



**These include:**

Equipotential bonding of conductive objects (e.g. metallic equipment, buildings, piping etc.) to the earthing system prevent the presence of dangerous voltages between objects (and earth).

- The earthing system provides a low resistance return path for earth faults within the plant, which protects both personnel and equipment.
- For earth faults with return paths to offsite generation sources, a low resistance earthing grid relative to remote earth prevents dangerous ground potential rises (touch and step potentials)
- The earthing system provides a low resistance path (relative to remote earth) for voltage transients such as lightning and surges / overvoltages
- Equipotential bonding helps prevent electrostatic build up and discharge, which can cause sparks with enough energy to ignite flammable atmospheres
- The earthing system provides a reference potential for electronic circuits and helps reduce electrical noise for electronic, instrumentation and communication systems.
- This calculation is based primarily on the guidelines provided by IEEE STD. 80 (2000), "Guide for safety in AC substation grounding".

## II. Earthing Standards

There are a variety of national and international standards available, which provide empirical formulae for the calculation of earthing design parameters and shock potential safety limits.

- BS7354 - 1990 Code of Practice for Design of High Voltage Open Terminal Stations
- IEEE Std. 80-2000 IEEE Guide for Safety in AC Substation Grounding
- EATS 41-24 - Guidelines for the Design, Installation, Testing & Maintenance of Main Earthing Systems in Substations.

## III. Terms Associated with Earthing:

### 1.1 Ground Potential Rise (GPR)

The substation earth grid is used as an electrical connection to earth at zero potential reference. This connection is not ideal due to the resistivity of the soil within which the earth grid is buried.

During typical earth fault conditions, the flow of current via the grid to earth will therefore result in the grid rising in potential relative to remote earth to which other system neutrals are also connected.

This produces potential gradients within and around the substation ground area - this is defined as ground potential rise or GPR.

The GPR of a substation under earth fault conditions must be limited so that step and touch potential limits are not exceeded, and is controlled by keeping the earthing grid resistance as low as possible.

### 1.2 Step, Touch, Mesh & Transferred Potentials

In order to ensure the safety of people at a substation, it is necessary to ensure that step and touch potentials in and around the substation yard during earth-fault conditions are kept below set limits.

These maximum permitted step and touch potentials are addressed within various national and international standards.

### 1.3 Step Potential

The step potential is defined as the potential difference between a persons outstretched feet, normally 1 metre apart, without the person touching any earthed structure.

### 1.4 Touch Potential

The touch potential is defined as the potential difference between a person's outstretched hand, touching an earthed structure, and his foot. A person's maximum reach is normally assumed to be 1 metre.

### 1.5 Earthing System Design Considerations

Conductors - a substation earthing grid will consist of an earthing system of bonded cross conductors.

The earthing conductors, composing the grid and connections to all equipment and structures, must possess sufficient thermal capacity to pass the highest fault current for the required time.

Also, the earthing conductors must have sufficient mechanical strength and corrosion resistance. It is normal practice to bury horizontal earthing conductors at a depth of between 0.5m and 1m - this ensures that the earth conductor has the following properties:

- Adequate mechanical protection
- It is situated below the frost line
- The surrounding earth will not dry out

### 1.6 Vertically Driven Earth Rods

Where there are low resistivity strata beneath the surface layer then it would be advantageous to drive vertical earth rods down into this layer - to be effective the earth rods should be on the periphery of the site. The length of the earth rod is chosen so as to reach the more stable layers of ground below.

The earth rods would stabilise the earth grid resistance over seasonal resistivity changes at the grid burial depth.

**1.7 Substation Fences**

The earthing of metallic fences around a substation is of vital importance because dangerous touch potentials can be involved and the fence is often accessible to the general public.

Fence earthing can be accomplished in two different ways:

Electrically connecting the fence to the earth grid, locating it within the grid area or alternatively just outside  
Independently earthing the fence and locating it outside the earth grid area at a convenient place where the potential gradient from the grid edge is acceptably low.

**1.8 Other Substation Earthing**

The GPR at a substation is reduced by:

Overhead line earth wires which are connected to the substation earthing grid. This diverts part of the earth fault current to the tower footing earthing.

Cable entering and leaving the site. The armouring of such cables is usually earthed to the substation earthing grid at both ends. Part of the earth fault current will thus be diverted to a remote earthing grid via the cable armouring.

**Nomenclature and Given Data:**

NOMENCLATURE	
Symbol	Description
$\rho$	Soil Resistivity
$\rho_s$	Gravel Resistivity
$I_{efs}$	Symmetrical Short Circuit Current
$t_s$	Duration of Earth Fault Current
$h_s$	Thickness of Crushed Gravel
$h$	Depth of Earth Grid
$h_o$	Reference depth of the Grid
$\rho_\gamma$	Resistivity of Conductor Material
$\rho_\gamma$	Thermal co-efficient of resistivity at reference temperature
$T_m$	Max. allowable temperature in °C
$T_a$	Ambient temperature in °C
$K_o$	$1/a_0$ or $1/a_r - T_r$ in °C
$t_c$	Duration of Current in s
$TCAP$	thermal capacity per unit volume
$A_{mm^2}$	Conductor cross section in mm <sup>2</sup>
$K$	Reflection factor between different material resistivities
$C_s$	Surface layer derating factor
$E_{step70}$	Step Voltage for body weight of 70 kg
$E_{touch70}$	Touch Voltage for body weight of 70 kg
$E_{step50}$	Step Voltage for body weight of 50 kg
$E_{touch50}$	Touch Voltage for body weight of 50 kg
$n$	Number of parallel conductors
$D$	Conductor Spacing
$L_p$	Length of the conductor across perimeter
$N_r$	No. of Ground Rods
$L_r$	Length of Ground Rods
$L_R$	Total length of Ground Rods
$LT1$	Total length of buried conductor
$LT$	Total length of buried conductors & rods
$L_x$	Maximum length of conductor in X-Axis
$L_y$	Maximum length of conductor in Y-Axis
$A$	Area of the Grid
$R_g$	Grid Resistance
$I_g$	Maximum grid current in A
$D_f$	Decrement factor for the entire duration of fault, given in s
$K_i$	Corrective factor for current irregularity
$K_m$	Spacing factor for Mesh Voltage
$K_{ii}$	Corrective weighting factor that adjusts the effect of inner conductors on the corner mesh
$K_h$	Corrective weighting factor that emphasising the grid depth
$K_s$	Spacing factor for Step voltage

GIVEN DATA				
Sr. no.	Description	Notations	Unit	Value
1	Soil Resistivity	$\rho$	Ohm-M	25
2	Gravel Resistivity	$\rho_s$	Ohm-M	3000
3	Symmetrical Short Circuit Current	$I_{efs}$	A	40,000
4	Duration of Earth Fault Current	$t_s$	sec	0.5
5	Thickness of Crushed Gravel	$h_s$	m	0
6	Depth of Earth Grid	$h$	m	1.2
7	Reference depth of the Grid	$h_o$	m	1
8	Resistivity of Conductor Material	$\rho_c$	Ohm - M	0.0032
9	Thermal co-efficient of resistivity at reference temperature	$\alpha_r$	Ohm - M	20.1
10	Max. allowable temperature in °C	$T_m$	°C	419
11	Ambient temperature in °C	$T_a$	°C	40
12	$1/a_0$ or $1/a_r - T_r$ in °C	$K_0$	°C	293
13	Duration of Current in s	$t_c$	s	0.5
14	thermal capacity per unit volume	$TCAP$	J/cm <sup>3</sup> °C	3.93
15	Conductor cross section in mm <sup>2</sup>	$A_{mm^2}$	mm <sup>2</sup>	415.08
16	Number of parallel conductors	$n$	--	12
17	Conductor Spacing	$D$	m	2
18	Length of the conductor across perimeter	$L_p$	m	69.5
19	No. of Ground Rods	$N_r$	--	12
20	Length of Ground Rods	$L_r$	m	5
21	Total length of Ground Rods	$LR$	m	60
22	Total length of buried conductor	$LT_1$	m	248
23	Total length of buried conductors & rods	$LT$	m	308
24	Maximum length of conductor in X-Axis	$L_x$	m	25
25	Maximum length of conductor in Y-Axis	$L_y$	m	10
26	Area of the Grid	$A$	m <sup>2</sup>	247.5
27	Decrement factor for the entire duration of fault, given in s	$D_f$		0.415

**Calculations:**

**Calculation Of 220 Kv Bus Section**

**1.9 Size Of Earthing Conductor :**

$$A_{mm^2} = \frac{I}{\sqrt{\left(\frac{TCAP \times 10^{-4}}{t_c \alpha_r \rho_c}\right) \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}}$$

$A_{kcmil} = 819.37$  kcmil

$A_{mm^2} = 415.08$  mm<sup>2</sup>

The size of conductor selected = 23.0 mm

Diameter of the Grid Conductor  $d = 0.02299$  m

**1.10 Touch & Step Criteria:**

Reflection factor between different material resistivities  $K = \frac{\rho - \rho_s}{\rho + \rho_s}$

Surface layer derating factor  $C_s = \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2hs + 0.09}$

$K = -0.98$

$C_s = 0.01$

Therefore,

$$E_{step70} = (1000 + 6C_s \times \rho_s) \frac{0.157}{\sqrt{t_s}}$$

$$E_{step70} = 255.34 \text{ Volts}$$

$$E_{touch70} = (1000 + 1.5C_s \times \rho_s) \frac{0.157}{\sqrt{t_s}}$$

$E_{touch70} = 230.36$  Volts

**1.11 Grid Resistance:**

$$R_g = \rho \left[ \frac{1}{L_r} + \frac{1}{\sqrt{20A}} \left( 1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right]$$

A = Area of the Grid = 247.5 m<sup>2</sup>

R<sub>g</sub> = Grid Resistance = 0.74 Ω

**1.12 Maximum Grid Current:**

$$I_G = D_f \times I_g$$

I<sub>G</sub> = Maximum grid current in A = 40,000

D<sub>F</sub> = Decrement factor for the entire duration of fault, given in s = 0.415

I<sub>G</sub> = 16600 A

**1.13 Ground Potential Rise:**

$$GPR = 12287.2 \text{ Volts } GPR = I_g \times R_g$$

**Verification For Human Safety**

The safety to personnel is specified by IEEE 80, which requires limiting the development of electrical potential to dangerous value during earth fault current.

The regulation stipulates the following parameters to be within the permissible limit

- a) Step Voltage (Foot to Foot Contact)
- b) Touch Voltage (Hand to Foot Contact)

**1.14 Calculation For Actual Derived Step & Mesh Voltage**

**I. Mesh Voltage:**

$$E_{mesh}(Design) = \frac{\rho \times I_g \times K_m \times K_i}{L_c + \left[ 1.55 + 1.22 \left( \frac{L_r}{\sqrt{L_i + L_r}} \right) \right] \times L_s}$$

K<sub>i</sub> = Corrective factor for current irregularity

$$K_i = 0.644 + 0.148n$$

Where,

$$n = n_a \times n_b \times n_c \times n_d$$

$$n_a = \frac{2 \times L_r}{L_p}$$

n<sub>a</sub> = 7.1

n<sub>b</sub> = 1.050917456

n<sub>c</sub> = 1 for square and rectangular grids

n<sub>d</sub> = 1 for square and rectangular grids and L Shaped grids

Therefore, n = 7.48

K<sub>i</sub> = 1.75

$$K_m = \frac{1}{2\Pi} \ln \left[ \frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d} \right] + \frac{K_{ii}}{Kh} \ln \left[ \frac{8}{\Pi(2n-1)} \right]$$

$$K_{ii} = \frac{1}{(2 \times n)^{\frac{1}{n}}}$$

K<sub>ii</sub> = 0.60 and

K<sub>ii</sub> = 1.00 with ground rods

$$\sqrt{\left( 1 + \frac{h}{ho} \right)}$$

$K_h = 1.48$   
 $K_m = 0.57$   
 $E_{\text{mesh}} = 1169.50$  Volts (Designed)

Calculated Mesh Voltage is lower than the Tolerable Touch Voltage.

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**Step Voltage:**

Voltage developed for step as per the earthing system proposed during full Earth fault current.

$$E_{\text{step}}(\text{Design}) = \frac{[(K_s \times K_i \times \rho \times I_g)]}{[0.75 \times L_c + 0.85 \times L_r]}$$

Where,

$K_s$  = Spacing factor for Step voltage

$$K_s = \frac{1}{\Pi} \left[ \frac{1}{2h} + \frac{1}{D+h} + \left( \frac{1-0.5^{n-2}}{D} \right) \right]$$

$K_s = 0.388$

$$K_i = 0.644 + 0.148n$$

$K_i = 1.751772846$

$E_{\text{step}} = 1191.75$  Volts (Designed)

Calculated Step Voltage is lower than the Tolerable Step Voltage.

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#### IV. Conclusion

This paper has a focus on designing of a 220 kV HV/LV AC substation earthing system. The results for earthing system are obtained by computational method. For earthing conductor and vertical earth electrode, mild steel are used. The step by step approach for designing a substation earthing system is presented. The various kinds of conductor sizes for earth equipment are mentioned in this paper. Construction of earthing grid is expressed in here. The step and touch voltages are dangerous for human body. Human body may get electric shocks from step and touch voltages. When high voltage substations are to be designed, step and touch voltages should be calculated and values must be maintained specified standard. Importance to be given to the transfer of Ground Potential rise (GPR) under fault conditions to avoid dangerous situations to the public, customer and utility staff. The values of step and mesh voltages obtained for 220 kV substation are respectively 1191.75 Volt and 1169.50 Volt which are within the permissible limits.

#### References

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