# 18-A

## *Transient Overvoltage Surges, Surge Arresters and Insulation Co-ordination*

Introduction — Principle of Insulation Co-ordination — Lightning Surges and Surge Arresters — Switching Surge — Insulation Co-ordination.

### 18.1. INTRODUCTION

Each electrical equipment should have long service life of more than 25 years. The conductors are supported on insulators/embedded in insulation system. The internal and external insulation of every electrical equipment is exposed to continuous normal voltages and occasional abnormal over voltages. The equipment insulation should be designed such that the equipment *withstands* the highest power frequency system voltage, occasional temporary power-frequency overvoltages, occasional lightning/switching surges reaching the equipment (after the interception by surge arresters). The terms related with rated insulation levels are defined in the relevant IS/IEC Standard Specifications. Each equipment has assigned Rated Insulation Level, the capability is proved by Type tests/Routine tests for that equipment. (*e.g.* Table 16.1).

The insulation system is protected against abnormal p.f. overvoltages, lightning surges and switching surges.

— The *insulation requirements* are determined by considering the following :

— *Highest power frequency System voltage* (continuous)

— *Temporary Power-Frequency Overvoltages* (a few mill-seconds to seconds) caused by load throw-off, faults, resonance etc.

— *Transient Overvoltages Surges* (few hundred microseconds). caused by Lightning, Switching, Restrikes, Travelling waves etc. The Surge Arresters intercept the surges and protect the installation.

— *Withstand Levels of the equipment.* The BIL is specified and other withstand levels are then selected from relevant tables in standard specifications.

*Basic Impulse Insulation Level* (BIL) is reference level expressed in peak (crest) voltage value with standard 1.2/50 μs lightning impulse wave. Apparatus should be capable of withstanding test waves above BIL.

— *Protective levels of Surge arresters* and available *Protective Margin* against Lightning/Switching Surges.

$$\text{Protective Margin} = \begin{bmatrix}\text{Withstand Level}\\ \text{of Equipment}\end{bmatrix} - \begin{bmatrix}\text{Protective Level by}\\ \text{Surge Arrester}\end{bmatrix}$$

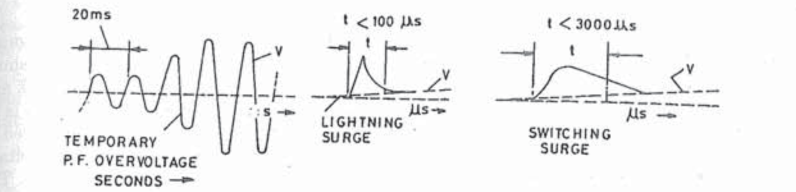
— Co-ordination with other equipment connected to same voltage level.

— Co-ordination between various voltage levels in the Network.

— System Neutral Earthing.

Fig. 18. A-1 illustrates the range of waveforms and durations of Power-frequency Overvoltage, Lightning Surges and Switching Surges. The time durations, rate of rise, peak values of these over-

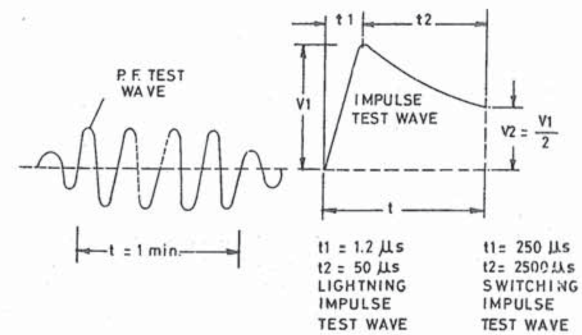





Temporary P.F. Overvoltage Lightning Surges

Fig. 18 A-1. Three Representative Wave forms* of P.F. Overvoltages and Surges occurring in Network.

voltages of actual overvoltages in the system differ widely. Hence stresses on insulation are also quite different. Power frequency overvoltages are of low overvoltage factor but longer duration. Lightning and Switching Surges are of higher over voltage factor and of lesser duration. The standard test waveforms have been obtained from field studies from several locations, over several years and are used as representatives for laboratory tests of equipment for proving the withstand *capabilities.*




P.F. Overvoltage Impulse Voltage Wave

Fig. 18 A-2. Standard Test Waveforms for Laboratory Tests.
(Word "Impulse" used for "test wave," "Surge" for "wave" in network)

**Table 18.1. Example of Rated Insulation Characteristics of an Outdoor Busbar**

| | |
|---|---|
| Nominal voltage* | 132 kV rms, 50Hz |
| Highest system voltage** | 145 kV rms, 50 Hz |
| 1 Min. 50 Hz Withstand*** | 300 kV rms |
| Lightning Impulse Voltage Withstand | 450 kV peak |
| Switching Impulse Voltage Withstand+<br>Lightning Surge Protective Level | 380 kV peak<br>390 kV p |
| Lightning Surge Protective Margin by S.A. | 60 kV |

* Rated voltage
** Design voltage for continuous withstand
*** Test voltage for 1 min. power frequency voltage withstand test
+ Switching overvoltage factor $K$, not specified for 132 kV busbars

**Basic Protections against Overvoltages**

The protection against Transient Voltage Surges is provided by *Surge Arresters.* The surge arresters, coordinated spark gaps, surge suppressors, overhead ground wires, neutral earthing, shunt capacitors etc. are located strategically to intercept the lightning surges or to reduce the peak and rate of rise of Surges. Protection against Temporary Power Frequency (50 Hz) Overvoltages is by Inverse Definite-Minimum Time Overvoltage Relay (IDMT). Overvoltage relay is connected to secondary of Voltage Transformer. During p.f. overvoltage beyond permissible limit; the overvoltage relay acts and sends appropriate command to busbar/line C.B. and the circuit breaker opens. The transformers and other equipment are protected against temporary power frequency overvoltages.

The Coefficient of Earthing co-relates the Insulation Levels with the Type of Neutral Earthing, the details are described in Ch. 18-B.

**Protections against Overvoltages and how fast they act ?**

| *Temporary Overvoltage (ms or s)* \| | *Lightning Surge (μs)* \| | *Switching Surge (μs)* \| |
|---|---|---|
| ↓ | ↓ | ↓ |
| Overvoltage | Surge Arrester | Surge Arrester |
| Relay & CB < 70 ms | 1.2 μs | 100 μs |

The overvoltage protection against *Voltage Surges* is provided by Surge Arresters which act within microseconds. The surge is diverted to earth by the Surge Arrester.

**Highest Power Frequency Voltages**

The AC Network has different nominal power-frequency voltage levels (*e.g.* 400 V, 3.3kV ; 220 kV, 400 kV rms continuous, at 50Hz). During low loads, the power frequency voltage at receiving end of transmission line rises. In a well voltage-regulate system, the permissible maximum system voltage allowed is called Highest System Voltage. Each nominal voltage level has certain corresponding Highest System Voltage (440 V, 3.6 kV ; 245 kV, 420 kV rms continuous). Each equipment is designed and tested to withstand the corresponding Highest Power Frequency System Voltage of that voltage level continuously without internal or external insulation failure.

**Protection against Temporary Power Frequency Overvoltages**

There is a difference between the characteristics of Power-Frequency Overvoltage and Transit Voltage Surges and the corresponding stresses on equipment and surge arresters. The temporary P.F. Overvoltages are of 50 Hz and of lesser peak, lesser rate of rise and of *longer duration (seconds or even minutes).* Every time a change in tap changing by one step-up may cause slight temporary overvoltage. In absence of proper voltage control (Ch. 45) the power frequency voltages go much beyond permissible highest system voltage values. Transformers are worst affected by temporary overvoltages above 1.1 pu. (due to high V/f and overfluxing.) Solid insulator supports are least affected. The protection against temporary P.F/Overvoltages is provided by Inverse Definite Minimum Time IDMT Overvoltage Relays connected to secondary of Bus VT and Circuit Breakers. The relay and breaker action is within several tens of milliseconds to a few seconds. The Overvoltage Relays connected to secondary of Voltage Transformer respond to the overvoltages and give tripping command to circuit breakers. The Circuit Breakers open and the Equipment (*e.g.* Transformer or Busbar) is protected against the temporary overvoltage.

**Protection against Transient Surges**

Surges in the Power System are of comparatively high peak, high rate of rise and last for a *few tens/hundreds of micro seconds* and are therefore called transients. During 1950s, Lightning Surges have resulted in failures. Several Transformers and Generators failed due to direct Lightning stroke on overhead lines near the substation/power station. By 1980s, the ZnO arresters were perfected. The failure rate due to Lightning and Switching has been minimised by proper insulation coordination and Surge Arrester Protection.



During 1960s and early 1970s, *Switching Surge Phenomena* were investigated, the Circuit-Breakers with low Switching Overvoltage Factors ($K < 2$) were developed. Surge arresters capable of diverting/absorbing switching surges were also developed.

Surges can cause spark over and flashover at sharp corners, flash over between phase and ground at *weakest point,* breakdown of gaseous/solid/liquid insulation, failure of transformers and rotating machines.

*Several defensive-device are installed in the Network to intercept Lightning Strokes and minimise the peak/rate of rise of surges reaching the equipment.* Ultimate and important protection is by ZnO Surge Arresters.

**Strategy of Insulation Co-ordination**

Following methods are applied to solve the problem of overvoltages and Insulation Co-ordination :

— Each Equipment has specified power frequency *Withstand Level and Impulse Withstand Levels.*

— The *Withstand Levels* of Equipment/Machines are co-ordinated with the *Protective Level* of nearest Surge Arrester. *Protective Levels* of Surge Arrester at each voltage level shall be coordinated.

— Every equipment is well protected and overall economy and reliability is achieved. In the event of occurrence of severe voltage-surge the damage is to least costly equipment (Spark Gap).

— Duplicate surge protection is provided in Substations, one surge arrester per phase at income bus and another surge arrester at Transformer terminal, for each phase.

— Rotating machines are provided with R-C Surge suppressors at the terminals.

— System Neutral is Earthed at every voltage level to reduce Coefficient of earthing and to discharge the surges.

*Insulation co-ordination* covers the following aspects :

— The causes and effects of Transient Overvoltages (Surges) and the Protection of Electrical Equipment Insulation.

— Standardisation of Nominal Voltage Levels, Highest Voltage Levels in the Network.

— Choice of Power Frequency withstand values for equipment insulation.

— Choice of BIL and Switching Impulse Withstand Levels for Equipment Insulation.

**Basic Impulse Insulation Level** (BIL) is the reference level expressed in kV peak (crest) voltage value with standard 1.2/50 μs Lightning impulse wave. Apparatus should be capable of withstanding test waves above BIL.

— Choice of Switching Impulse withstand levels for equipment insulation.

— Temporary power frequency overvoltage protection by overvoltage relays and circuit breakers.

— Co-ordination between the *Withstand Levels* of Equipment and the *Protective Levels* provided by surge arresters and the *Protective Margin* at various voltage levels for each equipment.

**Power Frequency Overvoltages**

The Power Frequency (50 Hz) overvoltages are the 50 Hz Overvoltages of value more than the Highest System voltage. For example in a 132 kV system, 145 kV is highest system voltage, and 150 kV rms is power frequency overvoltage. Such voltages are called temporary overvoltages.

*The power frequency voltage withstand level* of an equipment denotes the capability of the equipment to withstand p.f. overvoltage for a specified short duration (*e.g.* 1 min). The system experience occasional temporary power frequency over voltages arising during load-throw-off, wrong OLTC Operation, insufficient shunt compensation, resonance etc. Surge Arresters are not designed and installed for protection against the P.F. Overvoltages.

Overvoltage Relays are connected to bus-bars *via* voltage transformers and provide the protection against Temporary P.F. Overvoltages. The overvoltage relays respond to power frequency overvoltage and trip the circuit breakers against temporary overvoltages above permissible limits (*e.g.* 150 kV for a 132 kV System) within a few tens of milliseconds or seconds (with inverse characteristic). The insulation of transformers/generators/motors etc. connected to busbars is protected.

**Lightning Surges**

The equipment connected in the network are subjected to occasional *Lightning Surges* of high peak value, sharp rate of rise and short duration. The protection against lightning surges is given by *Lightning Arresters (Surge Arresters)*. The equipment has certain assigned *Lightning Impulse Voltage Withstand Level*, which is proved by conducting Lightning Impulse Voltage Test. The lightning a surges are simulated in High Voltage Test Laboratories by a representative 1.2/50 μs Lightning Impulse Wave obtained from an Impulse Generator.

**Switching Surge**

The *Switching Voltage Surges* occur during opening and closing unloaded EHV AC lines, breaking inductive loads, breaking capacitive loads etc. The switching surges are of comparatively longer duration (2500 μs), lower rate of rise and are represented by standard switching impulse test wave of 250/2500 μs. The peak value of switching surge is expressed in terms of Switching Overvoltage Factor. *Switching Impulse Withstand Level Test* is applicable to equipment rated 275 kV and above. The motor switching, reactor switching are special switching duties. (Ch. 18, Sec. 18.23 to 18.26), which generate switching surges.

The switching surges are simulated in High Voltage Test Laboratories by a representative 250/2500 μs Switching Impulse Wave obtained from an Impulse Generator.

The protective devices against Switching Surges are :

— ZnO surge arresters with high energy absorbtion capability, installed near the apparatus.

— RC Surge Suppressers, installed near the rotating machine terminals, circuit-breaker terminals.

Preventive Measures against Switching Surges are :

— Use of Circuit-Breaker with Low Switching Overvoltage Factor *K*.

— Use adequate phase-to-ground capacitance in the supply circuit to absorb the switching overvoltage.

**Equipment Insulation.** Each equipment has certain *internal* and certain *external* phase to ground insulation, and phase to phase insulation, creepage distance, clearances, insulation grading etc. The voltage grading rings improve the voltage stress profile and give high withstand values. These insulation requirements of AC electrical equipments are determined by the voltage stresses occurring during :

— Continuous Highest Power Frequency System-Voltage

— Occasional Temporary power frequency overvoltage caused by load-throw-off, oscillations, faults.

— Occasional Transient Lightning Surges

— Occasional Transient Switching Surges particularly due to switching of inductive/capacitive loads or EHV lines.

The dielectric stresses are imposed on internal and external, gaseous/solid and liquid insulation systems insulation systems of each equipment. The dielectric stresses depend on the peak vale, rate of rise, durations, of the voltage waveforms etc.

According to standard specification, each substation equipment has certain specified *withstand levels* of power frequency, lightning impulse and switching impulse voltage waveform. The withstand level is proved by relevant type tests and routine tests. The specified voltage withstand levels are :

— High Power Frequency Voltage Withstand Level for a short duration (U kV rms, 50 Hz for 1 minute).



— Lightning Impulse Withstand Level (Up kV peak, 1.2/50 μs lightning impulse test wave)

— Switching Surge Withstand Level (Up kV peak, 250/2500 μs switching impulse* test wave)

**Definition of Insulation Level of the equipment.** The combination of Rated Voltage and Specified one Minute Power Frequency Withstand level, Lightning Impulse Withstand Level, Switching Impulse withstand Level for the Equipment together are called *Insulation Level of the equipment.*

The grading between the Insulation Level of the equipment, Protective Level of Surge Arrester and the insulation levels/protective levels of the other equipment and surge arresters at the same voltage level, the grading between various voltage levels in the Network is called *Insulation Co-ordination.*

**Steps in Insulation Co-ordination**

1. Decide Equipment Insulation Level.
2. Decide Protective Level of Surge Arrester.
3. Co-ordination 1 and 2 for each equipment.
4. Co-ordination 3 for various equipment at the Voltage Level.
5. Co-ordination 3 between at various Voltage Levels.

The withstand levels of the equipment are co-related with the rated voltage of the equipment and the test values for type test and routine test and with the protective levels provided by the protective device (surge arrester, spark gap, surge absorbers, overvoltage relays, etc.) It is not economical/possible to design each equipment to withstand full lightning surge/switching surge/temporary overvoltage occuring in the network. Certain protective devices like Surge Arresters, Spark-gaps, Surge Absorbers, Overvoltage Relays are provided. These protective devices have certain protective levels against specified voltage waveforms.

Surge Arresters divert the switching surges/lightning surges above the protective level to earth within a few microseconds and protect the equipment against insulation failure. Spark gaps (coordinating gaps flashover externally during a voltage surge and protect the equipment insulation.

**Table 18.2. Overvoltages and Protective Devices**

**Temporary-Power-frequency overvoltages**

— Lasts for a few seconds to a few minutes

— Magnitudes approximately over 1.1 pu, phase to ground, rms

— Protection by inverse-overvoltage relay and opening of breakers

— Neutral earthing at each voltage level is necessary to avoid overvoltages in healthy phases single line to ground faults and arcing grounds.

**Switching Overvoltage Surges***

— Occur during circuit breaker operation while breaking of inductive currents, restrikes in C.B. while breaking capacitive currents, closing unloaded EHV AC lines, etc.

— Represented by standard 250/2500 μs Switching Impulse Test wave. Each EHV Equipment should have withstand capability against Standard Switching Impulse of specified peak and test conditions.

— Magnitude of test voltage are taken from standard tables.

— Circuit-breakers should be suitable for switching duty so that switching overvoltages are within specified limits (*e.g.* 2 pu peak).

— Surge arresters and Surge Suppressors are used for protection.

— Neutral Earthing dissipates overvoltage to earth and helps the system insulation.

* The word *Impulse* is used for test waves produced in laboratory by means of an impulse generator. The word *surge* is for the wave in power system.

**Lightning Overvoltage Surges**

— Occur due to lightning strokes or discharges on overhead lines, outdoor equipment and surges travel through conductors.

— Represented by 1.2/50 μs Impulse test wave

— Magnitude of test voltages are taken from standard tables.

— Protection by Overhead Shielding Wires, Surge Arresters

— Neutral Earthing dissipates the voltage surge to earth.

— Each substation equipment has assigned value of Lightning Impulse Withstand Level. (above the Protective Level of SA.

*The word *Surge* is used for the transient voltage waves occuring in the network.

### Basic Approach to Insulation Coordination In Power Systems

The rated voltages, withstand levels of equipment insulation are coordinated with the protective levels of the surge arresters such that protective levels are *less than* the withstand level with *certain protective margin.* This co-ordination between Insulation Levels of the equipment and protective levels of surge arresters is further coordinated for various equipments at the same voltage level and further for equipment at various voltage levels. Such a grading of withstand values and the protective levels of surge arresters at various voltage levels is called *Insulation Coordination.*

IEC (International Electrotechnical Commission) and IS (Indian Standards) Specification on Insulation Co-ordination on High Voltage Equipment; High Voltage Testing specify the values of

1. Nominal Power Frequency System Voltages
2. Highest Power Frequency System Voltages
3. Required Lightning Impulse Voltage Levels
4. Required Switching Impulse Voltage Levels
5. Protective Levels by Surge arresters
6. Withstand Levels of the Equipment against 2, 3, 4

System Designers/Consultants select the Insulation Levels at each voltage level from the Standards. These are coordinated for the entire Network having various voltage levels. The Equipment Insulation and Surge Arrester Protection Levels are graded (coordinated). The Equipment specifications are based on the coordinated values.

## 18.2. TERMS AND DEFINITIONS

1. **Insulation Level of an Apparatus.** A combination of withstand values both power frequency and impulse voltages which characterise the insulation of that apparatus with regard to the capability of withstanding dielectric stresses.

2. **Highest Voltage of Equipment/Apparatus.** The highest phase to phase voltage for which the equipment/equipment is designed; it corresponds to the Highest Power Frequency Phase to Phase System Voltage ($U_m$ rms).

3. **Over Voltage.** Any time dependant voltage (U) exceeding the value ($\sqrt{2}/\sqrt{3}\, U_m$) instantaneous, phase to ground or ($\sqrt{2}\, U_m$) instantaneous phase to phase.

$$U > \sqrt{2}/\sqrt{3}\, U_m \text{ instantaneous, phase to ground}$$

$$U > \sqrt{2}\, U_m \text{ instantaneous, phase to phase.}$$

4. **Phase to Phase per unit overvoltage.** The ratio of peak of phase to phase actual voltage (Up) to peak of highest phase to phase voltage of the equipment

$$\text{PU Overvoltage} = \frac{U_p \text{ phase to phase}}{\sqrt{2}\, U_m \text{ phase to phase}} \text{ p.u.}$$



5. **Protective Level of the Protective Device.** The highest peak value of voltage that should not exceed at the terminals of the protective device when standard impulse voltage wave is applied to the installation under specified conditions of test.

6. **Withstand Level of Apparatus/Equipment.** The value of Standard test wave (power frequency/ or impulse) which the Equipment/Apparatus is assigned to withstand under specified test conditions.

7. $$\text{Protective Margin} = \begin{bmatrix}\text{Protective Level}\\ \text{of Surge Arrester}\end{bmatrix} - \begin{bmatrix}\text{Withstand level}\\ \text{of the Apparatus}\end{bmatrix}$$

8. **Surge Arrester (Lightning Arrester).** A protective device which discharges excess voltage surges to earth and provides protection to the power system apparatus/equipment subjected to overvoltage surge.

Types : 1. Gapped SiC Arresters (Valve Type Arresters)
2. Gapless ZnO Arresters (Metal Oxide Arresters).

9. **Insulation Coordination.** Grading of Withstand Levels of Apparatus/Equipment with the Protective Levels of Surge Arresters and co-ordination at the entire voltage level and various other voltage levels.

10. **Switching Overvoltage Factor K of the switching duty**

$$K = \frac{\begin{bmatrix}\text{Actual } U \text{ peak phase to ground voltage}\\ \text{value during switching duty}\end{bmatrix}}{\text{Peak rated Highest System Voltage phase to ground}}$$

$$K = \frac{\text{Actual voltage phase to ground, peak}}{\text{Rated Highest System Voltage, phase to ground, peak}}.$$

11. **Switching Overvoltage.** The overvoltage surge produced in the system inductance/capacitance by opening/closing operation of circuit breaker.

12. **Temporary Power Frequency Overvoltages.** The overvoltage of 50 Hz waveform produced by load throw-off, faults, resonance, poor voltage regulation by OLTC/Shunt Compensation etc.

13. **Spark Gap, Co-ordinating Gap.** An adjustable air gap with lower flashover value than the insulator and placed in parallel with the equipment insulator for protection against voltage surge. [Spark gap was the basic protection before 1960s when Surge Arresters were not under development. Spark Gap characteristics are *not exact* and can have variation of ± 30% depending upon weather conditions and shape of surge].

14. **Overhead Shielding Wire.** A stranded and earthed galvanised steel conductor located above the transmission line conductors/outdoor busbars/outdoor equipment etc. with sufficient clearance. The Overhead Shielding conductor is connected to earth electrode via another earthing connector at each galvanised steel structure/transmission tower.

15. **Underground Earthing Mat (Mesh).** The horizontal underground mesh of welded steel rods and vertical earth electrodes which together gives low earth-resistance earthing system for Substations/Power Stations/Towers/Installations.

16. **BIL-Basic Impulse Insulation Levels.** Reference levels expressed in kV peak (crest) of 1.2/50 μs standard lightning impulse wave. The apparatus withstand characteristics should be above the BIL.

17. **Critical Flashover Voltage (CFO).** Peak impulse voltage for a 50% probability of flashover for a particular apparatus.

18. **Impulse ratio** for flash over or failure of insulation

$$= \frac{\text{Peak value of impulse voltage}}{\text{Peak value of power frequency voltage wave}}$$

to cause the flash over or failure of insulation.

## 18.3. CHOICE OF INSULATION LEVELS OF SUB-STATION EQUIPMENT

The insulation of substation equipment should withstand the over-voltages occuring due to internal and external causes.

The over-voltages are two categories :

— Power frequency voltages

— Impulse voltage surges due to lightning and switching.

The temporary power-frequency over-voltages occur due to regulation Ferranti, effect, load throw, etc.

The performance of insulation is verified by power frequency tests and impulse tests.

The surge arresters (lightning arresters) divert the transient overvoltages to earth and protect the sub-station insulation.

To achieve the desired insulation levels in the sub-station, following conditions should be satisfied :

1. Clearances should be as per recommendations of standards. These clearances are based on specified impulse withstand levels.
2. Each equipment should have specified impulse withstand level.
3. Surge arresters should be of specified protective level.
4. The protective ratio and protective margin should be correctly selected such that equipment design is economical and flash over/damage does not cause major damage to costly and important equipment.

**Table 18.3. Insulation Levels of Sub-station Equipment**

| *Normal Voltage line to line $U_m$* | *Highest system voltage (line to line) kV r.m.s. $U_m$* | *Impulse withstand test dry with standard full wave, + ve and negative polarities kV (crest)* | *1 minute Power frequency withstand under standard condition kV r.m.s.* |
|---|---|---|---|
| kv r.m.s | | | |
| 3.3 | 3.6 | 45 | 21 |
| 6.6 | 7.2 | 60 | 27 |
| 11 | 12 | 75 | 35 |
| 15 | 17.5 | 95 | 45 |
| 22 | 24 | 125 | 55 |
| 33 | 36 | 170 | 75 |
| 47 | 52 | 250 | 105 |
| 66 | 72.5 | 325 | 140 |
| 88 | 100 | 450 | 182 |
| 110 | 123 | 550 | 230 |
| 132 | 145 | 650 | 275 |
| 150 | 170 | 750 | 325 |
| 220 | 245 | 1050 | 460 |
| 400 | 420 | 1550 | 680 |



## 18.4. PROTECTIVE RATIO, PROTECTIVE MARGIN

The protection of equipment against impulse voltages waves by means of Surge arresters is expressed in terms of Protective Margin.

$$\text{Protective Ratio} = \frac{\text{Impulse Withstand Level of Equipment, kVp}}{\text{Protective Level of Surge Arrester, kVp}}$$

Separate protective ratio is specified for

(1) Lightning Impulse wave. (2) Switching Impulse wave.

Protective Ratios are usually above 1.2.

$$\text{Protective Margin} = \begin{bmatrix}\text{Equipment withstand} \\ \text{level}\end{bmatrix} - \begin{bmatrix}\text{Protective level of} \\ \text{Surge Arrest}\end{bmatrix}$$

Protective Margin may be expressed in terms of per cent of Equipment Withstand level

Protective levels are different for Lightning Impulse and Switching Impulse, *e.g.*

$$\frac{\text{Lightning Impulse Voltage withstand level}}{\text{Switching Impulse withstand level}} = 1.2$$

### PART I. Lightning Over-voltages

## 18.5. LIGHTNING

Benjamin Franklin (1706-90) performed his famous experiment (1745) of flying kite in thunder cloud. Before his discovery the lightning was considered to be "Act of God". Frankling proved that the lightning stroke is due to the discharge of electricity. Franklin also invented lightning rods to be fixed on tall buildings and earthed to protect them from lightning strokes. Hence Franklin is a pioneer scientist in this field. *The large spark accompanied by light produced by an abrupt, discontinuous discharge of electricity through the air, from the clouds generally under turbulent conditions of atmosphere is called lightning.*

Representative values of a lightning stroke :

| | |
|---|---|
| Voltage | $2 \times 10^8$ volts 200, MV (peak) |
| Current | $4 \times 4^4$ amp. |
| Duration | $10^{-5}$ sec. |
| kW | $8 \times 10^9$ |
| kWh | 22 |

$$\text{Energy} = \int u \cdot t \, dt = 22 \text{ kWh}$$

**Static induced charges.** An overhead conductor accumulate statically induced charge when a charged clouds come above the conductor. If the cloud is swept away from its place, the charges on the conductor is released. The charge travels on either sides giving rise to two travelling waves. The earth wire does not prevent such surges.

Another curious phenomenon is the unpredictable paths of lightning strokes. Normally they try to reach the earth and are therefore intercepted by lightning rods, trees, tall structures etc. Empire State Building of New York has been hit by several strokes. However some lightning strokes do not observe any rules. It has been reported that some strokes have travelled horizontally in all sorts of haphazard fashion.

*B* type stroke [Fig. 18.3 (*b*)] occurs due to sudden changes in charges of the cloud. If cloud 1 suddenly discharges to cloud 2, there is a sudden change in the charge on cloud 3. A discharge between cloud 3 and earth is called *B* stroke. Such stroke does not hit lightning rod, or earth wire. Therefore, no protection can be provided to the OH line against such strokes.

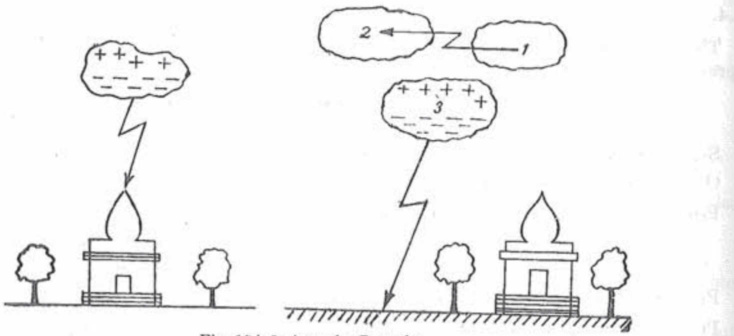


Fig. 18A-3. *A* stroke *B* stroke.

(*a*) A stroke occurs between charged cloud and earth. The lightning conductor or earth wire attracts such stroke.

(*b*) *B* stroke occurs because of sudden change in charge conditions in the clouds. Lightning conductor, or earth wires do not attract such strokes.

**Attractive effect of OH Ground Wire and Earth Rods (MASTS).** Earth rods (also called lightning rod) are placed on tall buildings. These are connected to the earth. The positive charges accumulate on the sharp points of the lightning rods, thereby the lightning strokes are attracted to them. The earth wires are placed above the OH transmission lines. At every tower this wire is grounded. The positive charges accumulate on this wire. The negatively charged strokes are attracted by the earth wire. In absence of the earth wire the lightning stroke would strike the line conductors causing a flashovers in transmission line.

Earth wires do not provide 100% protection. Weak strokes are not attracted by earth wires. *B* type strokes are also not attracted. However for the most dangerous "direct strokes" earth wire has proved to be a very good solution.

Practical experience has shown that earth wires have a shielding angle. The conductors coming in the shielded zone are protected against direct strokes. Shielding angle is between 30° to 40°. An angle of 35° is supposed to be satisfactory and economical for OH lines.

## 18.6. OVERHEAD SHIELDING SCREEN (*Earthed*)

The sub-station equipment are protected from direct lightning strokes by one of the following :

1. **Overhead shielding screen** (***Earthed***). Covering the outdoor sub-station and the overhead lines approaching the sub-station.

2. **Lightning Masts** installed at strategic locations in the switchyard. The tower-top is earthed. Mast is an independant structure.

Both the above methods are being used in India.

Lightning masts are preferred for outdoor switchyards upto 33 kV. For 66 kV and above, the lightning masts become too tall and uneconomical. The overhead shielding wires are preferred because they give adequate protection and the height of structures in the sub-station provided with overhead shielding wires is comparatively less than that with the of lightning masts.

**Overhead shielding screen** (***Earthed***). The entire switchyard is provided with earthed overhead shielding screen. The size of conductor is usually 7/9 SWG, galvanised steel round stranded conductor.

Transmission line conductors are protected by over head shielding conductor (earthed). The shielding angle ($\alpha$) defined as follows. A vertical line is drawn from the earth wire. Angle $\alpha$ is plotted on each side of this vertical line. The envelope within angle $2\alpha$ is called zone of protection.

The shielding angles are as follows :

American practice : 30°

British practice : 45°

The clearance between phase conductor and overhead shielding wire should be more than minimum phase to earth clearance.

OH = Overhead, above the conductor/apparatus. Ground = Earth.



## 18.7. LIGHTNING STROKE ON OH LINES (OVERHEAD LINE)

These can be the following :

(1) Direct strokes on line conductor. (2) Direct stroke on Tower Top.

(3) Direct stroke on Ground wire. (4) Indirect stroke or B stroke on OH lines conductor.

**Direct Strokes on OH conductors.** These are most harmful. The voltage being of the order of several million volts, the insulators flash-over, puncture and get shattered. The wave travels to both sides shattering line insulators, until the surge is dissipated sufficiently. The wave reaches the sub-station and produces stress on equipment insulators. Luckily, these strokes are prevented from striking the line conductor. All high voltage OH lines are protected by earth conductors. The outdoor switchyards are provided with overhead mesh of earth conductors. This mesh covers the complete switchyard.

**Direct strokes on tower-top**

Let, $L$ = Inductance of tower. $i$ = Current in tower.

$R$ = Effective resistance of tower. $e$ = Voltage surge between tower-top and earth.

$$e = L\frac{di}{dt} + Ri \text{ volts}$$

Let $$\frac{di}{dt} = 10 \text{ kA}/\mu\text{s}.$$

$$R = 5 \text{ ohm.} \quad L = 10\ \mu\text{H}$$

Then $e$ = 200,000 V. This surge voltage appears between the tower-top and earth. The line conditions are virtually at earth potential because of neutral grounding. Hence this voltage appears between line conductors and tower-top. If this surge voltage exceeds impulse flash-over level, a flash-over occurs between tower and line conductor. Hence $R$ is kept low for each tower.

A direct stroke on earth wire in the mid-span can cause a flashover between line conductor and earth wire or line conductor and tower.

Indirect strokes on line conductor can have the same effect as direct stroke on conductor. Indirect strokes are more harmfull for distribution lines but are not significant for EHV lines. Other factors are low tower footing resistance insulation level of lines. For lines rated 110 kV and above, the line insulation is high and back flashovers are rare. For line between 11 kV, 33 kV the insulation of lines is relatively low and back-flashovers are likely to occur.

## 18.8. PROTECTIVE DEVICES AGAINST LIGHTNING SURGES

**Table 18.4**

| *Device* | *Where applied* | *Remarks* |
|---|---|---|
| Rod gaps | Across insulator string, bushing insulators. Support insulators | — Difficult to co-ordinate<br>— Flashover voltage varies by ± 30%<br>— Create dead shot circuit<br>— Cheap |
| Overhead Ground Wires (earthed) | — Above overhead lines<br>— Above the sub-station area | Provide effective protection against direct strokes on line conductors towers sub-station equipment. |
| Vertical Masts | — In sub-stations | — Instead of providing overhead shielding wires |
| Lightning Spikes/Rods (earthed) | — Above tall buildings | Protect Buildings against direct strokes. Angle of Protection $\alpha$ = 30° to 40° |
| Lightning Arresters (Surge Arresters) | — On incoming lines in each sub-station | — Diverts over-voltage to earth without causing short-circuit |
| | — Near terminals of Transformers and Generators | — Used at every voltage level in every sub-station and for each line |
| | — Pole mounted on distribution lines. | — Phase to ground |
| Surge Absorbers | — Near rotating machines or Switchgear<br>— Across series reactor, valves. | Resistance Capacitance Combination absorbs the over voltage surge and reduces steepness of wave. |

## 18.9. ROD GAPS OR SPARK GAP

The simplest protection of line insulators, equipment, insulators and bushings is given by Rod Gaps or Coordinating Gaps. The conducting rods are provided between line terminal and earthed terminal of the insulator with an adjustable gap. The medium of gap is air. The rods are approximately 12 mm dia or square. The gap is adjusted to breakdown at about 20% below flash-over voltage of insulator. The distance between arc path and insulator should be more than 1/3 of the gap length, *i.e.* $l_1 > l/3$ (Fig. 18.4). Refer Table 18.4 for gap-settings.

Precise protection is not possible by rod gaps. The breakdown voltage varies with polarity, steepness and wave-shape, weather. The power frequency currents continue to flow even after the high voltage surge has vanished. This creates an earth fault only to be interrupted by circuit breaker. Operation of rod gap, therefore, leads to discontinuity of supply. The advantage of gap is low cost and easy adjustment on site. For more precise operation, surge arresters are used.

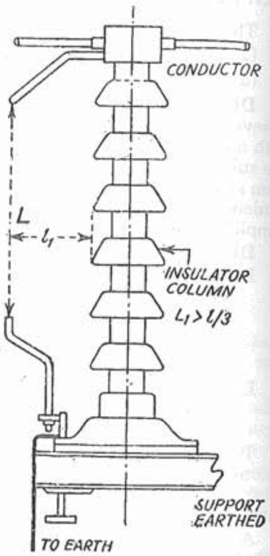


Fig. 18.4. Rod gap.

**Horn Gap.** The gap between horns is less at the bottom and large at the top. An arc is produced at the bottom during high voltage surge. This arc commutes along the horn due to electromagnetic field action and length increases. The arc may blow out.

**Impulse Ratio.** Impulse ratio of a protective device is the ratio of breakdown voltage on specified impulse wave to breakdown voltage at power frequency.

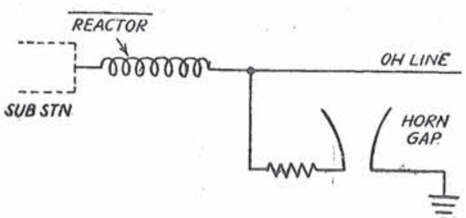


Fig. 18.5. Horn gap.

Typical impulse ratios :

| | | |
|---|---|---|
| Sphere Gap | : | 1 |
| Rod Gap | : | 1.6 to 3 |
| Horn gap | : | 2 to 3. |

## 18.10. SURGE ARRESTERS (LIGHTNING ARRESTERS)

*Surge Arresters* are usually connected between phase and ground (Fig. 17.1) in distribution system ; near the terminals of large medium voltage rotating machines and in HV, EHV, HVDC sub-stations to protect the apparatus insulation from lightning surges and switching surges.

The resistor blocks in the surge arrester offer low resistance to high voltage surge and divert the high voltage surge to ground. Thereby the insulation of protected installation is not subjected to the full surge voltage. The surge arrester does not create short-circuit like rod gaps and retains the residual voltage across its terminals.



Surge Arrester discharges current impulse surge to earth and dissipates energy in the form of heat.

After discharging the impulse wave to the earth, the resistor blocks in the surge arrester offers a very high resistance to the normal power frequency voltage and the arrester acts as open circuit. Surge arresters are not against temporary power frequency over voltages. They provide protection against surge voltage waves.

At present the following types of surge arrester are used :

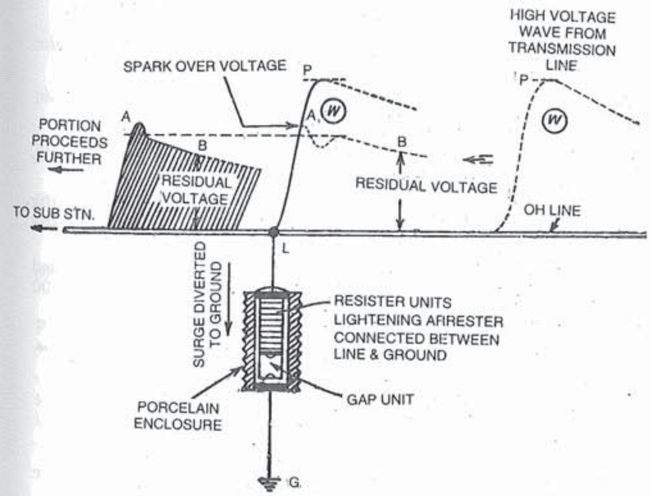
1. **Gapped Silicon-carbide Surge Arresters** called valve type or conventional Gapped Arresters. These consist of silicon-carbide discs in series with spark gap units.

2. **Zinc-Oxide Gapless Arresters** called ZnO Arresters or Metal-oxide Arresters. These are gapless and consist of zinc-oxide discs in series. ZnO arresters have superior V/I characteristic and higher energy absorption level. They are preferred for EHV and HVDC installations.

### Gap Type SiC Arrester

Surge arrester is connected between phase and earth. It consists of silicon-carbide (SiC) resistor elements in series with gap elements. The resistor elements offer non-linear resistance such that for normal frequency power system voltage the resistance is high. For discharge currents the resistance is low. The gap unit consist of air gaps of appropriate length. During normal voltages the surge arrester does not conduct. When a surge-wave travelling along the line reaches the arrester, the gap breaks down. The resistance offered being low the surge is diverted to the earth. After a few μ seconds the surge vanishes and normal power frequency voltage is set up across the arrester. The resistance offered by resistors to this voltage is very high. Therefore, arc current in gap units reduces and voltage across the gap is no more sufficient to maintain the arc. Therefore, the current flowing to the earth is automatically interrupted and normal condition is restored. Thus, high voltage surge is discharged to earth. Hence the insulation of equipment connected to the line is protected.*

Fig. 18.6 illustrates the operation of a surge arrester. When a lightning surge or switching surge travelling along the transmission line reached the terminal of the surge arrester, at a particular




*W* Surge travelling along OH line
*P* Peak of impulse wave
*A* Voltage at which LA sparks over
*B* Average residual voltage.

Fig. 18A-6. Illustrates the operation of Surge Arrester.

* Refer Sec. 17.2 for Location of Surge Arresters.

voltage (instantaneous value) A, depending upon steepness of wave front, the SA sparks over. The voltage is called impulse sparkover voltage. Hence the surge is diverted to earth through the SA and insulation on sub-section side is not subjected to peak voltage *P*. After breakdown the voltage across LA does not drop to zero like in rod gaps because of the series resistors. The voltage across the gap remains at residual value *B* for a short time. *Hence line to earth voltage remains at residual value during discharge.* A portion of wave proceeds further but the peak and steepness of wave front are reduced.

After short time of the order of some microseconds, the wave is discharged and normal frequency voltages appear across the SA. The normal voltage is not enough to maintain the arc in the gap units and the arc extinguishers. The SA restores the original condition (Fig. 18.8).

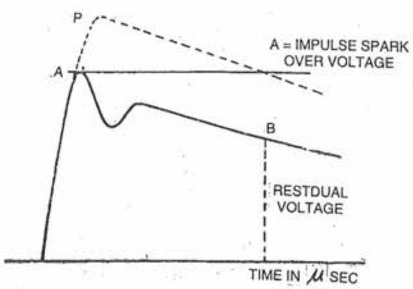



Fig. 18A-7. Voltage characteristic of surge arrester.

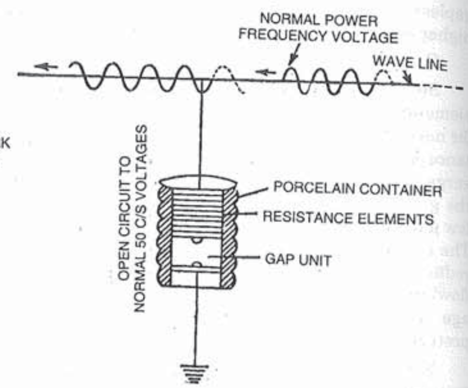



Fig. 18A-8. SA restores normal condition as the normal voltage is not enough to maintain the arc in the gap unit. The resistance offered to low currents by resistor elements is high — Gap is blown out by magnetic field.

**Classification of Surge Arresters**

The classification is based on voltage, current and energy capability. (Ref. Table 18.5).

(1) **Station Type SA.** This has highest capability for energy dissipation and lowest protective level.

(2) **Line Type Surge Arrester** (Intermediate type). These are generally used for protecting large transformers, intermediate sub-stations. These are smaller than station transformers. Rating upto 5000 A.

(3) **Distribution type and Rural or Secondary type surge arresters.** These are intended for pole mounting in distribution circuits for protection of distribution transformers. Rating : 2500 A and 1500 A. (Refer Table 18.2).

**Table 18.5. Classification of Surge Arrester**

| | *Station type* | *Line type* | *Distribution type* |
|---|---|---|---|
| Standard normal discharge current (amperes) peak | 10,000 | 5000 | 2500 : 1500 |
| Voltage rating kV r.m.s. | 3.3 — 245 | 3.3 — 123 | Upto 3.3 |
| Application (Ref. Sec. 18.6) | Large power-Station and Large Sub-station | Intermediate, Large Sub-station, Medium Power Station | Distribution system ; Rural Distribution |

Refer Definitions in Sec. 18.11.



## 18.11. SURGE ARRESTER SPECIFICATIONS AND TERMS

1. **Surge arrester** is a device designed to protect electrical equipment from transient high voltage, to limit the duration and amplitude of the follow current.

2. **Non-linear resistor.** The part of the arrester which offers a low resistance to the flow of discharge currents thus limiting the voltage across the arrester terminals and high resistance to power frequency voltage, thus limiting the magnitude of follow current.

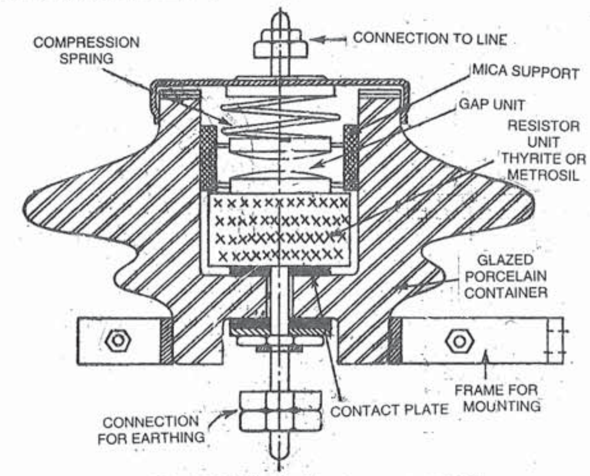



Fig. 18A-9. Distribution type surge arrester.

3. **Rated voltage of the arrester.** Maximum permissible RMS voltage between the line terminal and earth terminal of the arrester as designated by the manufacturer.

We have to note this term carefully. For all the other apparatus, the rated voltage is generally phase to phase. For Surge Arrester rated voltage is in terms of phase to ground. (Ref. Sec. 18.11).

4. **Follow current.** The current which flows from connected power source through lightning arrester following the passage of the discharge current.

5. **Normal Discharge Current.** Surge current which flows through the SA after the spark over, expressed in crest value (peak value) for a specified wave. This term is used in classifying the SA (station type, line type, distributor type).

6. **Discharge Current.** The surge current which flows through the arrester after the spark over.

7. **Power frequency spark-over voltage.** r.m.s value of power frequency 50 Hz voltage applied between the line and earth terminals of arrester and earth which causes sparkover of the series gap.

8. **Impulse spark-over voltage.** Highest value of voltage attained during an impulse of given polarity, of specified wave shape applied between the line terminal and earth terminal of an arrester before the flow of discharge current.

9. **Residual voltage (Discharge voltage).** The voltage that appears between the line terminals and earth, during the passage of the discharge current.

10. **Rated current.** Maximum impulse current at which the peak discharge residual voltage is determined.

11. **Coefficient of Earthing**

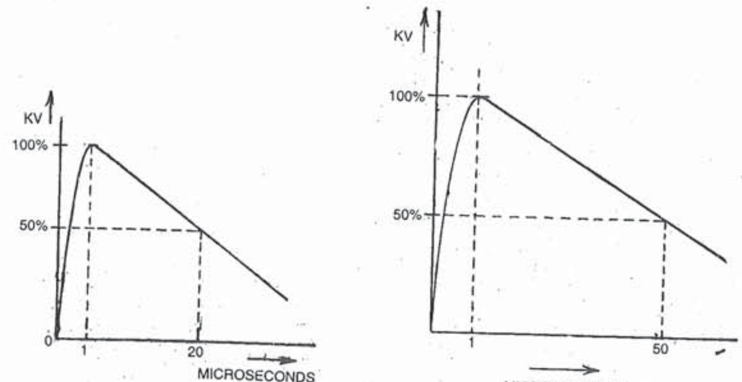
$$= \frac{\text{Highest r.m.s. voltage of healthy phase to earth}}{\text{Phase to phase normal r.m.s. voltage}} \times 100$$

(during earth fault on one phase).

## 18.12. TESTS ON SURGE ARRESTERS

The standard impulse test waves are shown in Fig. 18.10 (*a*) and (*b*). Tests performed on SA are the following :

1. 1/50 impulse sparkover test.
2. Wave front impulse sparkover test.
3. Peak discharge residual voltage at low current.
4. Peak discharge residual voltage at rated diverter current.
5. Impulse current withstand test.
6. Switching-impulse voltage test.
7. Discharge capability of durability.
8. Transmission line discharge test.
9. Low current long-duration test.
10. Power duty cycle test.
11. Pressure-relief test.




(*a*) 1/20 Impulse current wave (*b*) 1/50 Impulse wave (Voltage wave)

Fig. 18.10

## 18.13. RATED VOLTAGE OF SURGE ARRESTER

It is the maximum power frequency voltage between the terminals of the Surge Arrester at which the Surge Arrester is capable of performing its rated duty. For a Surge Arrester to be connected phase to earth, the minimum required voltage is calculated as follows.

$U_n$ = Nominal system voltage r.m.s. phase to phase

$U_m$ = Highest system voltage, phase to phase

$U_a$ = Rated voltage of the Surge Arrester, kV rms (phase to ground)

$C_e$ = Coefficient of earthing.



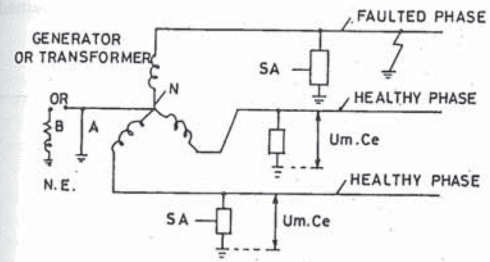
The surge arrester pole is connected between phase and ground. The rated voltage should be more than the phase to ground voltage on unfaulted phase during a single line to ground fault on any other phase. (Ref. Sec. 18.11.)

During a single phase to earth fault on one phase, the phase to ground voltage of other two healthy phases rises to $(U_m \cdot C_e)$. The Rated Voltage of surge arrester $(U_a)$ should be more than $(U_m \cdot C_e)$ rms kV continuous across the terminals.

$$U_a > U_m \times C_e \text{ kV rms}$$

**Note :** $U_a$ is across the terminals of the Surge Arrester Pole. Surge Arrester should be capable to perform its rated duties at rated rms voltage $U_a$ across its terminals. The leakage currents through the surge arrester pole during normal system voltage and after diverting the surge should be only a few mA.

In a system without neutral-earth, the phase to earth voltage of phase $A$ and phase $B$ rises to $3\ U_m$ during a single phase to earth fault ($F$) on phase $C$. In an neutral earthed system the voltage of healthy phases rises to $C_e \cdot U_m$.




SA-1— in unfaulted phase, during a single phase to earth fault *F*.
A — Solid or Effective Neutral Earthing : $C_e < 0.8$
B — Non-Effective Neutral Earthing : $0.8\ C_e < 1$
$U_m$ — Highest phase to phase power system voltage
$C_e$ — Coefficient of Earthing

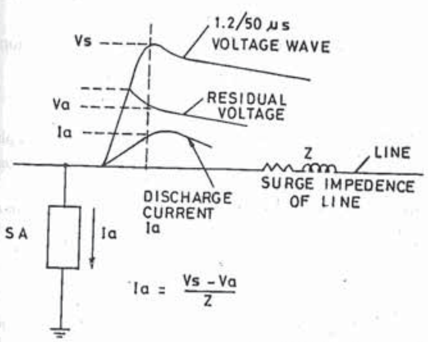
Fig. 18 A. 13. Explaining the voltage across the Surge Arrester

## 18.14. COEFFICIENT OF EARTHING ($C_e$) is the ratio :

$$C_e = \frac{\text{Highest phase to ground voltage of healthy phase}}{\text{Phase to phase voltage } U_m \text{ rms}} \times 100$$

measured during a single phase to ground fault.

For Non-Effectively Earthed System $C_e = 1$.




$V_s$ = Surge Voltage, kV*
$V_r$ = Residual Voltage of SA, kV*
$Z$ = Surge Impedance of transmission line, on m
$I_a$ = Discharge current through the SA, kA*
*Instantaneous values from waveform

Fig. 18.14. Explaining Surge Current Calculation.

### $C_e$ For Effectively Earthed System

For *effectively earthed* system, (solid neutral earthed system) Coefficient of earthing $C_e < 0.8$. Therefore, the Surge arrester rated voltage is

$$U_a > 0.8\ U_m \text{ rms}$$

*Surge Voltage* ($V_s$). *kV instantaneous* is taken as 2.5 times Critical Flashover Voltage (CFOV) of Line Insulation. Therefore Discharge Current $I_a$ is given by :

$$I_a = \frac{2.5\text{ CFOV of Line–Residual Voltage of Arrester}}{\text{Surge Impedance of Line}} = \frac{2.5\text{ CFOV} - V_r}{Z}$$

## SUMMARY

**Insulation Coordination :** Coordination between Withstand Levels of Equipment, Protective Levels of protective devices, with adequate protective margin such that overall economy is obtained and least damage is caused to the electrical installation during overvoltage surges.

**Table of Summary Type of Overvoltages ; Protections/Time, Withstand, Tests.**

| Temporary Power Frequency Overvoltage (ms or s) | Lightning Surge (μs) | Switching Surge (μs) |
|---|---|---|
| ↓ | ↓ | ↓ |
| Overvoltage Relay & CB < 70 ms | Surge Arrester app. < 1.2 μs | Surge Arrester app. < 100 μs |
| ↓ | ↓ | ↓ |
| Power Frequency Voltage Withstand Level kV rms | Lightning Surge Withstand Level kV peak | Switching Surge Withstand Level kV peak |
| ↓ | ↓ | ↓ |
| One minute P.F. Voltage Withstand Test | Lightning Impulse Test Withstand Test | Switching Impulse Withstand Test |

Peak Value = Crest in kV instantaneous.

**Basic Impulse Insulation Level** (BIL) is reference level of the expressed in peak (crest) voltage value with standard 1.2/50 μs. Lightning impulse wave. Apparatus should be capable of withstanding test waves above BIL.

Other withstand levels get co-related with BIL as per applicable Standard Specifications (IEC/IS).

## QUESTIONS

1. State the difference between the Nominal System Voltage and Highest System Voltage. Give example.
2. Which are the Voltage Withstand Values assigned to a High Voltage Equipment ? Which are the corresponding tests for proving these Withstand Capabilities.
3. Explain the Protective Characteristic of a Surge Arrester against the Withstand Characteristic of Equipment on a Voltage/Time Curve.
4. Define the terms :
   — Insulation Coordination
   — Rated Voltage of Surge arrester
5. A 132 kV Busbar needs a surge arrester protection. The system neutral is non-effectively earthed. The surge impedance of the incoming line is 400 ohm. The highest system voltage is 145 kV rms ph. to ph. Calculate : (A) Voltage Rating of the Surge arrester for the Busbar Surge Protection. (B) Discharge Current corresponding to surge voltage Vs= 300 kV instantaneous, residual voltage $V_r = 250$ kV instantaneous.



6. Define: "Coefficient of Earthing." What is the significance of the coefficient of earthing in the selection of voltage rating of Surge Arrester ?
7. State the various protective installations for intercepting Lightning Surges. Sketch a typical wave of Lightning Surge. Explain operation of a ZnO Surge Arrester.
8. Explain the basic difference between the construction, operation and characteristics of a SiC Gapped Surge Arrester and ZnO Surge Arrester.
9. State the following for a 400 kV High Voltage Equipment :
   Withstand Levels to be Specified :
   — Name of proving test :
   — Names of Protective equipment.
10. What is *Shielding Angle* of an overhead ground wire ? What are the values as per American and European Practices ?
11. Explain the origin of Switching Overvoltage Surges. What are the time duration of a Switching Surges ? Define Switching Overvoltage Factor.
    During no-load closing of a 400 kV transmission line, the peak of switching over voltage in one phase was 880 kV peak. Calculate the switching over voltage factor. The highest system voltage is 420 kV rms.
12. Explain the function of (A) Preinsersion Resistors (B) Opening Resistors ; with a 400 kV Circuit Breaker.
13. Explain the causes of overvoltages at Medium High Voltages (< 33 kV) and the principle of Surge Absorber Protection for a Rotating Machine.

# 18-B

# *Neutral Grounding (Neutral Earthing)*

Introduction — Terms and Definitions — Ungrounded Systems — Disadvantages — Advantages of Neutral Grounding — Types of Neutral Grounding — Solid Grounding ; Reactance Grounding, Resonant Grounding, Resistance Grounding. Reactance in Neutral Connection — Arc Suppression Coil (Peterson Coil, Earth-Fault Neutraliser), Coefficient of Earthing. Generator Neutral Grounding — Earthing Transformer-Ratings of Neutral Device — Summary.

## 18.15. INTRODUCTION TO NEUTRAL GROUNDING

The three phase 50Hz AC power systems *with neutral grounding at every voltage level* are used for generation, transmission, distribution and utilization. The neutral points (star points) of star-connected 3 phase winding of power transformers, generators, motors, earthing transformers are connected to low resistance ground. (earth electrode/earth mat). Such a connection is called Neutral Grounding (Neutral Earthing).

Before 1950s the power systems were often without neutral grounding. Such systems were called *Ungrounded Systems.* Such systems experience repeated arcing grounds.* In ungrounded systems, insulation failures occur in several equipment, during single phase to ground faults elsewhere. The earth fault protection of ungrounded systems is difficult. Insulation failures may occur in several equipment and machines over entire voltage level during a single earth fault at remote location. The ungrounded systems must necessarily have equipment insulation withstand level corresponding to next higher system voltage to avoid cascade insulation failures. The ungrounded neutral system needs a costlier insulation system of next higher voltage level (*e.g.* 11 kV insulation for 6.6 kV Busbars and Motors, transformers, CTs, VTs, etc.).

*Ungrounded Systems* have *advantage* of negligible earth fault current but *disadvantage* of arcing grounds. Modern power systems are with grounded neutrals except some continuous process systems and essential protection/auxiliary supply systems where single phase to ground faults should not to trip entire bus supply.

*Equipment Grounding* is different from the Neutral Grounding. Equipment grounding is the connection between non-current carrying metallic parts in electrical installation to earth. By earthing the part, the voltage is within safe value even during earth fault. Equipment grounding is for Safety and for discharging earth fault currents effectively (till protection operates on earth fault and faulty part is disconnected).

## 18.16. TERMS AND DEFINITIONS

1. **Earthing or grounding.** Connecting to earth or ground.

2. **Neutral earthing or system neutral earthing (grounding).** Connecting to earth, the neutral point, *i.e.* the star point of generator, transformer, rotating machine, neutral point of a grounding transformer.

The calculations of third harmonic and zero sequence earth fault currents is covered in Ch. 23.

* Intermittent, repeating phase to ground arc through air insulation on overhead line/exposed conductor due to charging and discharging of phase to ground capacitance.



3. **Reactance earthing.** Connecting the neutral point to earth through a reactance.

4. **Resistance earthing.** Connecting the neutral point to earth through a resistance.

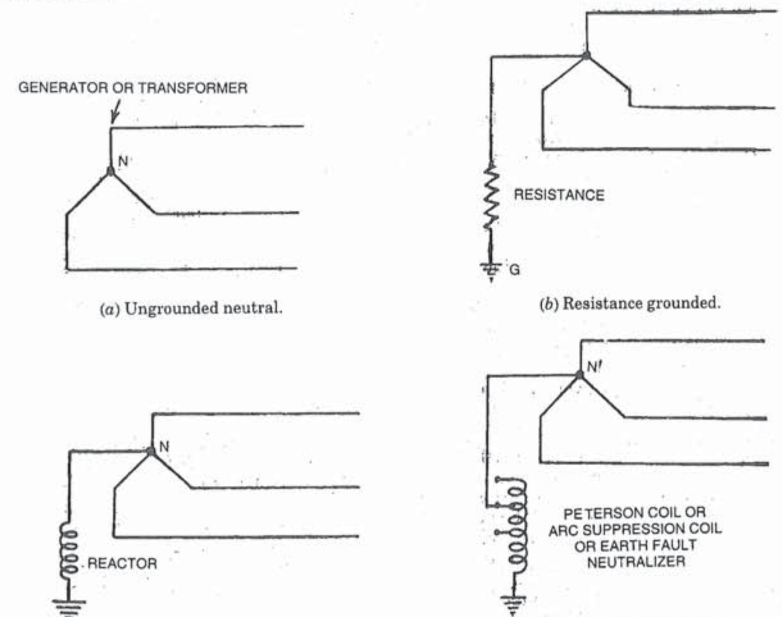
5. **Non-effective earthing.** When an intentional resistance or reactance is connected between neutral point and earth. Coefficient of earthing > 80%.

6. **Solid earth or effective earthing.** Connecting the neutral point to earth without intentional resistance or reactance, coefficient earthing < 80%.

7. **Resonant earthing.** Earthing through a reactance of such a value that power frequency current in the neutral or ground connection is almost equal opposite to power frequency capacitance current between unfaulted phases and earth. In this case the reactance between the neutral point and earth is selected to neutralise the power frequency capacitive current between line and earth. Resonant earthing is in fact a reactance earthing, with a selected value of reactance to match with line to ground capacitance.

8. **Coefficient of Earthing.** Refer Sec. 18.13

9. **Petersen coil, arc suppression coil, ground fault neutraliser.** All the three terms have the same meaning. The adjustable reactor (specially constructed) connected between neutral and earth, the reactance is such that power-frequency current between line and earth due to capacitance of healthy lines and earth is equal and opposite to the current in the earth connection. In other words, the reactor used in resonant earthing is called Peterson coil or arc suppression coil or earth fault neutralizer.




(*a*) Ungrounded neutral. (*b*) Resistance grounded. (*c*) Reactance grounding. (*d*) Resonant grounding.

Fig. 18B-1. Types of neutral grounding.

10. **Ungrounded system.** The system whose neutral points are not earthed. The system is also called Isolated Neutral System.

11. **Earth Fault Factor.** It is calculated at the selected point of the system for a given system. It is a ratio :

$$\text{Earth fault factor} = \frac{V_1}{V_2}$$

when $V_1$ = Highest rms phase-to-phase power frequency voltage of healthy phases during earth fault on another phase.

$V_2$ = rms phase to earth power frequency voltage at the same location with fault on the faulty phase removed

**Nature of the Problem**

Consider a high voltage line connected to supply and without load. Even if no currents are drawn by the load, the conductors of the system continue to charge the system capacitance alternately to positive and negative polarity. The distributed capacitance between phases and earth draw charging currents from the source. The charge is given by

$$Q = CV$$

where $Q$ = charge, coulombs

$C$ = capacitance, farads

$V$ = voltage, volts.

For high voltage systems, the capacitance and the charging currents are significant and the reactive power may be of the order of hundreds of kVAr. Therefore, the reactive kVAr influences the total kVA of the system. The reactive kVAr becomes very important and should be controlled. During ground faults, the reactive kVAr cause substantial flow of capacitance current flow with ground as a return path. Neutral grounding is a simple method of reducing such currents.

## 18.17. DISADVANTAGES OF UNGROUNDED SYSTEMS

In earlier years of the electrical power systems, the power systems were without neutral grounding. The following difficulties are encountered in ungrounded systems. Therefore, ungrounded systems are no more used.

1. **Arcing grounds.** The phenomena of arcing ground is commonly experienced with ungrounded systems. A temporary fault caused by falling on a branch, lightning surge, etc. creates an arc between phase conductor and ground. The arc extinguishes and restrikes in a repeated, regular manner. The phenomena is called "arcing ground". Arcing current is low due to high resistance of arc-path through air. But voltages of other two phases overshoot repeatedly.

Consider overhead line, $R, Y, B$ connected to the system at normal voltage.

Each line has an inherent distributed capacitance with respect to earth. Consider an earth fault on phase $B$. The distributed capacitance discharges through the fault when the gap between $F$ and ground breaks down. The capacitance, again gets charged and again discharged. Such repeated charging and discharging of line to ground capacitance resulting in repeated arcs between line and ground is called Arcing Grounds. Arcing ground produce severe voltage oscillations reaching three to four times normal voltage. Secondly, a temporary fault grows into a permanent fault due to arcing grounds. The problem of arcing ground is solved by earthing the neutral through a coil called Petersen coil or Arc suppression coil or earthing reactor.

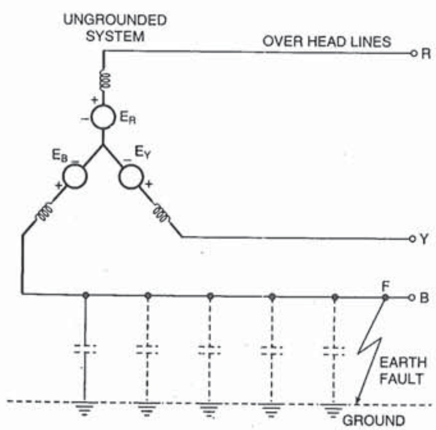



Fig. 18B-2. (*a*) Phenomena of Arcing Grounds. (The distributed capacitance gets changed and then discharged through the earth fault).



The charging currents, $I_B, I_Y$ are neutralised by $I_L$, the current flowing through the neutral connections, *i.e.*

$$I_R + I_Y + I_L = 0$$

Thereby the arc in the phase to ground fault is extinguished.

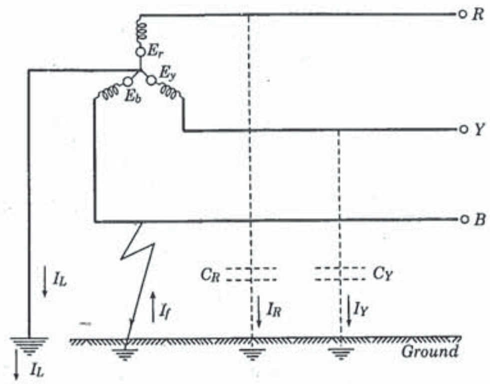



Fig. 18B-2. (*b*) Effect of Grounding.

2. In ungrounded systems, the voltage of healthy phases above earth is increased by $\sqrt{3}$ times when an earth fault occurs on a phase. This causes stress on the insulation of all the machines and equipment connected to the system. The voltage rise of the phase above earth is sustained and thereby insulation failure is likely to occur in connected machines, though fault current in arcing ground may be negligible.

Consider a system (Fig. 18B-3) in which one phase is faulted to ground. The potential of the phase becomes earth potential. Therefore, the voltage of healthy phases ($R$ and $Y$ above ground becomes equal to line voltage which is $\sqrt{3}$ times the phase voltage.

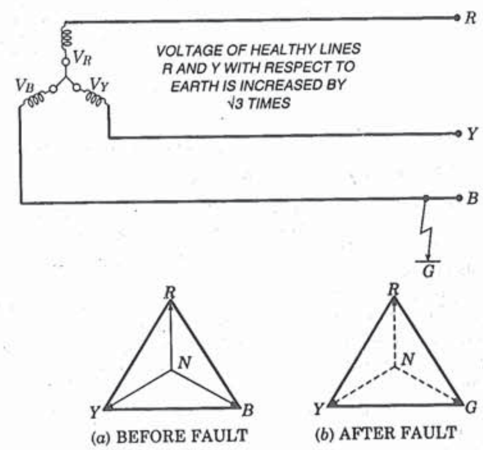



Fig. 18B-3. Effect of an earth fault on an ungrounded system.

Suppose a voltmeter is taken and the voltage of phases $R$, $Y$, $B$, is measured. During healthy state the voltages of phases $R$, $Y$, $B$ above earth will be equal to phase voltage. The voltages between $RY$, $YB$, $BR$ will be $\sqrt{3}$ time phase voltage. When an earth fault occurs on phase $B$, the voltage of $B$ with respect to earth becomes zero. The voltage of health phases $R$ and $Y$ with respect to ground are increased to $\sqrt{3}$ times their normal value. The phase to phase voltage $V_{RY}$, $R_{YB}$, $V_{BR}$ remains unchanged.

3. In ungrounded systems, earth faults cannot be easily sensed and the earth fault relaying becomes complicated. In grounded system, earth fault current is enough operate earth fault relay. Secondly, the current in neutral circuit can be used to operate earth fault relay (Refer Fig. 18.B-4)

4. The overvoltages due to induced static charges are not discharged to earth in ungrounded systems. The voltages due to lightning surges do not find path to earth.

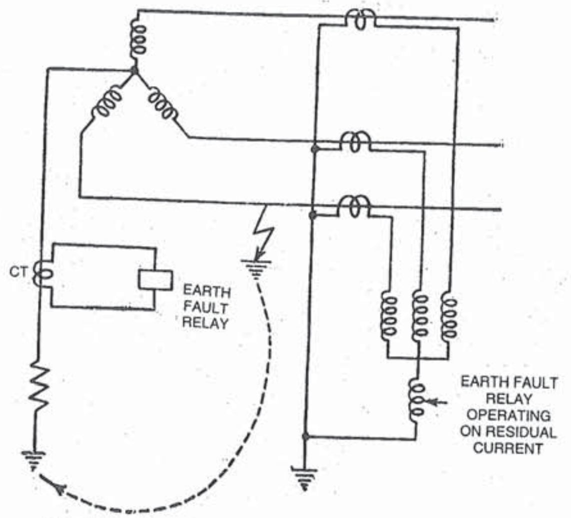



Fig. 18B.4. Neutral grounding is useful in earth fault relaying.

## 18.18. ADVANTAGES OF NEUTRAL GROUNDING

1. Arcing grounds are reduced or eliminated. The arcing ground current flowing through the neutral to ground connections is made almost equal and opposite to the capacitive current from healthy lines to ground. Thereby $I_L + I_R + I_Y = 0$ and arcing grounds are eliminated. The system is not subjected to overvoltage surge due to arcing grounds.

2. The voltages of healthy phases lines with respect to earth remain at normal value. They do not increase to $\sqrt{3}$ time normal value as in the case of ungrounded system.

3. The life of insulation is long due to prevention of voltage surges caused by arcing grounds. Thereby reduced maintenance, repairs, breakdowns. Improved continuity.

4. Stable neutral point.

5. The earth fault relaying is relatively simple. Useful amount of earth fault current is available to operate earth fault relay.

6. The over-voltages due to lightning are discharged to earth.

7. By employing resistance or reactance in earth-connection, the earth fault current can be controlled.

8. Improved service reliability due to limitation of arcing grounds and prevention of unnecessary tripping of circuit-breakers.



9. Greater safety to personnel and equipment due to operation of fuses or relays on earth fault and limitation of voltages.

10. Life of equipments, machines, installation is improved due to limitation of voltage. Hence overall economy.

## 18.19. TYPES OF GROUNDING

1. **Ungrounded system.** It is used no more. The neutral is not connected to earth. Also called insulated neutral system.

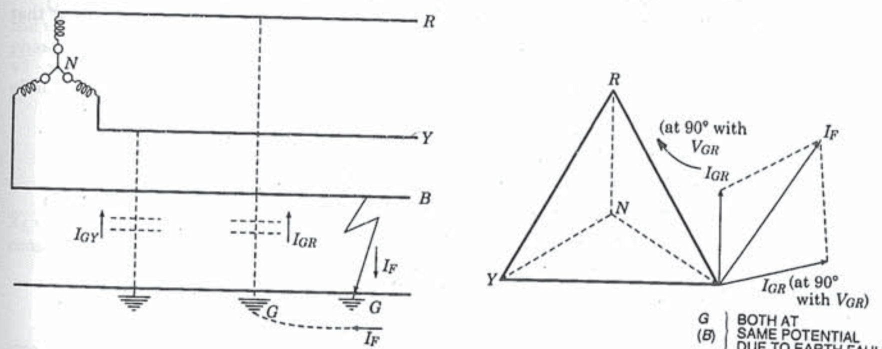
2. **Solid Grounding or Effective Grounding.** The neutral is directly connected to ground without any intentional impedance between neutral and ground. The coefficient of earthing is less than 80% for such systems.

3. **Reactance Grounding.** Reactance is connected between neutral and ground.

4. **Resonant Grounding.** An adjustable reactor of correctly selected value to compensate the capacitive earth currents is connected between neutral and earth. The coil is called Petersen coil or Arc suppression coil or Earth fault neutralizer.

**Principles**

(A) **Ungrounded System** (Fig. 18B.5). $I_F$ is 90° is ahead of $V_{GN}$ or $V_{BN}$. $I_{GY}$ capacitive current from $Y$ to earth is 90° ahead of $V_{GY}$ and capacitive current $I_{GY}$ from line $R$ is 90° ahead of $V_{GR}$. Though the neutral is not grounded, earth fault is fed by the two capacitive currents $I_{YG}$ and $I_{GR}$ through earth connection. The earth fault current is very low.




(a) Ungrounded system. (b) Simplified explaination.

Fig. 18B-5. Ungrounded system, fault on phase $B$.

(B) **Solid of Effective Earthing.** The situation is dramatically changed if neutral is grounded (Fig. 18.B.7). Referring to Fig. 18B.5 a fault occurs between line $B$ and ground. $I_F$ the fault current lags behind $V_{NB}$ by 90° since the circuit is predominantly inductive (due to transformer/machines and line inductances). The potential of neutral is held at earth potential due to grounding. That is $N$ and $G$ will be at the same potential neglecting impedance of link $NG$. Capacitance current $I_{GY}$ leads voltage $V_{GY}$ by 90°, and $I_{GR}$ leads $V_{GR}$ by 90°. Their vector, *i.e.* $I_{GY} + I_{GR} = I_G$, the net capacitance current. From the geometry of the vectors, we can see that $I_F$ is in phase opposition with $I_L$. Hence $I_F$ due to arcing grounds is eliminated or reduced by $I_G$.

**Solid or Effective Earthing.** By solid grounding, the earth fault current during arcing grounds is partially or completely eliminated by the capacitive ground current. Hence arcing grounds are substantially reduced. Secondly the potential of healthy phases above earth is held on at approximately constant value. However earth fault current is high.

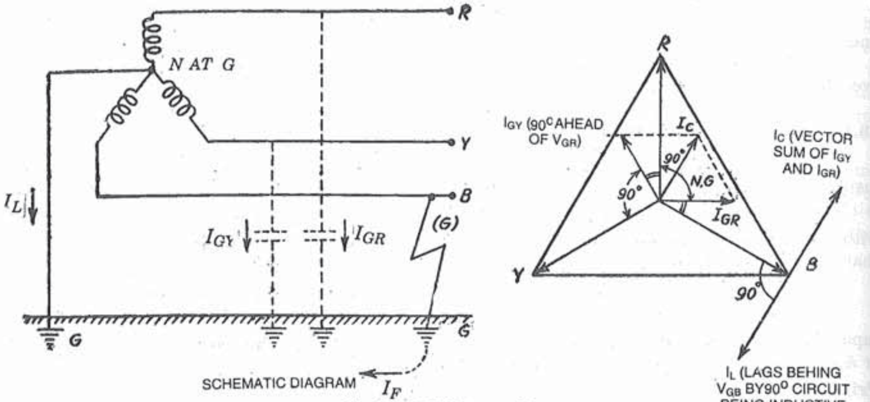



Fig. 18B.6. Solid grounding.

(C) **Resistance Earthing.** For circuit between 3.3 kV and 33 kV, the capacitive ground current ($I_{GY}$, $I_{GB}$) may not be large enough to demand reactance grounding. Secondly the ground fault current for solid grounding become excessive. Hence it is a practice to connect the neutral point of circuits of this voltage range (3.3 to 33 kV) through resistance. The resistance in the ground-neutral connection limits the fault current. From the theory of symmetrical components, we know that single line to ground fault current is :

$$I_F = \frac{3E}{Z_1 + Z_2 + Z_0}$$

$$Z_0 = Z_{g0} + 3Z_n$$

where $E$ = Voltage per phase r.m.s.

$Z_1$ = Positive sequence impedance Thevenin's equivalent.

$Z_2$ = Negative sequence impedance Thevenin's equivalent.

$Z_0$ = Zero sequence impedance. [Ref. Fig. 23.1]

$Z_{g0}$ = Thevenin's equivalent of zero sequence circuits.

$Z_n$ = Impedance in neutral to ground connection.

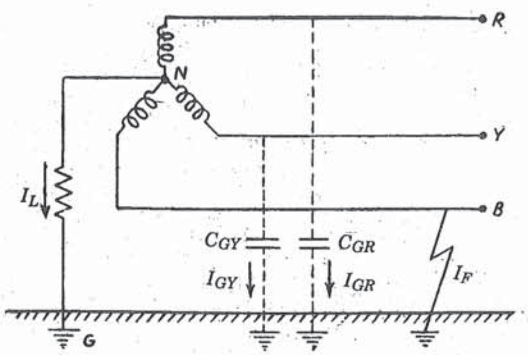



Fig. 18B.7 Resistance earthing.



[It is observed that the zero sequence components $I_{RO}$, $I_{YO}$, $I_{BO}$ find the path through $Z_n$, hence the impedance $Z_n$ is multiplied by 3 [Refer Chapter 23]. Therefore, by inserting a resistance in the circuit the fault current is limited.

For circuits below 3.3 kV, *i.e.* say 400 volts distribution networks, the external resistance in neutral circuit is unnecessary because the voltage available between phase and earth is only 230 volts. The earth resistance of earth plate, earthing connections etc. is of the order of 1.5 ohms. The earth current is limited to 230/1.5, *i.e.* 153 Amperes even if the grounding resistance is not used.

For circuits above 33, kV solid grounding is used. The capacitive ground current are enough to neutralize the reactive fault currents. Hence no resistance is necessary in neutral connection.

(D) **Reactance Earthing.** For circuits between 3.3 kV and 33 kV, the earth fault currents are likely to be excessive, if solid grounding is used. Either resistance or reactance is connected in neutral to ground connection. In Britain resistance grounding is a popular practice. In Europe, reactance grounding is favoured. The reactance connected between neutral and earth provides a lagging current which neutralizes the capacitive current (Fig. 18.B.8).

There is no rule as regards which grounding should be used-resistance or reactance. If resistance is used fault current is limited and system reactance provides the necessary phase opposition between capacitive ground current and fault current.

The reactance grounding provides additional reactance. Thereby the capacitive currents are neutralized. Hence for circuits where high charging currents are involved such as transmission lines, underground cables etc. Reactance grounding is preferred. For network where capacitance is relatively low, resistance grounding is preferred.

## 18.20. REACTANCE IN NEUTRAL CONNECTION

**Ungrounded System.** The charging current of phase to earth is, say, $I$. During earth fault the voltage across line to earth is increased by $\sqrt{3}$ times. Hence charging currents become $\sqrt{3}\, I$ per phase. The charging currents of phase $R$ and $Y$ are displaced by 120°. Hence their vector sum is $\sqrt{3} \cdot \sqrt{3} I$, *i.e.*, $3I$, where $I$ is charging current of line to ground of one phase.

$$I = \frac{V_{ph}}{X_c} = \frac{V_{ph}}{1/\omega C} \qquad ...(1)$$

$$I_c = 3I = 3V_{ph}\, \omega C$$

If the grounding is through a reactance $X_L = 2\pi f L$. Where $L$ is reactance in neutral connection

$$I_L = \frac{V_{ph}}{X_L} = \frac{V_{ph}}{\omega L} \qquad ...(2)$$

To obtain satisfactory cancellation of arcing grounds, the inductance $L$ should be related to the capacitance, and

$$I_L = I_C$$

$$V_{ph}/\omega L = 3V_{ph} \times \omega C$$

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

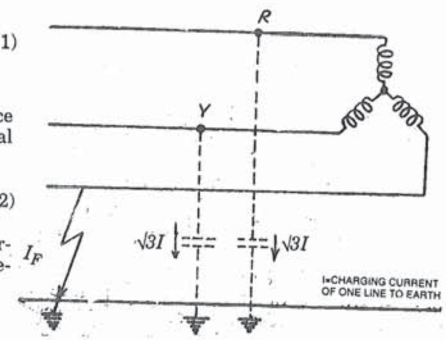



Fig. 18B.8. Current in arcing ground.

where $L$ = inductance in neutral to ground connection in henry
or inductance of Petersen coil
or inductance of earth fault neutralizer

$\omega = 2\pi f$

$C$ = capacitance per phase line to ground, farads,

$f$ = frequency (50 Hz)

From this relation the inductance is calculated.

## 18.21. CONNECTION OF THE ARC SUPPRESSION COIL*

Arc suppression coil is provided with tappings. This permits selection of reactance of the coil depending upon the length of the transmission line and the capacitance to be neutralized. The arc suppression coil is connected between neutral and ground. The reactance of the coil can be calculated from expression.

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

$\omega = 2\pi f$

$C$ = capacitance line to ground per phase, farad

$f$ = frequency, Hz

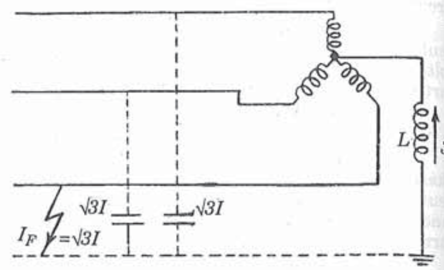



Fig. 18B.9. Reactance grounding current relations.

The coil is rated at continuous rated current equal to maximum earth fault current. However, if a second earth fault develops or double phase to ground fault develops, more current is likely to flow in the coil. To avoid this condition, a circuit-breaker closes after a certain time lag and the earth fault current flows through the parallel circuit by-passing the arc suppression coil.

CB is normally open. It closes after the relay $R$ closes the trip circuit thereby the arc suppression coil is by passed (Fig. 18B-10).

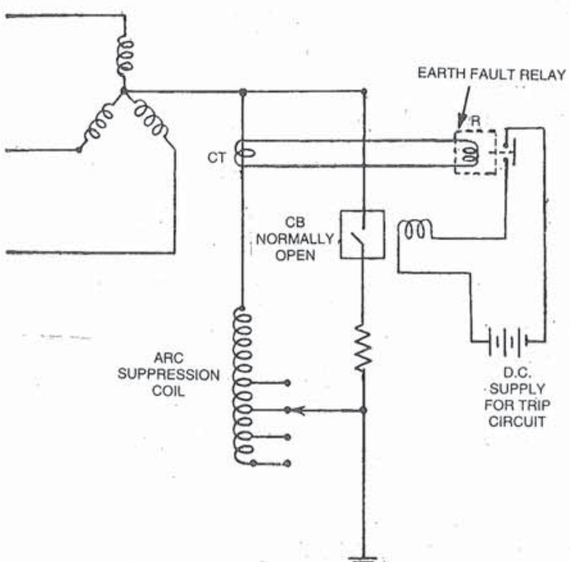



Fig. 18B.10. Connections of arc suppression coil.

* The three names : Arc suppression coil, Peterson coil, Ground fault neutralizer — have the same meaning. In such grounding the reactance of the coil is matched with the capacitance between phase and earth. The grounding is called Resonant Grounding.



## 18.22. NEUTRAL POINT EARTHING OF TRANSFORMER L.V. CIRCUITS.

$$Z_n = \frac{V^2}{n \times \text{kVA} \times 1000} \text{ ohms}$$

where $Z_n$ = impedance in neutral circuit in ohms

$V$ = Ph. to Ph. voltage LV side, volts

kVA = rating of transformer

$n$ = neutral short circuit current in terms of full load line current.

**Example 18.1.** *Calculate the ohmic value of impedance to be connected in the neutral to ground circuit of a 2000 kVA transformer with earth fault relay set to 40%, with respect to 400 V side.*

**Solution.**
$$Z_n = \frac{(400)^2}{0.4 \times 2000 \times 1000} = 0.2 \text{ ohm.}$$

**Example 18.2. Peterson Coil.** *Determine the value of reactance to be connected in the neutral connection to neutralize the capacitance current, of a cverhead line to ground capacitance of each line equal to 0.015 μF. Frequency = 50 Hz.*

**Solution.**
$$L = \frac{1}{3\omega^2 C} \text{ Henries}$$

where $L$ = inductance of coil connected in neutral to ground circuit (Henries)

$Z = 2\pi f$, $f$ = frequency Hz

$C$ = capacitance to earth of each phase, $f$

Here, we have to determine $L$,

$$L = \frac{1}{3 \times (314)^2 \times 0.015 \times 10^{-6}} = \frac{1}{98596 \times 0.045 \times 10^{-6}}$$

$$= \frac{10^6}{4437} = 22.6 \text{ Henries.}$$

**Example 18.3.** *In a 50 Hz. overhead line the capacitance of one line to earth was 1.5 μF. It was decided to use an earth fault neutralizer. Calculate the reactance neutralize the capacitance of :*

*(a) 100% of the length of line.* *(b) 90% of the length of line.*
*(c) 95% of the length of line.*

**Solution.** (*a*)

$$C = 1.5 \times 10^{-6} \text{ F}$$

$$\omega = 2\pi f = 2 \times \pi\, 50 = 314$$

$$ZL = \frac{1}{3 \times 1.5 \times 314}$$

$$L = \frac{704}{304} = \mathbf{2.25\ H.}$$

To neutralize capacitance of 100% of the line reactance required 2.15 H.

(*b*) $C$ of 90% length of line = $1.5 \times 0.9 = 1.35$

$$L = \frac{1}{3 \times \omega^2 \times C} = \frac{1}{3 \times (314)^2 \times 1.35 \times 10^{-6}} = \mathbf{2.5\ H}$$

or
$$L = 2.25 \times \frac{1}{0.9} = \mathbf{2.5\ H}$$

(C)
$$L = 2.25 \times \frac{1}{0.95} = \mathbf{2.37\ H.}$$

**Example 18.4.** *A 33 kV, 3 phase, 50 Hz, OH line 50 km long has a capacitance to earth line equal to 0.019 μF per km. Determine the inductance and kVA rating of the arc suppression coil.*

**Solution.** $L = \dfrac{1}{3\omega^2 C} = \dfrac{1}{3 \times (314)^2 \times 0.01 \times 50 \times 10^{-6}} = 6.75 \text{ H}$

$\omega L = 2\pi f L = 314 \times 6.75 = 2120.$

For ground fault, the current in neutral is given by

$$I_N = \frac{V_{ph}}{\omega L} = \frac{33 \times 1000}{\sqrt{3} \times 2120} = 8.99 \text{ A}$$

The voltage across the neutral phase voltage.

$$\text{kVA rating} = V_{ph} \times I_N = 8.99 \times \frac{33}{\sqrt{3}} = 169.3 \text{ kVA}$$

$$\left.\begin{aligned} L &= \mathbf{6.75\ H} \\ \text{kVA rating} &= \mathbf{169.3} \end{aligned}\right\} \textbf{ Ans.}$$

### 18.23. NEUTRAL GROUNDING PRACTICE

1. Generally one-neutral ground is provided at each voltage level. Between generator voltage level and distribution voltage level there are several voltage levels. One ground is provided at each voltage level (Fig. 18B.11).

2. The grounding is provided at source end and not at load end (Fig. 18B.11).

3. Each major bus section is grounded.

4. **Generator Neutral Grounding**

There are several alternatives of generator neutral grounding methods depending upon :

- method of generator connection with bus bars, *i.e.*, whether connected to bus bars or to unit transformers.
- method of ground fault protection
- fault currents
- insulation levels.
- number of generators in parallel, etc.

**Neutral Grounding for Classical Generator Connection**

For Generators connected to busbars without unit transformers in-between :

(Refer Sec. 17.6.1*a*, Fig. 17.3).

- When several generators are operating in parallel only one generator neutral is grounded. If more neutrals are grounded, the zero sequence components of circulating currents create disturbance.
- In generating station there is provision to earth neutral of at least two generators. Though only one is grounded at a time. The other generator neutral is grounded when the first generator is out of service. Under any circumstances one generator neutral must be grounded.
- When there are one or two power sources, no switching equipment is used in the grounding circuit.
- A neutral bus is provided in case there are several generators. The neutral bus is connected to earth directly or through reactance. The neutral point of one generator is connected to neutral bus through circuit-breaker.

**Neutral Grounding in Unit System of Generator Connection**

Refer Sec. 17.6.2, Fig. 17.14 describing unit system, of generator connection in which each generator, associated unit transformer, unit a auxiliary transformer form a 'unit'.

The earth fault protection of generator requires neutral grounding of each generator (Refer Sec. 33.6 *a*, Fig. 33.11).



The generator winding is star connected and generator terminal are connected to step-up transformer low voltage delta connected winding. High voltage winding is star connected and taken to bus bars for transmission. Because of delta connection of low voltage side of transformers, the generators operating in parallel are, isolated from each other and also from high voltage bus so far as ground fault currents are concerned. Therefore, generator neutral of each unit is earthed.

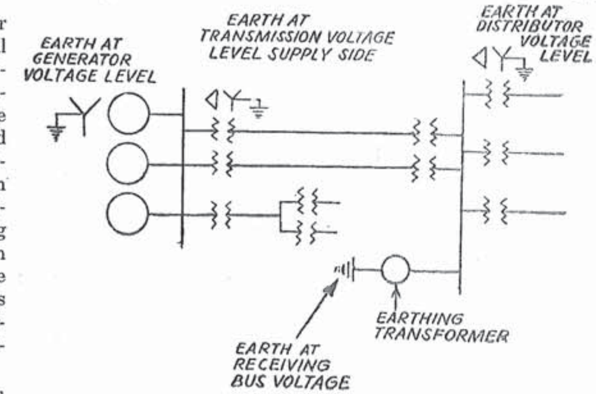



Fig. 18B.11. Earth at every voltage level at source end.

The generator neutral grounding is through resistor or reactor or a voltage transformer (Refer Fig. 23.11). The grounding practice in unit system of generator connection is as follows :

**Main generator neutral.** Grounded through resistor or reactor or a VT.

**Step up transformer.** Neutral on star connected HV side is earthed through neutral grounding resistor.

**Unit auxiliary transformer.** It is delta connected on generator side and star connected as auxiliary bus side. The star connected LV side neutral is earthed directly. In this case also the delta connected LV of unit auxiliary transformer isolates the auxiliary system from generator as far as earth fault currents are concerned.

5. **Grounding of Neutral of Power Transformer.** For protection purpose, the neutral point of star side is usually earthed (Fig. 32.16).

6. **Grounding of Protective CTs, VTs.** The star connected secondary sides of protective CTs and VTs are earthed at one point [Fig. 32.16, Fig. 32.10 (*b*)]. This ensures stable neutral, proper measurement of voltages and currents, kWh and kVA on secondary side measuring instruments and controls.

The control circuits and battery circuits should also have a single earth point.

### 18.24. EARTHING TRANSFORMER

The neutral point (star point) is usually available at every voltage level from generator or transformer neutral. However if no such point is available due to delta connections or if neutral point is desired on bus-bars, the most common method is using a zig-zag transformer. Such a transformer has no secondary. Each phase of primary has two equal parts. There are three limbs and each limb has two windings providing opposite flux during normal condition. The two stars (1) and (2) are connected together as shown in Fig. 18B-14. Since the fluxes oppose, the transformer takes very small magnetising currents during normal condition. During earth faults on the circuit in primary side, the zero sequence currents which have the same phase for three components $I_{RO}$, $I_{YO}$, $I_{ZO}$ flow in the transformer winding through earth connection. The earth fault current finds little impedance.

The grounding transformers are of short time ratings (10 seconds to 1 minute). Therefore, their size is small as compared to the power transformer of same ratings, almost one-tenth.

If grounding transformer is not available, a star-delta transformer can be used without loading the delta side (Fig. 18B.12)

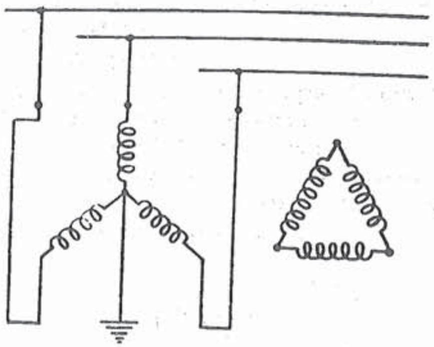


Fig. 18B.12. Use of star-delta transformer for grounding.

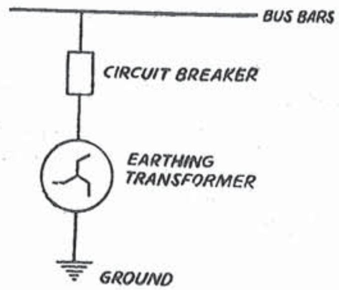



Fig. 18-B.13. Connection of earthing transformer. Current transformer not shown.

## 18.25. RATINGS OF NEUTRAL DEVICES

The ratings of equipment is neutral connection such as resistors, reactors, circuit-breaker etc. is usually 10 seconds or extended time.

On unit system grounding 10 seconds rating is used.

For feeders at generator voltage, 1 minute rating is used.

For distribution schemes, extended time ratings are used.

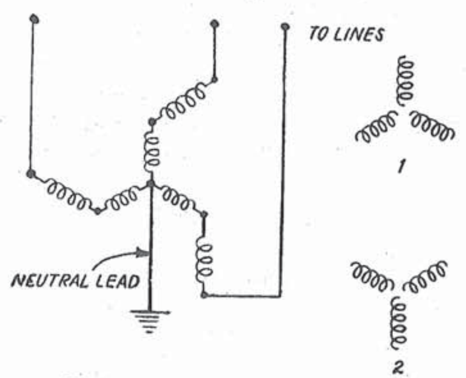



Fig. 18B.14. Winding of zig-zag transformer.

## SUMMARY

The *neutral points* of three phase AC System are usually earthed at each voltage level for :

— Eliminating arcing grounds (frequent charging and discharging of phase to ground capacitance through the temporary arcing fault).

— Holding phase to ground voltages of two unfaulted phases at nearly original level during earth fault on third phase.



— Facility for Earth fault protection.

— Reducing Coefficient of earthing to < 0.8.

— Flow of 3rd Harmonic current through the earth (Ref. Ch. 23 Fig. 23.1). Reactance Grounding is preferred for compensating capacitive earth fault currents. Resistance grounding is preferred for reducing earth fault currents. Solid grounding is preferred for sensitive earth fault protection.

## QUESTIONS

1. State the difference between Equipment Earthing and Neutral Earthing.
2. What are the merits and demerits of Reactance Earthing compared to Solid Earthing ?
3. Explain the phenomena of "Arcing Grounds" on overhead transmission lines. How does Neutral Earthing oppose arcing ground currents ?
4. Though Neutral Earthing results in higher ground fault currents, it is a *universal practice* to earth power system neutrals. Explain the merits of Neutral Earthing.
5. Explain by means of a diagrams :

   (*a*) The phase to earth voltage rise in unfaulted lines during a single phase to earth fault in a 3 phase system without (*a*) neutral earthing (*b*). The situation with neutral earthing.
6. A 36 kV, 3 phase distribution line is to be provided with Surge Arresters at the receiving substation. The transformer neutral is effectively earthed. Coefficient of earthing is 0.8. What would be the phase-to ground voltage of Unfaulted phases during a single phase to ground fault on one of the phases ?

   State the rated voltage of surge arrester. The Surge of 185 kV peak is discharged by the surge arrester with residual voltage of 130 kV, the surge impedance of line is 500 ohm. Calculate the Discharge current through the surge arrester.
7. A 132 kV, 3 phase 50 Hz overhead distribution line has phase to ground shunt capacitance of 0.0157 μF per km. Determine the inductance and kVA rating of arc supression coil to be connected between neutral and earth.

   [**Ans.** 4.3 H and 4300 kVA, single coil]
8. An 50 Hz, 3 phase overhead line has phase ground shunt capacitance of 0.08 μF. Determine the inductance required in neutral to ground circuit to eliminate an arcing-ground at (*a*) the other end of line (*b*) at 70% length of line from the neutral earthing end.

# 18-C

# *Substation Earthing System and Equipment Earthing*

Introduction — Equipment Earthing — Parts to be Earthed — Station Earthing System — Earth Mat — Touch Potential — Step Potential — Earth Resistance Measurement by Low Current Method and High Current Method — Earth Resistance Values — Summary.

## 18.26. EQUIPMENT EARTHING (GROUNDING)

The non current carrying metallic parts in every electrical installation are connected to the underground earthing mesh at earth potential for safety of personnel and for discharging fault currents. The connecting of non current carrying metallic parts to underground earthing system is called *Equipment Earthing (grounding).*

The equipment grounding also helps in the earth fault protection. The earth fault current from the equipment flows through the earthing system to the earth and is sensed by protection system and circuit breakers are opened. The faulty equipment is then repaired and recommissioned. The earthed parts remain at approximately earth potential even during flow of fault current. The equipment earthing ensures safety to personnel.

The core of the real earth has hot, liquid malma with low electrical resistivity. Earth is a good conductor except in the dry and rocky upper layers near the surface. The surface-soil and internal geological layers are with different resistivities.

The *Station Earthing System* should have *low earth resistance ; low touch potential and low step potential.* Modern Station Earthing System has burried horizontal mesh of steel rods and vertical electrodes (spikes) welded to the mesh. Further, the vertical risers and the galvanised steel earthing strips/copper bars etc. are connected between the earthing mesh and the points to be earthed.

The Earthing is of two principal types :

1. Neutral Earthing. (Chapter 18-B)
2. Equipment Body Earthing

The earthing system is also required for :

— Reference earthing
— Discharge earthing
— Overhead Shielding.



**Table 18-C.1**

| *Type of Earthing* | *Points Earthed* | *Purpose* |
|---|---|---|
| Neutral Earthing | — Transformer Neutral | — Holding neutral at ground potential |
| | — Generator Neutral<br>— Star point of load | — Prevent Arcing grounds on OH lines. |
| | — Neutral of circuit | — Discharge of voltage surges |
| | — Star point of CT/PT secondary | — Path for out-of-balance currents, |
| | | — Simpler earth Fault Protection |
| Equipment Earthing (body earthing) | — Metallic noncurrent-carrying parts | — Holding the metallic parts at earth potential even on earth fault |
| | | — Safety |
| Reference Earthing | — The floating point in the circuit | — Holding the point and the conductor at zero potential |
| Discharge Earthing | Earthing-terminal of, | — To discharge the surge voltages, capacitor charge, currents to earth |
| | — Earthing Switch, and currents | |
| | — Surge Arresters, | |
| | — Capacitor/Filter Bank, | |

**Note :** Neutral Points and Equipment Earthing Parts are connected to the common Underground Earth mat *via* separate earthing conductors.

## 18.27. FUNCTIONS OF SUBSTATION EARTHING SYSTEM

1. **Safety of Operation and Maintenance Personnel.** The earthing system ensures safety against shocks to Operation and Maintenance Staff working in Substation. The earthed part are safer than unearthed parts. Deaths by shocks can be avoided completely by proper equipment earthing. Before commissioning, the earthing system should be checked and certified. Before carrying it any maintenance work, the equipment is isolated and earthed from both ends. Hence equipment earthing is also called as "Safety Earthing".

The earthed parts are held at near ground potential and safety is ensured.

2. **Discharge of Electrical Charges to Earth.** The earthing system provides return path for discharging fault currents and discharge currents/voltages from the earthed points of lightning masts, lightning conductors, earthing switches, surge arrester, etc. These parts are connected to the underground earthing system by solid or flexible earthing conductors of adequate short-time current carrying capability and low resistance.

3. **Earthing of Overhead Shielding Wires.** The overhead shielding wires and earthed-flanges of insulators and bushings are held at earth potential by connection with the earthing system. Thereby the protection zone against lightning strokes is obtained for the outdoor, exposed conductors and equipment.

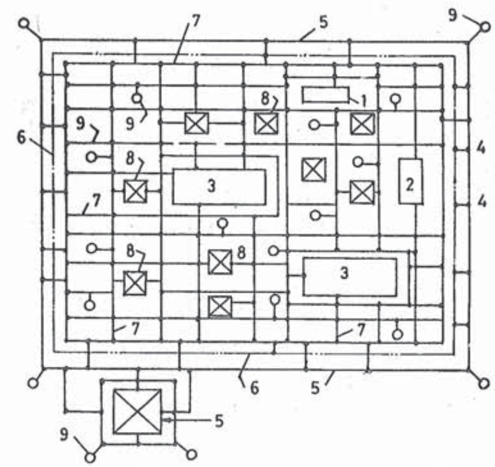
4. **Electro Magnetic Interference.** The earthing system ensues freedom from Electromagnetic interference in communication and data processing equipment in the substation. Earthing of chassis of instruments, earthed screening of control room, computer room ensures freedom from electro magnetic disturbances on operation of isolators, thyristors in main power circuits. The control rooms are provided with earthed screen in the walls and windows to ensure freedom from electromagnetic disturbances.

## 18.28. CONNECTION OF ELECTRICAL EQUIPMENT TO STATION-EARTHING SYSTEM

**Table 18-C.2. Connection of Electrical Equipment to Station-Earthing System.**

| *Apparatus* | *Parts to be earthed* | *Method of connection* |
|---|---|---|
| Support of bushing insulators, lightning arrester, fuse, etc. | Device flange or base plate | 1. Connect the earthing bolt of the device to station earthing system. In the absence of earthing bolt or in case of connection to non-conducting structures, connect fastening bolt to earth. |
| | Earth terminal of each pole of 3 phase. Surge Arrester | 2. When the device is mounted on a steel structure, weld the structure, mounting the device flange; each supporting structure of apparatus to earthing mesh *via* separate conductor. |
| Cabinets of control and relay panels | Frameworks of switchgear and cabinets | Weld the framework of each separately mounted board and cabinet minimum at two points to the earth conductor of earthing system. |
| High-voltage circuit breakers | Operating mechanism, frame provided with earth-bus | Connect the earthing bus on the frame and operating mechanism of c.b. to earthing system. |
| Isolator | Isolator base (frame), operating mechanism bedplate. | Weld the isolator base frame, connect it to the bolt on operating mechanism base plate and station earth. |
| Earthing Switch | Lower pad/terminal | For discharging capacitance after opening of Isolator |
| Steel Doors, Fence, Screens | Each panel | Connected by flexible conductor to earth mat |
| Lightning Masts | Earthed member | Connected by earthing strip to Earth Mat |
| Foundation frames, Support Structures | Earthed member | Connected by earthing strip to Earth Mat |
| Overhead Shielding Conductors | Earthed point | Connected by Flexible conductor along each Tower or Structure to Earth Mat |
| Neutral Points | Earthed point | Connected to earth mat by Strips/Cable/ Flexible conductor. |
| Surge Arrester | Lower earth point of each pole | To be directly connected to the earth mat. |
| Potential transformer | Potential transformer tank, LV neutral, LV winding phase lead (if stipulated by the designers) Structure. | 1. Connect the transformer earthing bolt to earthing system. 2. Connect LV neutral of phase lead to case with flexible copper conductor. |
| Current transformer | Neutral points of secondary, structure. | Connect secondary winding to earthing bolt on transformer case with a flexible copper conductor, the case being earthed in the same way as support insulators. |
| Power transformer | Transformer tank, Neutral point. | Connect the earthing bolt on transformer tank to station earth. Connect the Neutral to Earthing system. |

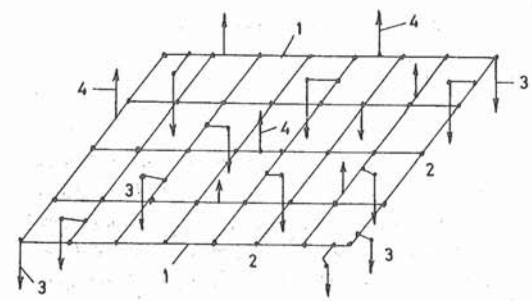





1. Metal Tank
2. Transformer Foundation
3. Building
4. Welded joints+
5. Tower
6. Fence
7. Earthing rods of mesh+
8. Structures in substation
9. Earthing spikes/electrodes+

+Below ground level.

Fig. 18-C. 1 A. Substation Earthing System.




1. Horizontal earthing rods+
2. Welded joint
3. Vertical electrodes/spikes+
4. Vertical risers

+Below ground level.

Fig. 18-C. 2. Three-dimensional view of the Earthing System.

## 18.29. SUBSTATION EARTHING SYSTEM

Before 1960s the design criterion of substation earthing system was "low earth resistance." (ER < 0.5 ohms for High Voltage installations). During 1960s, the new criteria for the design and evaluation of Substation Earthing System were evolved particularly for EHV AC and HVDC Substations. The new criteria are :

1. Low Step Potential   2. Low Touch Potential   3. Low Earth Resistance.

The conventional "Low earth resistance criterion" and Low Current Earth Resistance Measurement continues to be in practice for Substations and Power Station upto and including 220 kV.

The parts of the Earthing System include the entire solid metallic conductor system between various earthed points and the underground earth mat. The earthed points are held near-earth potential by low resistance conductor connections with earthmat.

— *An Underground Horizontal Earth Mesh (Mat / Grid)*

The mesh is formed by placing mild steel bars placed in $X$ and $Y$ directions in mesh formation in the soil at a depth of about 0.5 m below the surface of substation floor in the entire substation area except the foundations. The crossings of the horizontal bars in $X$ and $Y$ directions are *welded.* The earthing rods are also placed the border of the fence, surrounding building foundations, surrounding the transformer foundations, inside fenced areas etc. The mesh ensures uniform and zero potential distribution on horizontal surface of the floor of the substation hence low "step potential" in the event of flow of earth fault current.

— *Earthing Electrodes (earthing Spikes).* Several identical earth electrode are driven vertically into the soil and are welded to the earthing rods of the underground Mesh. Larger number of earth electrodes gives lower earth resistance.

(A) The number of Earth-Electrodes (Spikes) $N_s$ for soil resistivity 500 ohm meter and earth fault current $I_s$ is :

$$N_s = \frac{I_s \text{ Amperes}}{250}$$

*i.e.*, approximately 250 Amp per spike, for soil resistivity of 500 ohm-meter.

(B) The number of Earth-Electrodes (Spikes) $N_s$ for soil resistivity 5000 ohm meter is

$$N_s = \frac{I_s \text{ Amperes}}{500}$$

*i.e.*, approximately 500 Amp per spike, for soil resistivity of < 5000 ohm-meter.

$I_s$ = Short Circuit level of the substation, A

*e.g.* 33 kV sub stations : 25000 to 31000 A
400 kV Substations : 40000 A

— *Earthing Risers.* These are generally mild steel rods bent in vertical and horizontal shapes and welded to the earthing mesh at one end and brought directly upto equipment / structure foundation.

— *Earthing Connections.* (Galvanised Steel Strips or Electrolytic Copper Flats or Strips/Stranded Wires (Cables)/Flexibles. These are used for final connection (bolted/welded/clamped) between the Earthing Riser and the points to be earthed. For Transformer Neutral/High Current Discharge paths copper strips/stranded wires are preferred, Galvanised Iron Strips/stranded wires are more common for all other earthing connections. The earthing strips are finally welded or bolted or clamped to the *Earthed Point.*

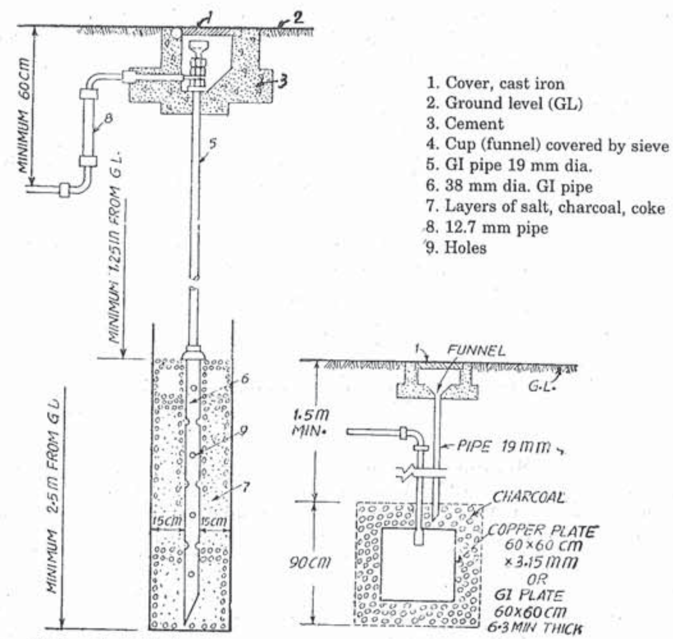
## 18.30. EARTH ELECTRODES

Several vertical galvanised-steel pipes are inserted in the earth and their heads are connected solidly to the Earthing Mat by means of horizontal earthing rods/earthing strips.

Fig. 18-C.3 illustrates the typical Earth electrode. For low voltage, low current installations, plate electrodes may be preferred. Use of salt, charcoal, chalk powder in the earth pits surrounding the electrodes and irrigation of the soil gives lower earth resistance.

The size of conductor is based on temperature rise permissible to avoid fusing at the joints.






(*a*) Pipe Earth Electrode. (*b*) Plate Earth Electrode.

Fig. 18-C.3. Typical Earth Electrodes.

**Table 18C-2. Description of an Earthing System**

| | |
|---|---|
| 1. | **Earthing Mat** |
| | 40 mm dia, 2 to 3 m length per piece mild steel rods welded to get straight lengths and are placed in horizontal $X$-$Y$ formation with mesh spacing 2 m to 3 m at 0.6 m depth in soil. Joints between $X$ and $Y$ rods are arc-welded. |
| 2. | **Earthing Electrodes (Spikes)** |
| | 30 to 40 mm dia GI pipes, 3m long, are driven in soil vertically ($Z$ direction) and welded to $X$-$Y$ rods of earth mesh via horizontal earthing rods. Surrounding Earth pits filled with salt, charcoal, chalk and irrigated periodically. |
| 3. | **Riser** |
| | 40 mm dia vertical rods welded to Earthing Mat brought upto the structures to be earthed. — Alternatively, 75 × 10 mm or 45 × 8 mm GI Flats welded to the earth mat and taken up vertically for bolting/welding with the point to be earthed. |
| 4. | **Earthing Strips or Flexible stranded wires** |
| | 75 × 10 mm Galvanised Iron Flats/or Copper Flats Welded/Bolted to the nearest riser and Welded/Bolted to the point to be earthed. Flexible stranded ACSR cables are connected between the overhead shielding wires and tower footing. Tower footing is connected to the earthing system. |
| | Welded joints covered by bituminous paint to prevent rusting. |

**Earthing System for Installations Within a Buildings.** The Earthing System is planned as a part of civil design and construction. The earthing rods are placed in mesh formation in the floor and in the area surrounding the building Risers are placed in walls. Earth connections are by galvanised iron strips or copper strips/ stranded wires provided between the individual body/neutral point and the Risers. Earthing strips are placed in the floor and walls and are connected to that several places to the Earthing Mesh.

Sensitive Measuring Instruments, Communication Equipment, Computer Facility etc. need proper low resistance earthing system spread in the various rooms of the building. *Electro-Magnetic Disturbances are eliminated by proper Earthing.*

The thin wire mesh earthed screen is provided in the glass windows, portable single phase devices are provided with 3-pin plugs :

The three pins are for : Phase, Neutral and Earth (green).

The earth wire/strip is provided with the wiring of all the rooms. The earthing is via the earthing strips/earthing wire.

Current leakage through wet walls, floors and worn out old insulation; earth fault through pipe or reinforcement, minor occasional sparking are some causes of electric shocks within residential/commercial buildings.

**Earthing System for Metallic Enclosure of Switchgear.** Earthing Strip is provided along the entire length or periphery of the Metallic Enclosure. The Earthing Bus in the metallic enclosures is connected to the Station Earthing system at two or more points by Earthing Conductors. The individual neutral points, reference points and equipment bodies, doors etc. within the Metallic enclosure are connected to the Earthing Bus.

**Earthing with Withdrawable Earthing Truck.** With Drawout type Switchgear, there should be provision for busbar earthing after isolation from supply feeders. Earthing trucks consisting of a breaker with shorted terminals on one side and mounted on withdrawable truck. Before doing maintenance/repair work on the switchgear, the busbars are earthed by means of earthing truck.

**Earthing Devices.** Before doing any maintenance work, the overhead bus bars/other equipment in substations are disconnected, and then earthed by means of earthing device consisting of an insulating rod with a earthing hooks connected with insulated wires, the other end of the wire is connected to the earthing system.

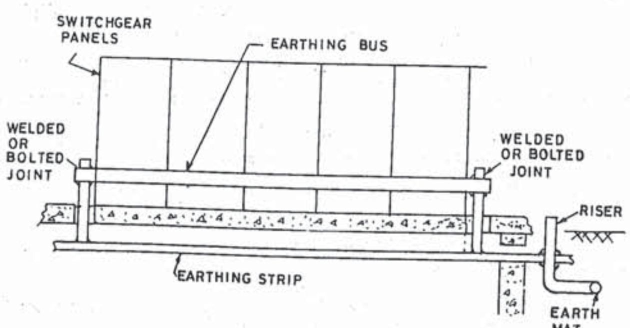



Fig. 18-C.4. Equipment Earthing Facility in Metal Clad-Switchgear.



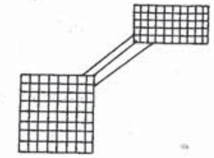
## 18.31. INTEGRATED EARTHING SYSTEMS FOR TWO OR MORE INSTALLATIONS

The Earthing Systems of two or more Substations/Generating Stations/Industrial/Commercial Installations may connected by a few earthing rods as shown in Fig. 18-C.5 between individual earthing meshes of these installations. The Individual Earthing Systems are thereby connected in parallel ensuring very low earth resistance ($E_{Rc}$) of the integrated Earthing Systems

$$\frac{1}{E_{Rc}} = \frac{1}{E_{R1}} + \frac{1}{E_{R2}} + \frac{1}{E_{R3}} + \ldots\ldots$$

$E_{Rc}$ = Resistance of Combined Earthing Systems

$E_{R1}, E_{R2}$ = Resistance of Individual Earthing Systems



1, 2, 3 ... Individual Station Earthing Systems
$U_{RC}$ = Underground Earthing rod connections

Fig. 18-C.5. Concept of Integrated Earthing System.

## 18.32. STEP POTENTIAL AND TOUCH POTENTIAL

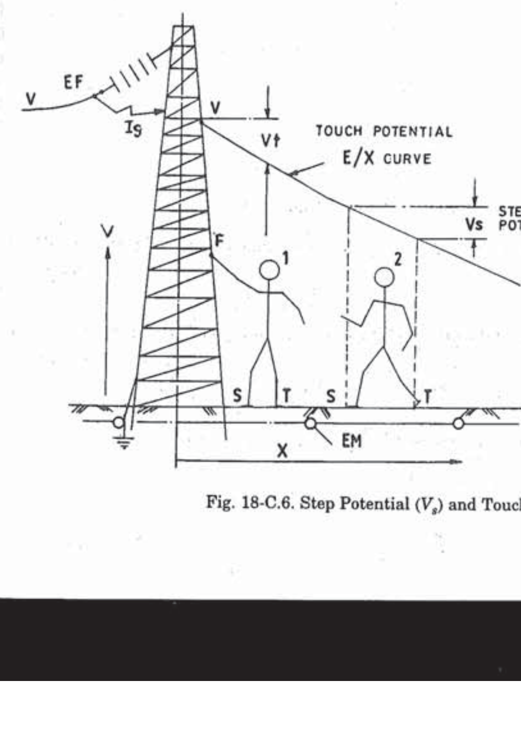
A person touching a faulted structure should not get a shock during flow of fault current through the structure.

A person walking on substation floor should not get a shock during flow of fault current through the earth mat. These conditions are ensured by low Touch Potential and low Step Potential.

*Step Potential* is the voltage between the feet of a person standing on the floor of the substation, with 0.5 m spacing between two feet (one step), during the flow of earth fault current $I_s$ through the earthing system.

*Touch Potential.* The voltage between the fingers of raised hand touching the faulted structure and the feet of the person standing on substation floor. The person should not get a shock even if the earthed structure is carrying fault current. In other words the touch potential should be low.

Refer the curve $V/X$ in Fig. 18-C.6. The point $F$ is at potential $V$ of faulted structure. The feet $ST$ of Man 1 are on ground. The potential difference between $F$ and $ST$ is the Touch Potential ($V_t$) for Man 1. The potential between $S$ and $T$ of man 2 is Step potential $V_t$.




$V_s$ = Step Potential between point $S$ and $P$ during flow of $I_s$.
$V_t$ = Touch Potential
$E_F$ = Earth fault
$F$ = Raised finger
$S, T$ = Steps of a person
$I_s$ = Short-circuit current.

Fig. 18-C.6. Step Potential ($V_s$) and Touch Potential $V_t$

## 18.33. EARTH-RESISTANCE OF EARTHING SYSTEM

"Earth Resistance ER" is the resistance of the earthing electrode/earthing mat to the real earth and is expressed in ohms. ER is the ratio of $V/I$, where $V$ is measured voltage between the electrode and the voltage spike and $I$ is injected current during the earth resistance measurement through the electrode. The desirable values of earth resistance measurement (average of 12 monthly readings) are :

**Table 18C.3.**

| | |
|---|---|
| EHV AC Installations* | < 0.01 ohm |
| High Voltage Installations above 33 kV | < 0.5 ohm |
| Medium Voltage Installation 1kV to 33 kV | < 0.5 ohms |
| Low Voltage Installations up to 1 kV | < 1 to 2 ohm |
| Residential buildings | < 2 ohm |

*Measured by High Current Method.

— For installations rated below 1000 V and earth fault current ($I_s$) less than 500 A, the earth resistance shall be less than $125/I_s$

— For installations rated less than 2000 kVA and 1000 V, (Residential Loads), the earth resistance should not exceed 2 ohms.

Earth resistance value obtained would depend on :

— Whether the soil is dry or wet. During the rainy season lower values are obtained and during summers, higher values are obtained. It is a good practice to irrigate the earth electrodes regularly during summers and winters.

— The resistivity of soil varies widely between 1 ohm m to 10000 ohm m (Table 18-C.3) depending on the type of soil.

— The design of station earthing system.

— Method of measurement.

**Table 18-C.4. Soil Resistivity**

| *Type of Soil* | *Resistivity ohm m* |
|---|---|
| Marshy | 1 — 5 |
| Clay | 3 — 150 |
| Clay and Gravel mixture | 10 — 1250 |
| Chalk | 60 — 500 |
| Sand | 90 — 1000 |
| Sand and gravel mixture | 500 — 5000 |
| Slate | 100 — 500 |
| Crystaline Rock | 500 — 10,000 |

Let $ER$ be earth resistance for one electrode in ohm.

$$\text{Resistivity of Soil (ohm m)} = \frac{\text{Earth-resistance } ER \text{ in ohm}}{0.003}$$

*e.g.* With $ER = 0.3$ ohm, soil resistivity $= \dfrac{0.3}{0.003} = 100$ ohm metre

With $ER = 12$ ohm, soil resistivity $= \dfrac{12}{0.003} = 4000$ ohm m



## 18.34. EARTH RESISTANCE MEASUREMENT

The measurement involves the Electrode under test, a current spike and a voltage spike. Current is injected into earth through the electrode under test and returned from the current spike. Voltage between the voltage spike and the electrode is measured.

$$ER = \frac{V_{dc}}{I_{dc}} \text{ ohms}$$

where,

$V_{dc}$ = Voltage between voltage spike and earth electrode under test, volts

$I_{dc}$ = Current injected through the Earth Electrode into earth and returned through the Current spike, ohms

The two different methods of Earth Resistance Measurement are :

1. *Low Current Method (Conventional Method)* used mostly for installations upto 400 kV. The test current is 10 mA to 100 mA.

2. *High Current Method* for 400 kV and 500 kV Substations. This method gives more realistic measurement for earth mats of more than 300 m diameter/length.

The test current is 10 A to 100 A.

**Description**

1. **Low, Current Method (Conventional Method),** Measurement is by means of standard *Earth Resistance Tester,* with standard accessories like Current Spike and Voltage Spike. (Fig. 18-C.7) The test is conducted as per applicable Standard Specification.

The Earth Resistance Tester has a built-in ohm meter and a hand driven DC Generator. The DC generator supplies current ($I$) via the Earth Electrode under test and the Current Spike (CS). The voltage ($V$) develops between the Earthing System under test and the Voltage Spike. The Ohm Meter in the Earth Resistance Tester measures the ratio $V/I$. Several readings of $V/I = R$ are taken for different positions of the Voltage Spike. The graph of distance $X$ versus $R$ is plotted. The flat portion of the curve or $R$ is considered to be the Earth Resistance of the Earth Point under measurement. The resistance value can be between a fraction of ohm to a few hundred ohms depending upon the soil resisting and depth of electrode. Electrode design may be suitably modified in case of hard rock.

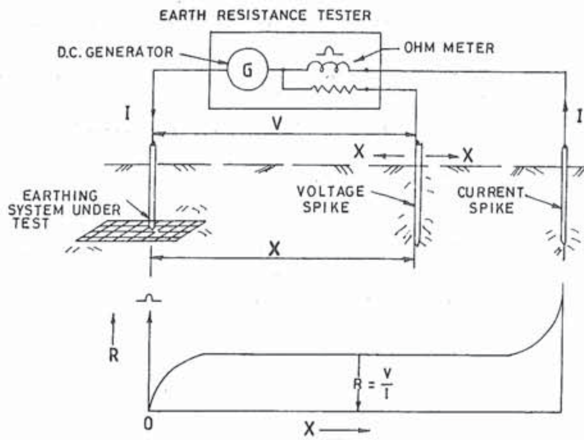



Fig. 18-C.7. Measurement of Earth Resistance by Low-Current method.

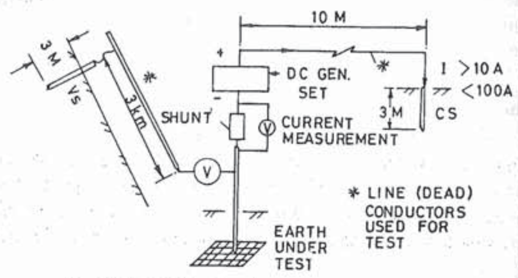
[The voltage spike is placed at various points ($X$) and measurements of $R$ are taken for each point of $X$. The graph $X$ versus $R$ is plotted. The uniform value of '$R$' is called earth Resistance of the Earthing System Under Test.]

2. **High Current Method of Earth Resistance Measurement.** The low current method does not reflect the true earth resistance for large earth mats designed for high short circuit currents. High Current Method gives more realistic value of earth resistance of Large Earthing Mats of 400 kV Substations and HVDC Substations in which fault levels are more than 30 kA. Fig. 18-C.8 gives the schematic.

In High Current method of Earth Resistance Test,

— The Current Spike (CS) should be at least 3 m long and should be located at least 10 km away from the Earth Mat under test. The location should be marshy/wet place.

— The Voltage Spike (VS) should be at least 5 km away from the Earth Mat under test.




$V_s$ = Voltage Spike, 3 m deep
$CS$ = Current Spike, 3 m deep
Fig. 18-C.8. Earth Resistance Measurement by High Current Method.

— The Voltage Spike should be separated from Current Spike by at least 500 m. The location should be marshy/wet place.

— The angle between voltage conductor and current conductor (marked *) should be greater than 90°, preferably 180°.

The line Conductors outgoing from the substation are temporarily disconnected (dead) and used as Voltage Conductor and Current Conductor. *Sufficient precautions should be taken to avoid shocks due to induced currents / live conductors,* by discharging the charges and avoiding induced voltages.

— The current Source can be a D.C. generator. (Welding Generator). The current flowing through the earth mat $= I_e = V/r$

— The Measurement is by DC Voltmeter with a Shunt and an Ammeter.

$$\text{Earth Resistance ER of Earth Mat} = \frac{V_v}{I_c}, \text{ ohm}$$

where,

$V_v$ = D.C. Voltage between the Voltage Spike and the earth mat

$V$ = Voltage across shunt '$r$' ohms.

$I_e$ = DC current flowing through the Current Spike and the earth and returning through the earth mat. Current is measured by means of a shunt as shown in Fig. 18-C.8. $(V/r)$

**Table 18-C.5 Results of High Current Method of Earth Resistance Measurement in a 400 kV/500 kV HVDC Substation**

| |
|---|
| Current $I_c$ = 36 A DC |
| Voltage $V_v$ = 0.103 V DC |
| Earth Resistance $ER = V_v/I_c$ = 0.00516, ohms |
| Size of Earth mat = 500 m × 30 m |
| Number of Earth electrodes = 167 |



## 18.35. EARTHED SCREENS

When equipment are not supported on earthed structures of 2.5 height (minimum), earthed screens are provided on ground for preventing persons entering unsafe safety zone.

## SUMMARY

*Station Earthing System* is an underground horizontal mesh of metallic rods with vertical earthing spikes to which various neutral points, equipment bodies to be earthed are solidly connected such that the resistance to earth is low.

Equipment bodies, fences, doors, support structure, are connected to station earthing system.

The essential components of the earthing system are :

— Underground earth mat and earthing electrodes.

— Risers and Earthing Strips.

The Touch Potential, the Step Potential, Earth Resistance should be low for safety of personnel against electric shocks.

Equipment Earthing is for safety and Electrical Inspectors shall not permit charging of installation unless the earthing is properly done. The Earth Resistance is given by $ER = V/I$, and is measured by : (1) Low Current Method (< 1 A) for medium and low voltage installations and (2) High Current Methods for 400 kV installations. Earthing System is common for equipment Earthing and Neutral Point Earthing. Earth resistance shall be less than 0.5 ohm for medium/high voltage installations rated upto 200 kV and less than 0.01 ohms (as measured by high current method) for 400 kV installations.

## QUESTIONS

1. Define : Neutral Earthing and Equipment Earthing.
2. Explain in brief, the four essential functions of Station Earthing System.
3. State which points in an electrical installation are connected to station earthing system.
4. State the modern criteria for the design of earthing system. How does it differ from the earlier criterion ?
5. Explain clearly the terms Touch Potential and Step Potential.
6. Describe a typical Station Earthing System and state the values of Earth Resistance to be achieved.
7. Describe High Current Method of Earth Resistance Measurement. Explain how the Earth Resistance can be minimised by integrated earthing system.
8. Describe the Low Current Method of Earth Resistance Measurement.
9. Design an earthing system for a 33 kV outdoor substation having area within fence of 200 m × 100 m.

   The soil resistivity is 1000 ohm m. Short circuit level of the substation is 25 kA rms.

   Give a Sketch and final specifications of your design.
10. Describe the Equipment Earthing Facility for a Metal Clad Switchgear and its Draw-out unit.