to these capacitive currents, the power source also supplies the fault current I_F. This fault

current will go from fault point to earth, then to neutral point N and back to the fault point through the faulty phase. The path of I_C is capacitive and that of I_F is inductive. The two currents are in phase opposition and completely cancel each other. Therefore, no arcing ground phenomenon or overvoltage conditions can occur.

4. When there is an earth fault on any phase of the system, the phase to earth voltage of the faulty phase becomes zero. However, the phase to earth voltages of the remaining two healthy phases remains at normal phase voltage because the potential of the neutral is fixed at earth potential. This permits to insulate the equipment for phase voltage. Therefore, there is a saving in the cost of equipment.
5. It becomes easier to protect the system from earth faults which frequently occur, when there is an earth fault on any phase of the system, large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earth fault relay.

The following are the disadvantages of solid grounding:

i. Since most of the faults on an overhead system are phase to earth faults, the system has to bear a large number of severe shocks. This causes the system to become unstable.
ii. The solid grounding results in heavy earth fault currents. Since the fault has to be cleared by the circuit breakers, the heavy earth fault currents may cause the burning of circuit breaker contacts.
iii. The increased earth fault current results in greater interference in the neighbouring com-munication lines.

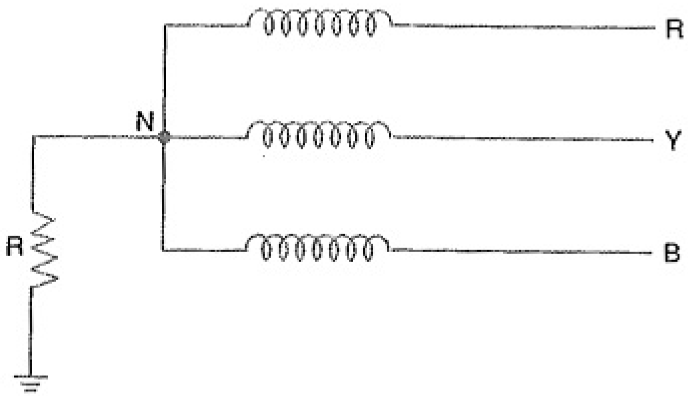
Applications:

Solid grounding is usually employed where the circuit impedance is sufficiently high so as to keep the earth fault current within safe limits. This system of grounding is used for voltages upto 33 kV with total power capacity not exceeding 5000 kVA.

Resistance Grounding:

In order to limit the magnitude of earth fault current, it is a common practice to connect the neutral point of a 3-phase system to earth through a resistor. This is called Resistance Grounding.

When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.) is connected to earth (i.e. soil) through a resistor, it is called Resistance Grounding.

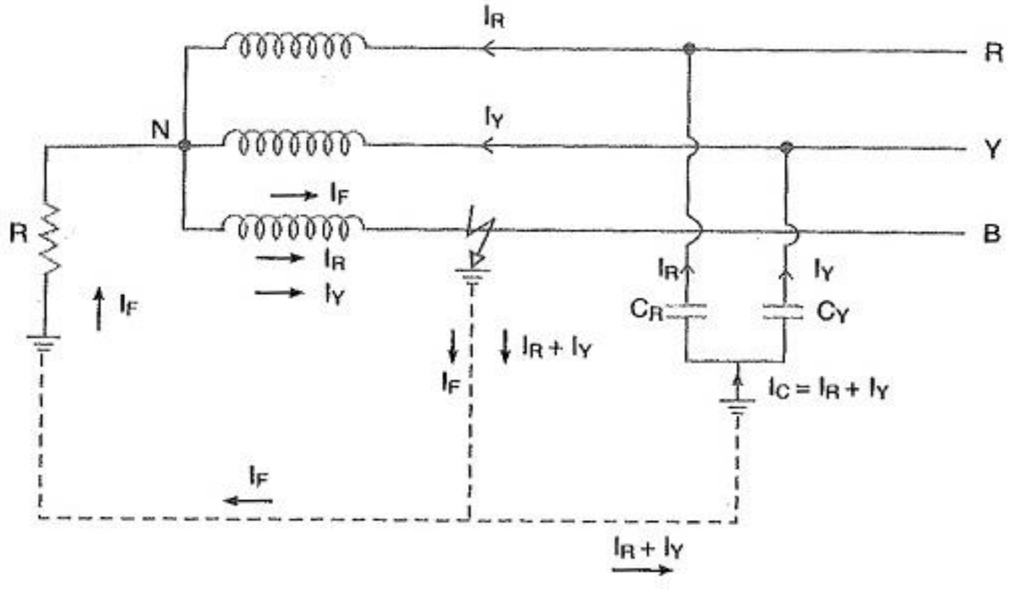


Grounding of neutral point through a resistor R

The above figure shows the grounding of neutral point through a resistor R. The value of R should neither be very low nor very high. If the value of earthing resistance R is very low, the earth fault current will be large and the system becomes similar to the solid grounding system. On the other hand, if the earthing resistance R is very high, the system conditions become similar to ungrounded neutral system. The value of R is so chosen such that the earth fault current is limited to safe value but still sufficient to permit the operation of earth fault protection system. In practice, that value of R is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.

The Resistance grounding of neutral point has explained below:

1. By adjusting the value of R, the arcing grounds can be minimized. Suppose earth fault occurs in phase B as shown in Figure. The capacitive currents I_R and I_Y flow in the healthy phases R and Y respectively. The fault current I_F lags behind the phase voltage of the faulted phase by a certain angle depending upon the earthing resistance R and the reactance of the system upto the point of fault. The fault current I_F can be resolved into two components viz.



Earth fault occurs in phase B

(a) I_{F1} in phase with the faulty phase voltage.

(b) I_{F2} lagging behind the faulty phase voltage by 90°.

The lagging component I_{F2} is in phase opposition to the total capacitive current I_C. If the value of earthing resistance R is so adjusted that $I_{F2} = I_C$, the arcing ground is completely eliminated and the operation of the system becomes that of solidly grounded system. However, if R is so adjusted that $I_{F2} < I_C$, the operation of the system becomes that of ungrounded neutral system.

2. The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.
3. It improves the stability of the system.

The following are the disadvantages of Resistance grounding:

i. Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.
ii. This system is costlier than the solidly grounded system.
iii. A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

Applications:

It is used on a system operating at voltages between 2.2 kV and 33 kV with power source capacity more than 5000 kVA.

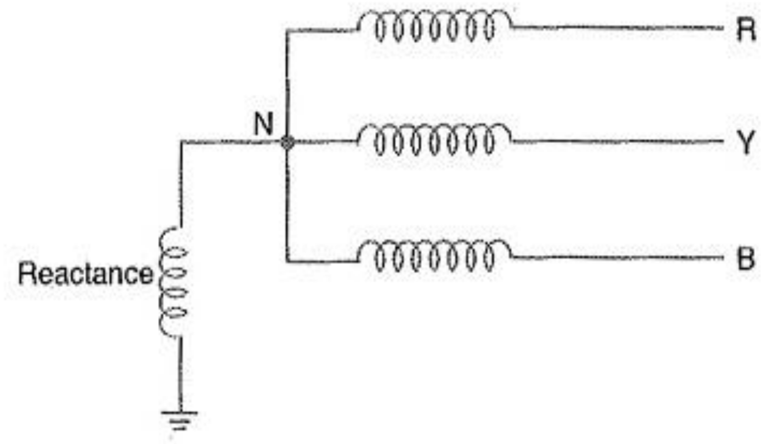
Reactance Grounding:

A reactance grounded system is one in which the neutral is grounded through impedance which is highly reactive. In fact whether a system is solidly grounded or reactance grounded depends upon the ratio of X_0/X_1.

For reactance grounded system $\frac{X_0}{X_1} > 3.0$

For solid grounded system $\frac{X_0}{X_1} < 3.0$

In this Reactance Grounding system, a reactance is inserted between the neutral and ground as shown in Figure. The purpose of reactance is to limit the earth fault current by changing the earthing reactance, the earth fault current can to changed to obtain the conditions similar to that of solid grounding.



Reactance is inserted between the neutral and ground

This method is not used these days because of the following disadvantages:

i. In this system, the fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.
ii. High transient voltages appear under fault conditions.

Resonant Grounding or Arc Suppression Coil Grounding or Peterson Coil Grounding:

We have seen that capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and earth. If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current I_F flowing through L will be in phase opposition to the capacitive current I_C of the system. If L is so adjusted that $I_L = I_C$ then resultant current in the fault will be zero. This condition is known as Resonant Grounding.

When the value of L of arc suppression coil is such that the fault current I_F exactly balances the capacitive current I_C, it is called Resonant Grounding.

What is Petersen Coil?

Petersen Coil is nothing but an inductor used to connect ground of three phase system to the earth. In other words, the neutral of three phase system is grounded through Peterson Coil. Basically, such grounding is adopted to minimize the capacitive charging current during fault in the lines. This also eliminates the arcing ground. This type of grounding is also known as Resonant Grounding.

How does Petersen Coil Work?

Petersen Coil must take current equal to the fault current I_C so that it neutralizes the fault current. This is the reason, it is also known as fault neutralizer.

Circuit details:

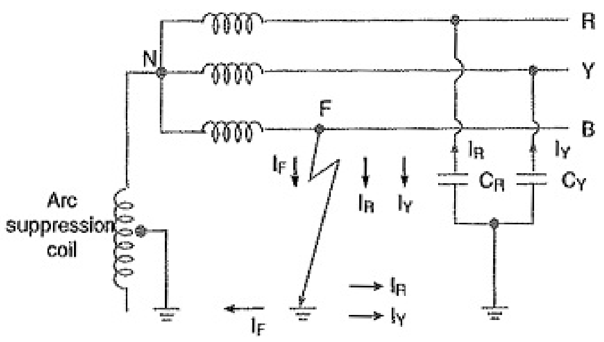


Figure (i) Resonant Grounding

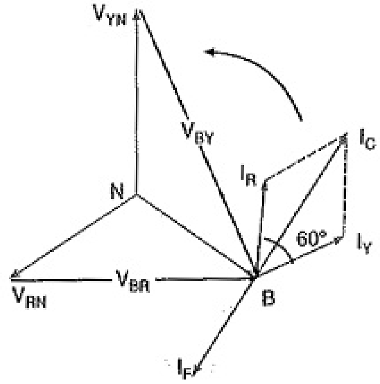


Figure (ii) Phasor Diagram

An arc suppression coil (also called Peterson coil) is an iron-cored coil connected between the neutral and earth as shown in above figure. The reactor is provided with tapping to change the inductance of the coil. By adjusting the tappings on the boil, the coil can be tuned with the capacitance of the system i.e. resonant grounding can be achieved.

Operation:

The above figure (i) shows the 3-phase system employing Peterson coil grounding. Suppose line to ground fault occurs in the line B at point F. The fault current I_F and capacitive currents I_R and I_Y will flow as shown in figure (i). Note that I_F flows through the Peterson coil (or Arc suppression coil) to neutral and back through the fault. The total capacitive current I_C is the phasor sum of I_R and I_Y as shown in phasor diagram in figure (ii). The voltage of the faulty phase is applied across the arc suppression coil. Therefore, fault current I_F lags the faulty phase voltage by 90°. The current I_F is in phase opposition to capacitive current I_C shown in figure (ii) or phasor diagram. By adjusting the tappings on the Peterson coil, the resultant current in the fault can be reduced, If inductance of the coil is so adjusted that $I_L = I_C$ then resultant current in the fault will be zero.

Value of L for resonant grounding:

For resonant grounding, the system behaves as an ungrounded neutral system. Therefore, full line voltage appears across capacitors C_R and C_Y.

$$\mathbf{I_R = I_Y = \frac{\sqrt{3}V_{ph}}{X_C}}$$

$$I_C = \sqrt{3} I_R = \sqrt{3} X \frac{\sqrt{3}V_{ph}}{X_C} = \frac{3V_{ph}}{X_C}$$

Here, X_C is the line to ground capacitive reactance.

$$\mathbf{I_F = I_L = \frac{V_{ph}}{X_L}}$$

Here, X_L is the inductive reactance of the arc suppression coil.

For resonant grounding:

$$I_L = I_C$$

$$\frac{V_{ph}}{X_L} = \frac{3V_{ph}}{X_C}$$

$$\frac{1}{X_L} = \frac{3}{X_C}$$

$$X_L = \frac{X_C}{3}$$

$$\omega L = \frac{1}{3\omega C}$$

$$L = \frac{1}{3\omega^2 C}$$

L= the value of inductance L of the arc suppression coil for resonant grounding.

The Peterson coil grounding has the following advantages:

i. The Peterson coil is completely effective in preventing any damage by an arcing ground.
ii. The Peterson coil has the advantages of ungrounded neutral system.

The Peterson coil grounding has the following disadvantages:

i. Due to varying operational conditions, the capacitance of the network changes from time to time. Therefore, inductance L of Peterson coil requires readjustment.
ii. The lines should be transposed.

Ex-1: - Calculate the reactance of Peterson coil suitable for a 33 kV, 3-phase transmission line having a capacitance to earth of each conductor as 4.5μF. Assume supply frequency to be 50Hz.

Solutions: Supply frequency, f = 50 Hz

Line to earth capacitance, C = 4.5 μF = 4.5 × 10–6 F

For Peterson coil grounding, reactance X_L of the Peterson coil should be equal to $\frac{X_C}{3}$ where X_C is line to earth capacitive reactance.

∴ Reactance of Peterson coil, $X_L = \frac{X_C}{3} = \frac{1}{3\omega C}$ $(\because I_L = I_C)$

$$= \frac{1}{3*2\Pi fC}$$

$$= \frac{1}{3x2\Pi x50x4.5x10^{-6}} = 235.8\Omega$$

EX-2: A 230 kV, 3-phase, 50 Hz, 200 km transmission line has a capacitance to earth of 0.02 μF/km per phase. Calculate the inductance and kVA rating of the Peterson coil used for earthing the above system.

Solutions: Supply frequency, f = 50 Hz

Length of transmission line is = 200km

Capacitance to earth of per phase = 0.02 μF/km

Capacitance of each line to earth, C = length of T/L line x capacitance to earth of per phase

= 200 × 0.02

= 4×10^{-6} F

Required inductance of Peterson coil is

$$L = \frac{1}{3\omega^2 C}$$

$$L = \frac{1}{3x(2\Pi x50)^2 x4x10^{-6}}$$

$$L = 0.85\ H$$

Current through Peterson coil is

$$I_F = I_L = \frac{V_{ph}}{X_L} = \frac{\frac{230x10^3}{\sqrt{3}}}{2\Pi fL} = \frac{\frac{230x10^3}{\sqrt{3}}}{2\Pi x50x0.85}$$

$$I_F = I_L = 500A$$

Voltage across Peterson coil is

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{230x1000}{\sqrt{3}}$$

∴ Rating of Peterson coil = $V_{ph} x I_F$

$$= \frac{230x1000}{\sqrt{3}} x500x \frac{1}{1000} KVA$$

Rating of Peterson coil $= 66397\ kVA$

EX-3: A 50 Hz overhead line has line to earth capacitance of 1.2 μF. It is desired to use earth fault neutralizer. Determine the reactance to neutralize the capacitance of (i) 100% of the length of the line (ii) 90% of the length of the line and (iii) 80% of the length of the line.

Solution.

(i) Inductive reactance of the coil to neutralize capacitance of 100% of the length of the line is

$$X_L = \frac{1}{3\omega C} = \frac{1}{3x2\Pi x50x1.2x10^{-6}} = 884.19\Omega$$

(ii) Inductive reactance of the coil to neutralize capacitance of 90% of the length of the line is

Capacitance for 90% C = 90%x C $= 0.09X\ 1.2X10^{-6} = 0.108X10^{-6}F$

$$X_L = \frac{1}{3\omega C} = \frac{1}{3x2\Pi x50x0.108x10^{-6}} = 982.43\Omega$$

(iii) Inductive reactance of the coil to neutralize capacitance of 80% of the length of the line is

Capacitance for 80% C = 80%x C $= 0.08X\ 1.2X10^{-6} = 0.096X10^{-6}F$

$$X_L = \frac{1}{3\omega C} = \frac{1}{3x2\Pi x50x0.096x10^{-6}} = 1105.24\Omega$$

EX-4: A 132 kV, 3-phase, 50 Hz transmission line 200 km long consists of three conductors of effective diameter 20 mm arranged in a vertical plane with 4 m spacing and regularly transposed. Find the inductance and kVA rating of the arc suppression coil in the system.

Solutions: Radius of conductor, r = 20/2 = 10 mm = 0.01 m

Conductor spacing, d = 4m

∴ Capacitance between phase and neutral or earth

$$= \frac{2\Pi\varepsilon_0}{\log_e \frac{d}{r}} F/m = \frac{2\Pi x8.855x10^{-12}}{\log_e \frac{4}{0.01}} F/m$$

.

$$= 9.285x10^{-12} F/m$$

$$= 9.285x10^{-12} x \frac{10^3}{10^3} F/m$$

$$= 9.285x10^{-12} x10^3 F/km$$

$$= 9.285x10^{-9} F/km$$

∴ Capacitance C between phase and earth for 200 km line is

$$C = \text{Length X Capacitance per km}$$

$$C = 200x9.285x10^{-9}F$$

$$C = 18.57x10^{-7}F$$

The required inductance L of the arc suppression coil is

$$L=\frac{1}{3\omega^2C} = \frac{1}{3x(2\Pi x50)^2x18.57x10^{-7}}$$

$$L=1.82H$$

Current through the coil

$$I_F=I_L=\frac{V_{ph}}{X_L}=\frac{V_L/\sqrt{3}}{\omega L}=\frac{132x10^3/\sqrt{3}}{2\Pi fL}$$

$$I_F=I_L=\frac{V_{ph}}{X_L}=\frac{132x10^3/\sqrt{3}}{2\Pi X50X1.82}$$

$$I_F=I_L=132\ A$$

∴ Rating of Peterson coil = $V_{ph}xI_F$

$$=\frac{132x1000}{\sqrt{3}}x132$$

$$=10060\ kVA$$

Example 11.1: A 132 kV, 3-phase, 50 Hz transmission line 192 km long consists of three conductors of effective diameter 20 mm, arranged in a vertical plane with 4 m spacing and regularly transposed. Find the inductance and kVA rating of the arc suppressor coil in the system. (CL WADHWA PAGE NO 252.) Ans: L=1.97H, 9.389 MVA per coil.

Example 11.2: A 50 Hz overhead line has line to earth capacitance of 1 μF. It is decided to use an earth fault neutralizer. Determine the reactance to neutralise the capacitance of (i) 100% of the length of the line, (ii) 90% length of the line, and (iii) 80% of the length of the line. (CL WADHWA PAGE NO 252.) Ans: (i) 1061 Ω (ii) 1179 Ω (iii) 1326Ω

Example 11.4: A transmission line has a capacitance of 0.1 μF per phase. Determine the inductance of Peterson coil to neutralize the effect of capacitance of (i) complete length of line, (ii) 97% of the line, (iii) 90% length of the line. The supply frequency is 50 Hz. (CL WADHWA PAGE NO 254.)

Example 11.5: A 132 kV, 50 Hz, 3-phase, 100 km long transmission line has a capacitance of 0.012 μF per km per phase. Determine the inductive reactance and kVA rating of the arc suppression coil suitable for the line to eliminate arcing ground phenomenon. (CL WADHWA PAGE NO 254.)

Grounding Practice:

i. One grounding is normally provided at each voltage level. Between generation and distribution, there are various voltage levels; it is desirable to have ground available at each voltage level.
ii. The generators are normally provided with resistance grounding and synchronous motors or synchronous capacitors are provided with reactance grounding.
iii. Where several generators are connected to a common neutral bus, the bus is connected to ground through a single grounding device. Disconnect switches can be used to ground the desired generators to the neutral bus.
iv. Where several generators are operating in parallel, only one generator neutral is grounded. This is done to avoid the interference of zero sequence currents. Normally two grounds are available in a station but only one is used at a time. The other is used when the first generator is out of service.
v. For low voltages up to 600 volts and for high voltages above 33 kV solid grounding is used whereas for medium voltages between 3.3 kV and 33 kV resistance or reactance grounding is used.

Protection Against Overvoltages

Causes of Overvoltages:

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

1. Internal causes
2. External causes (i.e. lightning)

Internal causes:

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.

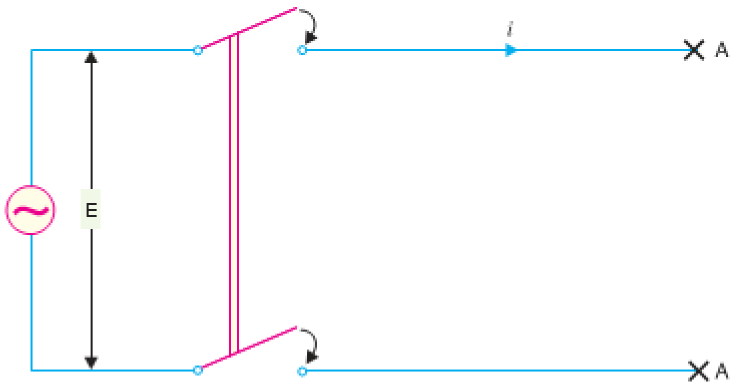
i. Switching surges
ii. Insulation failure
iii. Arcing ground
iv. Resonance

i. 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 :

(a) 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 figure.



Unloaded line

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 Er.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 $2\sqrt{2}$ E for a moment before settling down to the normal value.

(b) 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 Z_n i across the break (i.e. switch) where i is the instantaneous value of current at the time of opening of line and *Z_n is the natural impedance of the line.

(c) Current chopping:

Current chopping results in the production of high voltage transients across the contacts of the air blast circuit breaker. 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. Overvoltage's due to current chopping are prevented by resistance switching.

ii. 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.

iii. 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 pre- vented by earthing the neutral.

iv. Resonance:

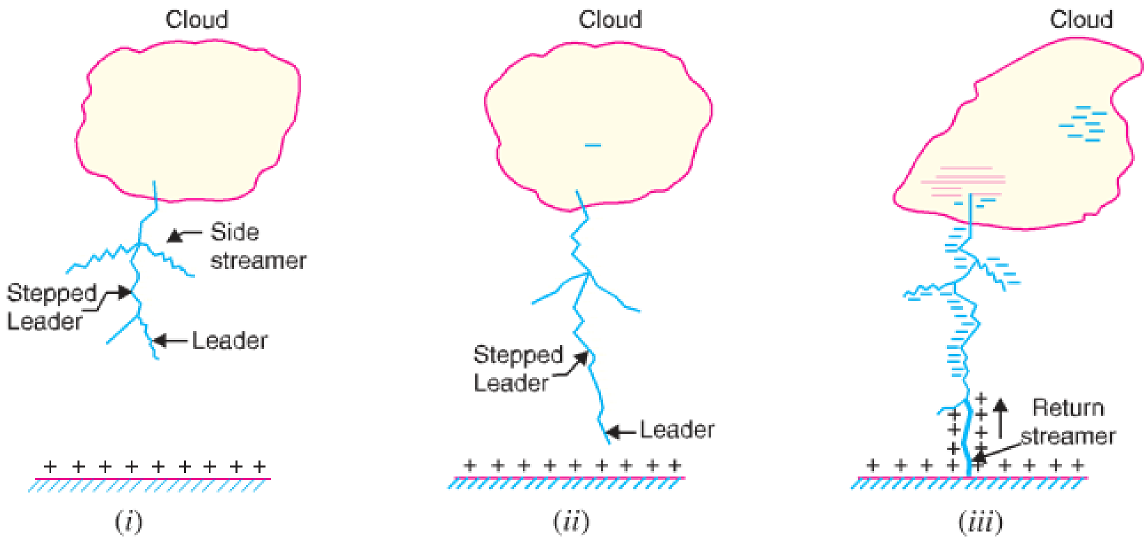
Resonance in an electrical system occurs when inductive reactance of the circuit becomes equal to capacitive reactance. Under resonance, the impedance of the circuit is equal to resistance of the circuit and the p.f. is unity. Resonance causes high voltages in the electrical system. In the usual transmission 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 5^{th} or higher harmonics and in case of underground cables too.

2. External causes:

Lightning: An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as lightning.

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. The below figure 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 Figure (i). The leader streamer will continue its journey towards earth as long as the cloud, from which its 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. Figure (i) show 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 [figure (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 [See Figure (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 discharge:

(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.

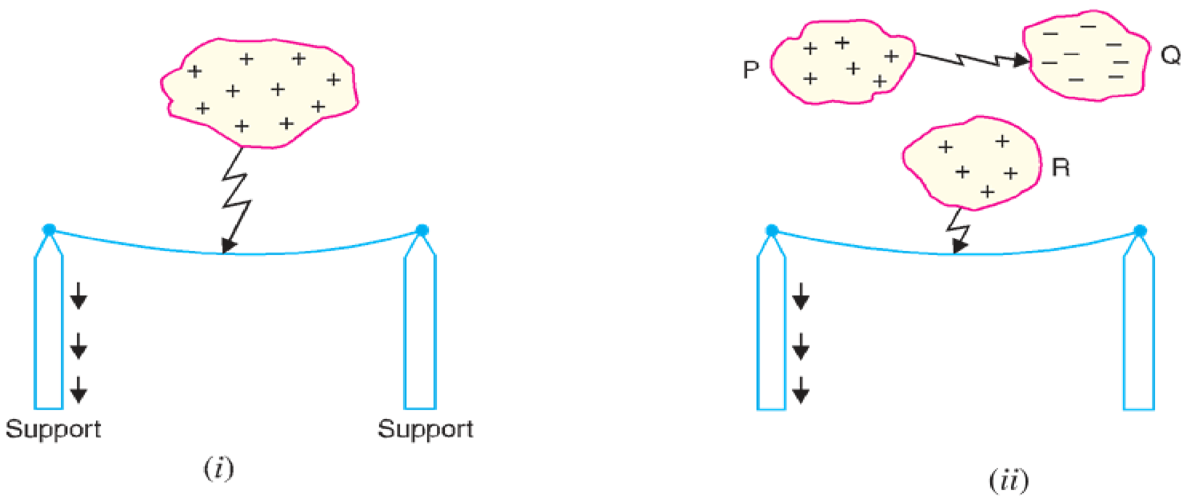
(d) Lightning discharge may have currents in the range of 10 kA to 90 kA.

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

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.

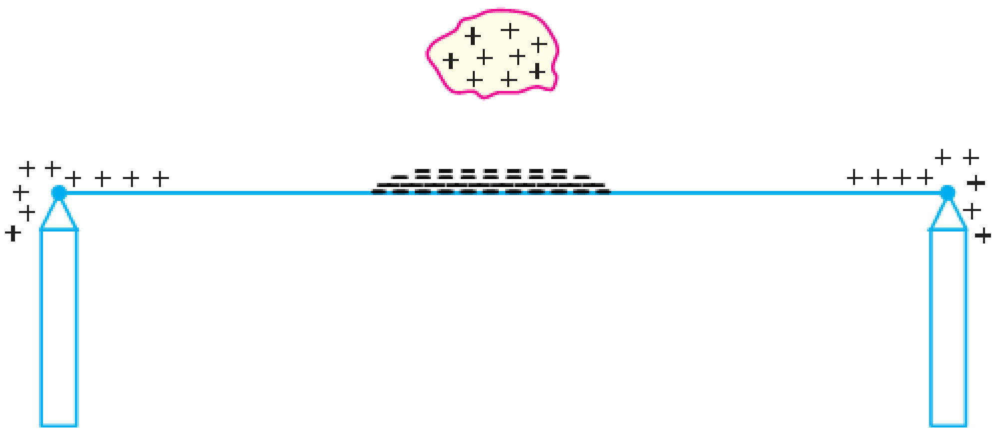


i. In stroke A, the lightning discharge is from the cloud to the subject equipment i.e. an over- head line in this case as shown in Figure (i). The cloud will induce a charge of opposite sign on the tall object (e.g. an overhead line in this case). When the potential between the cloud and line exceeds 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 Figure (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.

Indirect stroke. Indirect strokes result from the electrostatically induced charges on the conductors due to the presence of charged clouds. This is illustrated in below figure. 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 figure. 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.



Indirect stroke

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

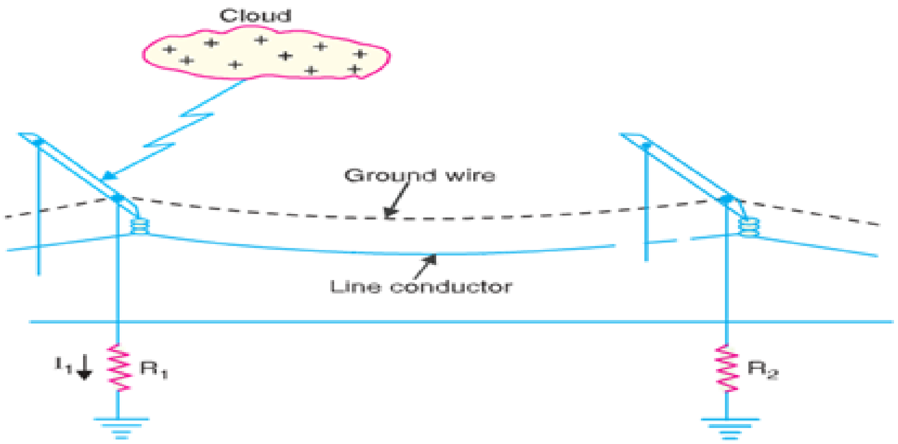
(iii) Lightning arresters or surge diverters

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.

The Earthing Screen:

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.

Overhead Ground Wires:



Overhead ground wires Transmission Line

The most effective method of providing protection to transmission lines against direct lightning strokes is by the use of overhead ground wires as shown in above figure. For simplicity, one ground wire and one line conductor are shown. The ground wires are placed above the line conductors at such positions that practically all lightning strokes are intercepted by them (i.e. ground wires). The ground wires are grounded at each tower or pole through as low resistance as possible. Due to their proper location, the ground wires will take up all the lightning strokes instead of allowing them to line conductors.

Advantages

i. It provides considerable protection against direct lightning strokes on transmission lines.
ii. A grounding wire provides damping effect on any disturbance travelling along the line as it acts as a short-circuited secondary.
iii. It provides a certain amount of electrostatic shielding against external fields. Thus it reduces the voltages induced in the line conductors due to the discharge of a neighbouring cloud.

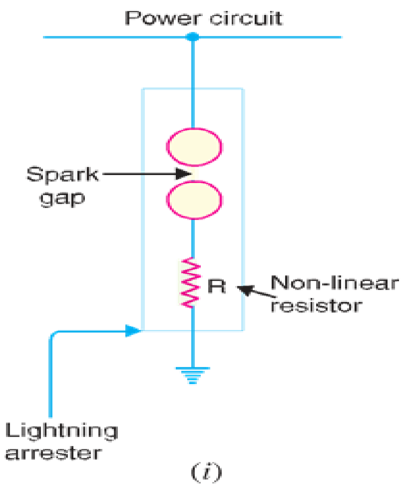
Disadvantages

i. It requires additional cost.
ii. There is a possibility of its breaking and falling across the line conductors, thereby causing a short-circuit fault. This objection has been greatly eliminated by using galvanised stranded steel conductors as ground wires. This provides sufficient strength to the ground wires.

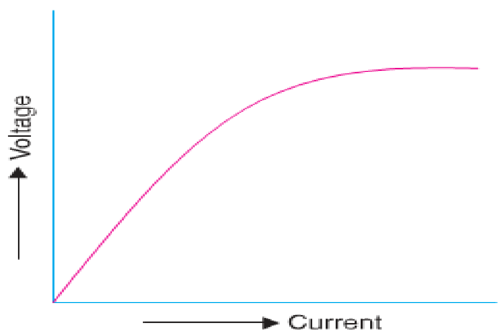
Lightning Arresters:

The earthing screen and ground wires can well protect the electrical system against direct lightning strokes but they fail to provide protection against travelling waves which may reach the terminal apparatus. The lightning arresters or surge diverters provide protection against such surges.

A lightning arrester or a surge diverter is a protective device which conducts the high voltage surges on the power system to the ground.



(i)



(ii)

Figure (i) shows the basic form of a surge diverter. It consists of a spark gap in series with a non-linear resistor. One end of the diverter is connected to the terminal of the equipment to be protected and the other end is effectively grounded. The length of the gap is so set that normal line voltage is not enough to cause an arc across the gap but a dangerously high voltage will break down the air insulation and form an arc. The property of the non-linear resistance is that its resistance decreases as the voltage (or current) increases and vice-versa. This is clear from the volt/amp characteristic of the resistor shown in figure (ii).

Two things must be taken care of in the design of a lightning arrester. Firstly, when the surge is over, the arc in gap should cease. If the arc does not go out, the current would continue to flow through the resistor and both resistor and gap may be destroyed. Secondly, I R drop (where I is the surge current) across the arrester when carrying surge current should not exceed the breakdown strength of the insulation of the equipment to be protected.

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:

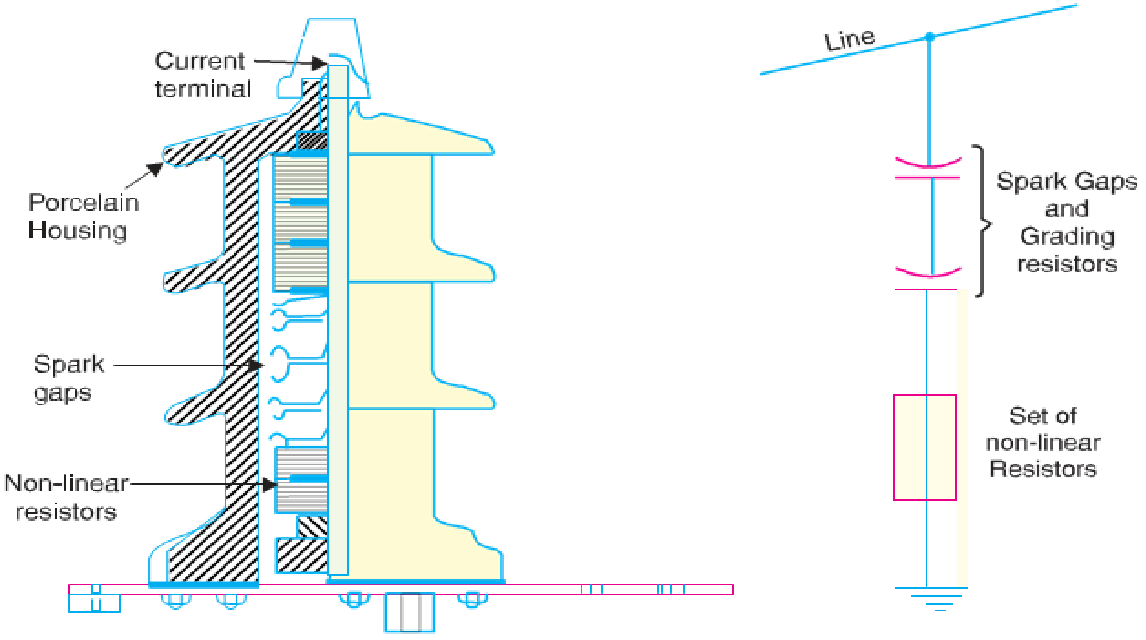
1. Rod gap arrester
2. Horn gap arrester
3. Multigap arrester
4. Expulsion type lightning arrester
5. **Valve type lightning arrester**

Valve type arrester:

Valve type arresters incorporate non-linear resistors and are extensively used on systems operating at high voltages. Figure (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.



(*i*) (*ii*)

Working:

Under normal conditions, the normal system voltage is insufficient to cause the break-down 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.

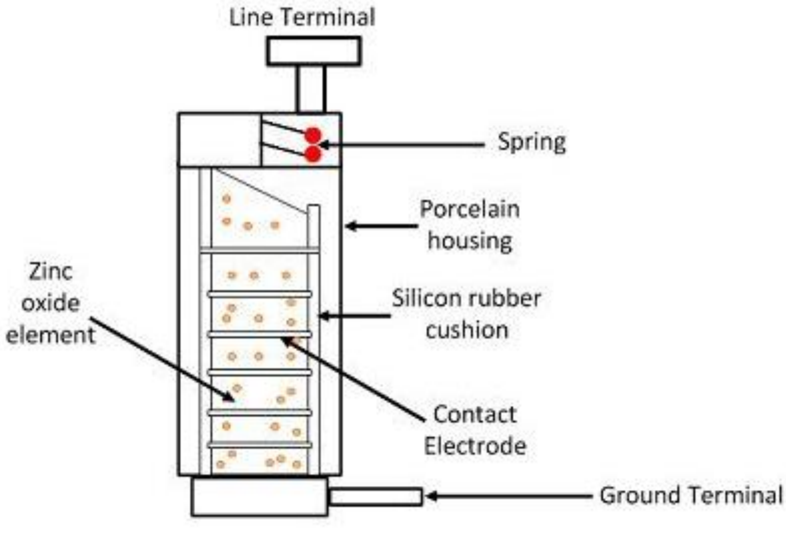
Metal Oxide Surge Arrester:

Definition: The arrester which uses zinc oxide semiconductor as a resistor material, such type of arrester is known as a metal oxide surge arrester or ZnO Diverter. This arrester provides protection against all types of AC and DC over voltages. It is mainly used for overvoltage protection at all voltage levels in a power system.

Construction & Working of Metal Oxide Surge Arrester

The zinc oxide is a semiconducting material of N-type. It is pulverised and finely grained. More than ten doping materials are added in the form of fine powders of insulating oxides such as Bismuth (Bi_2O_3), Antimony Trioxide (Sb_2O_3), Cobalt Oxide(CoO), Manganese Oxide (MnO_2), Chromium oxide (Cr_2O_3). The powder is treated with some processes, and the mixture is spray dried to obtain a dry powder.

The dry powder is compressed into disc-shaped blocks. The blocks are sintered to obtain a dense poly- crystalline ceramic. The metal oxide resistor disc is coated with a conducting compound to protect the disc from undesirable environmental effect.



Zinc Oxide Surge Arrester

The conducting coating also provides proper contacts and uniform current distribution. The disc then enclosed in a porcelain housing filled with nitrogen gas or SF6 gas. Silicon rubber is used to keep the disc in a position. It also helps in heat transfer from disc to the porcelain housing. The disc is held under pressure using suitable springs.

The ZnO element eliminates series sparks gaps in the diverter. The voltage drop in ZnO diverter takes place at the grain boundaries. There is a potential barrier at the boundary of the each grain of ZnO and this potential barrier control the flow of current from one grain to the next.

At normal voltage, the potential barrier does not allow the current to flow through it. At over voltage the barrier collapse and sharp transition of current from insulating to conducting state take place. The current start flowing and the surge is diverted to ground.

After the travelling of the surge, the voltage across the diverters falls, and the current is reduced to the negligible value of the resistor units, and there is no power follow current.

Advantages of Metal Oxide Surge Arrester

The metal oxide surge arrester has the following merits:

1. It eliminates the risk of spark over and also the risk of shock to the system when the gaps break down.
2. It eliminates the need of voltage grading system.
3. At the normal operating condition, the leakage current in the ZnO is very low as compared to other diverters.
4. There is no power follow current in ZnO diverter.
5. It has high energy absorbing capability.
6. ZnO diverters possess high stability during and after prolonged discharge.
7. In ZnO diverter, it is possible to control the dynamic overvoltages in addition to switching surges. This results in economic insulation coordination.

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 Different types of Types of Surge Absorber.

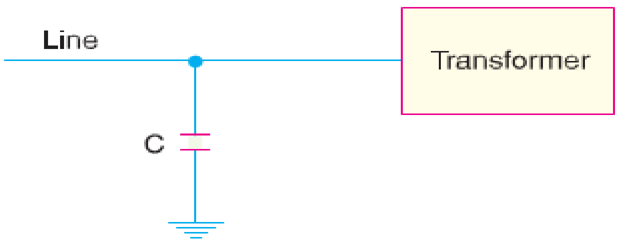
A surge absorber is a protective device which reduces the steepness of wave front of a surge by ab-sorbing surge energy.

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.

Different Types of Surge Absorber are

1. Condenser or Capacitor Surge Absorber
2. Inductor and Resistance Surge Absorber
3. Ferranti Surge Absorber

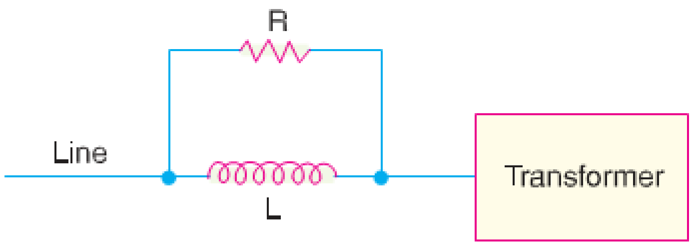
1. Condenser or Capacitor Surge Absorber:



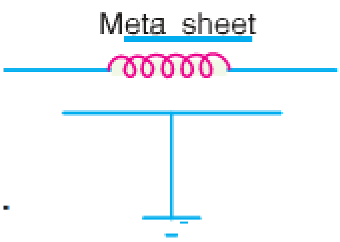
A condenser connected between the line and earth can act as a surge absorber. The above figure shows how a capacitor acts as surge absorber to protect the transformer winding. Since the reactance of a condenser is inversely proportional to frequency, it will be low at high frequency and high at low frequency. Since the surges are of high frequency, the capacitor acts as a short circuit and passes them directly to earth. However, for power frequency, the reactance of the capacitor is very high and practically no current flows to the ground.

2. Inductor and Resistance Surge Absorber:

Another Types of Surge Absorber consists of a parallel combination of choke and resistance connected in series with the line as shown in below figure. The choke offers high reactance to surge frequencies ($X_L=2\pi fL$). The surges are, therefore, forced to flow through the resistance R where they are dissipated.



3. Ferranti Surge Absorber:



The above figure shows the Types 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 for the protection of transformers.

The above figure (i) shows the schematic diagram of 66 kV Ferranti surge absorber while figure (ii) shows its equivalent circuit.