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Design of Earthing System for 400 kV AC Substation: A Case Study

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Abstract

This paper presents the design of Earthing system for 400 kV substation and calculation of its parameters. Successful operation of entire power system depends to a considerable extent on efficient and satisfactory performance of substations. Hence substations in general can be considered as heart of overall power system. In any substation, a well designed earthing plays an important role. Since absence of safe and effective earthing system can result in mal-operation or non-operation of control and protective devices, earthing system design deserves considerable attention for all the substations. earthing system has to be safe as it is directly concerned with safety of persons working within the substation. Main purpose of this work is designing safe and cost effective earthing systems for 400 kV substations situated at such locations where soil of the substation site is not uniform. Initially significance of earthing is explained & methodology for design of substation earthing system is discussed for 400 kV substations. Standard equations are used in the design of earthing system to get desired parameters such as touch and step voltage criteria for safety, earth resistance, grid resistance, maximum grid current, minimum conductor size and electrode size, maximum fault current level and resistivity of soil. By selecting the proper horizontal conductor size, vertical electrode size and soil resistivity, the best choice of the project for safety can be performed. This paper mentions the calculation of the desired parameters for 400 kV substations & which are simulated by MATLAB program. Some simulated results are evaluated. A case study is done at 400 kV substations at Aurangabad in Maharashtra state of India.

Keywords: Earthing, earth grid, 400 kV substations, Power systems, Safety, Touch and Step voltages,

1. INTRODUCTION

Earthing practices adopted at Generating Stations, Substations, Distribution structures and lines are of great importance. It is however observed that these items are most often neglected. The codes of practice, Technical Reference books, Handbooks contain a chapter on this subject but they are often skipped considering them as too elementary or even as unimportant. Many reference books on this subject are referred to and such of those points which are most important are compiled in the following paragraphs. These are of importance for every practicing Engineer & In-charge of Substations. earthing systems thus design must be easily maintained and future expansion must be taken into account while designing the dimensions of earth mat

Substation earthing system is essential not only to provide the protection of people working in the vicinity of earthed facilities and equipments against danger of electric shock but to maintain proper functioning of electrical systems. Reliability, security and statutory obligations are to be taken in considerations for proper design. (IEEE,Indian standards on electrical safety and environmental aspects). This paper is concerned with earthing practices and design for outdoor 400 kV AC substation for power frequency of 50 Hz [1, 2]

1.1 IMPORTANCE

The earthing system in a plant / facility is very important for a few reasons, all of which are related to either the protection of people and equipment and/or the optimal operation of the electrical systems. These include:

Equipotential bondings of conductive objects (e. g. metallic equipment, buildings, piping etc) to the earthing system prevent the presence of dangerous voltages between objects and objects& 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 earth 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 / over voltages
- Equipotential bonding helps prevent electrostatic buildup 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 [1, 3]

These calculation are based primarily on the guidelines provided by IEEE STD. 80 (2000), "Guide for safety in AC substation earthing".

2. EARTHING DESIGN METHODOLOGY

Earthing System in a Sub Station comprises of Earth Mat or Grid, Earth Electrode, Earthing Conductor and Earth Connectors.

2.1 Earth Mat or Grid

Primary requirement of Earthing is to have a low earth resistance. Substations involves many Earthlings through individual Electrodes, which will have fairly high resistance. But if these individual electrodes are inter linked inside the soil, it increases the area in contact with soil and creates number of parallel paths. Hence the value of the earth resistance in the inter linked state which is called combined earth value will be much lower than the individual value.

The inter-link is made through flat or rod conductor which is called as Earth Mat or Grid. It keeps the surface of substation equipments as nearly as absolute earth potential as possible. To achieve the primary requirement of Earthing system, the Earth Mat should be design properly by considering the safe limit of Step Potential, Touch Potential and Transfer Potential. [4]

2.2 Most affected parameters for the Earth Mat design are:

- Magnitude of Fault Current
- Duration of Fault.
- Soil Resistivity
- Resistivity of Surface Material (soil structure and soil model)
- Shock Duration.
- Material of Earth Mat Conductor
- Earthing Mat Geometry (Area covered by Earth mat).
- Permissible touch and step potentials

2.3 The design parameters are :

- Size of Earth Grid Conductor
- Safe Step and Touch Potential
- Mesh Potential (E_{mesh})
- Grid configureuration for Safe Operation
- Number of Electrodes required

The different methodologies are adopted for earthing grid designs. Here we adopted universal method as per IEEE-80.

An earthing design starts with a site analysis, collection of geological data, and soil resistivity of the area. Typically, the site engineer or equipment manufacturers specify a resistance-to-earth number. The National Electric Code (NEC) states that the resistance-to-earth shall not exceed 25 Ω for a single electrode. However, some reputed manufacturers will often specify 3 or 5 Ω, depending upon the requirements of their equipment and safety. For sensitive equipment and under extreme circumstances, a 1 Ω specification may sometimes be required. When designing a earthing system, the difficulty and costs increase extremely as the target resistance-to-earth approaches the unobtainable goal of zero Ω. [5, 6]

2.4 The earth resistance shall be as low as possible and shall not exceed the following limits:

Table 1: Earth Resistance Values

Sr. No.	Particulars	Permissible Values
1	Power Stations	0. 5 Ω
2	EHT Substations	1. 0 Ω
3	33 kV Stations	2. 0 Ω
4	Distribution transformer centers	5. 0 Ω
5	Tower foot resistance	10. 0 Ω

3 CALCULATION OF PARAMETERS

3.1 Prerequisites:

The following information is required / desirable before starting the design calculations:

- A layout of the site
- Soil resistivity measurements at the site (for touch and step only)
- Maximum earth fault current into the earthing grid
- Maximum fault clearing time
- Ambient (or soil) temperature at the site
- Resistivity of any surface layers intended to be laid (for touch and step only)

The following procedure is to be adopted for earthing design

- ➢ Find out Area of grid from substation layout Plan
- ➢ Measure soil resistivity by selection of different test location throughout the substation as shown in Figure:1

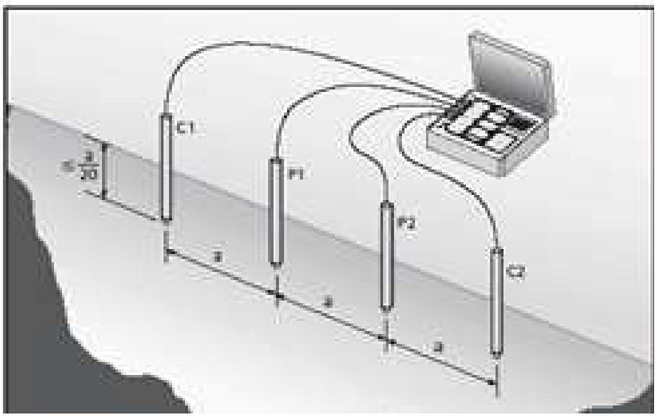

Figure 1: Earth tester

(Wenner 4 pin electrode method is recommended for approximate measurement of soil resistivity and provides average resistance for whole substation area)

- ➢ Determine the maximum earth fault current and fault clearing duration from authority

- Determine size of Earth mat conductor (As per IEEE-80)
- Determine corrosion correction factor:
  (For moisture and softy soil -15 % allowance, for rocky area - 0 % allowance are permissible)
- Find Resistivity of surface layer ρ_s

The crushed metal or gravel is used in substations in order to reduce the risk of possible high step potential for safety concern. It is recommended to spread the metal or gravel of 8-20 mm in switch yard Soil resistivity is the key factor that determines the resistance or performance of an electrical earthing system. It is the starting point of any electrical earthing design

Depending on soil resistivity, the earth conductor (flats) shall be buried at the following depths.

Table 2: Depth of Earth Conductor according to Soil Resistivity

Sr. No.	Soil Resistivity in Ω per meter	Economical Depth of Burial in meters
1	50 – 100	0. 5
2	100 – 400	1. 0
3	400 – 1000	1. 5

To keep the earth resistance as low as possible in order to achieve safe step and touch voltages, an earth mat shall be buried at the above depths below earth and the mat shall be provided with earthing rods at suitable points. All non-current carrying parts at the substation shall be connected to this grid so as to ensure that under fault conditions, none of these parts are at a higher potential than the earthing grid. [7]

- Following points should be referred to keep the earth resistance as low as possible.
- Remove oxidation on joints and joints should be tightened
- Pour sufficient water in earth electrode
- Use bigger size of Earth Electrode
- Electrodes should be connected in parallel
- Earth pit of more depth & width-breadth

3.2 Step and Touch Voltage Criteria

The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energized. The maximum driving voltage of any accidental circuit should not exceed the limits defined as follows. [3]

3.2.1 For step voltage the limit is

- The tolerable step voltage criteria is

$$E_{Step} = [1000 + (6 \times C_s \times \rho_s)]\frac{0.116}{\sqrt{t_s}} \quad (1)$$

- The tolerable touch voltage criteria is

$$E_{Touch} = [1000 + (1.5 \times C_s \times \rho_s)]\frac{0.116}{\sqrt{t_s}} \quad (2)$$

Where,
E_{step} = the step voltage in Volts
E_{touch} = the touch voltage in Volts
Cs= 1 for no protective layer
ρ_s = the resistivity of the surface material in Ω meters
t_s = the duration of shock current in seconds

- The earth grid conductor size formula is mentioned below [8, 9]

$$I = A\sqrt{\frac{(TCAP \times 10^4)}{t_c \times \alpha_r \times \rho_r} ln\left(\frac{k_0+T_M}{k_0+T_a}\right)} \quad (3)$$

Where,
I = rms of current value in kA
A = conductor sectional size in mm²
T_m = maximum allowable temperature in ˚C for joints (welded or bolted)
T_r = Ref. temperature for material constant in degrees Celsius(C ^{o}) = 20°C
T_a = ambient temperature for material constants in˚C
α_0= thermal coefficient of resistivity at 0˚C
α□ = thermal coefficient of resistivity at reference temperature 20°C
ρ□ = the resistivity of the earth conductor at reference temperature 20°C in µΩ/cm
K_0 = 1/α_0 or 1/α_0-Tr
tc = time of flow of fault current in sec
TCAP = thermal capacity factor

- Spacing factor for mesh voltage (Km)

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

Where,
D = spacing between conductors of the grid in meters
d = diameter of grid conductors in meter
K_m = spacing factor for mesh voltage
K_{ii} = 1 for grids with rods along perimeter
K_h = Corrective weighting factor for grid depth

- Spacing factor of step voltage (Ks)

$$K_S = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{(D+h)} + \frac{1}{D}(1 - 0.5^{n-2})\right] \quad (5)$$

Where
D = spacing between conductors of the grid in meters
h = depth of burial grid conductor in meters

n = number of parallel conductor in one direction

- **Evaluation of earth resistance**

A good earthing system provides a low resistance to remote earth in order to minimize the ground potential rise (GPR). For most transmission and other large substations, the earth resistance is usually about 1 Ω or less. In smaller distribution substations, the usually acceptable range is between 1 Ω to 5 Ω, depending on the local conditions. [3, 10]

For calculation of earthing resistance, the following equation can be referred.

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{\frac{20}{A}}}\right)\right] \quad (6)$$

Where

ρ = soil resistivity Ω m

L_t = total length of grid conductors in meters

A = total area enclosed by earth grid in m^2

h = depth of earth grid conductor in meters

- **For calculation of grid current, equation[11, 12]**

$$I_G = (C_P \times D_f \times S_f \times I) \quad (7)$$

Where:

I = rms of current value in kA

I_G = Maximum grid current in kA

C_P = Corrective projection factor (For future expansion)

D_f = Decrement factor

S_f = Current division factor

- **For calculation of earth potential rise(GPR)**

$$GPR = (I_G \times R_g) \quad (8)$$

- **Actual Step Potential & Touch Potential Calculations**

Mesh voltage can be calculated using following equation

$$E_m = \left[\frac{\rho \times K_m \times K_{im} \times I_G}{LL+LB+LA+(1.15 \times LE)}\right] \quad (9)$$

Step voltage can be calculated using following equation

$$E_s = \left[\frac{\rho \times I_G \times K_i \times K_{is}}{LL+LB+LA+(1.15 \times LE)}\right] \quad (10)$$

Where

ρ = soil resistivity, Ω m

E_m = mesh voltage at the center of corner mesh in Volts

E_s = step voltage between two steps in Volts

K_m = spacing factor for mesh voltage

K_{is} = spacing factor of step voltage
K_{im} = correct factor for grid geometry
LL= Length of grid conductor along length of switch yard
LB= Length of grid conductor along breadth of switch yard
LA= Length of riser and auxiliary mat in switch yard
LE= Length of earth electrodes in switch yard
LT= Total length of earth conductor in switch yard

$$LT = (LL + LB + LA + LE) \tag{11}$$

4 MATLAB PROGRAMMING

- **Steps**

STEP 1: Conductor design
Minimum cross section area (A) = 793 mm2

STEP 2: Touch and step voltage criteria
E_{touch} (50) = 648. 7258 V
E_{step} (50) = 2103. 2 V

STEP 3: Design of earth mesh
N_a = Number of conductor in X-axis = 39 No’s
N_b = Number of conductor in Y-axis = 59 No’s
N_r = Quantity of earth rod = 98 rods
D = Earth rod spacing = 7m
h = Depth of burial grid conductor = 0. 6 m
L_t = Total length of conductor = 34405 m

STEP 4: Substation grid resistance (Rg)
Rg = 0. 3017 ohm

STEP 5:Grid current (Ig)
Ig = 20 kA

STEP 6: Grid potential rise (GPR)
GPR = Ig x Rg
GPR > E_{touch}

STEP 7: Mesh and step voltage
K_{im} for E_m
K_{is} for E_s
K_m
K_s

STEP 8: Check touch voltage and step voltage
$E_m < E_{touch}$ OK
$E_s < E_{step}$ OK

- **Flowchart**

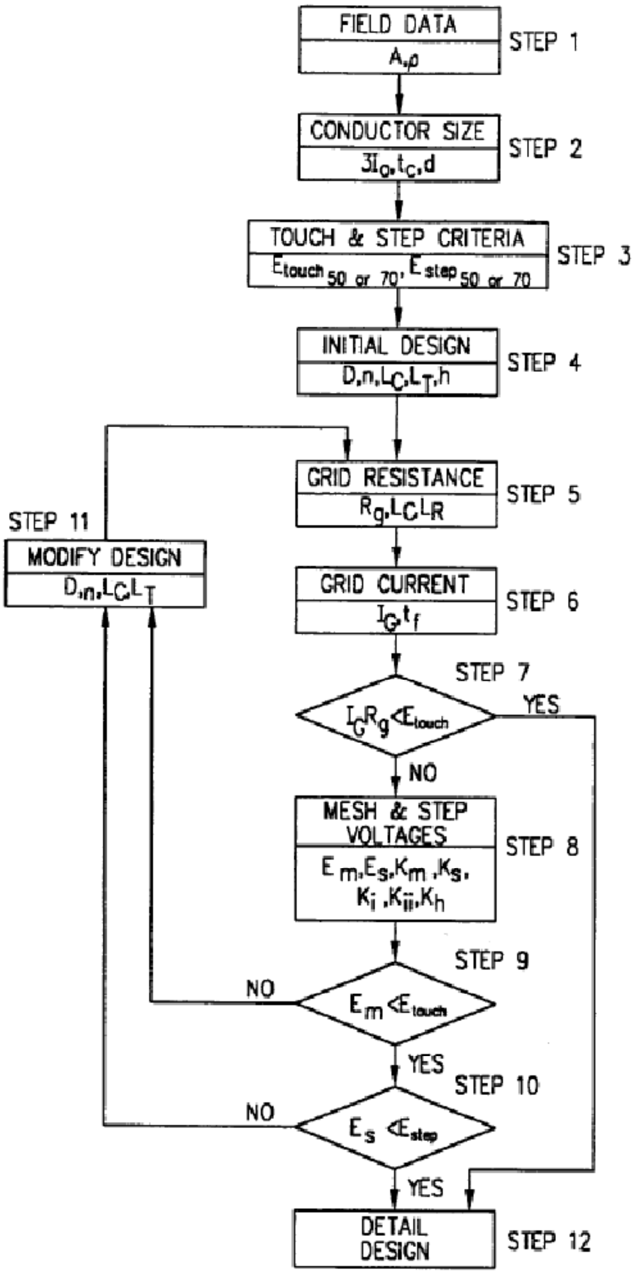

Figure 2: Design Procedure Flow Chart [3]

5 RESULT

The Input Constant values referred for design calculations & Output results of grid construction design are shown in following graphs & tables obtained from implemented MATLAB program.

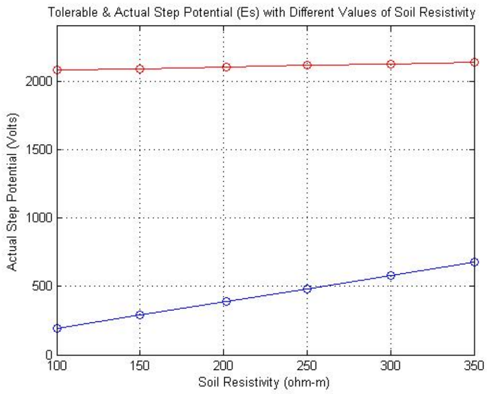

Figure 3 : Tolerable & Actual Step Potential with different values of soil resistivity

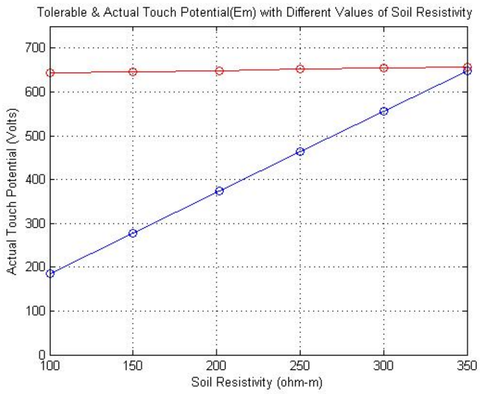

Figure 4: Tolerable & Actual Touch Potential with different values of soil resistivity

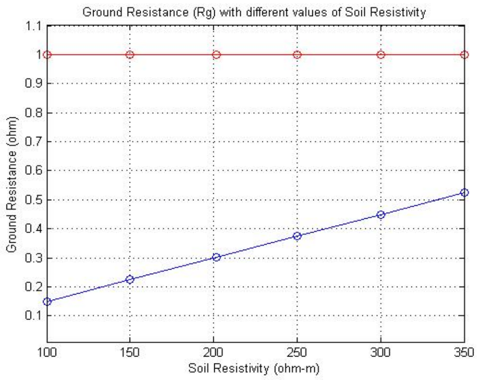

Figure 5: Earth resistances (Rg) with different values of soil resistivity

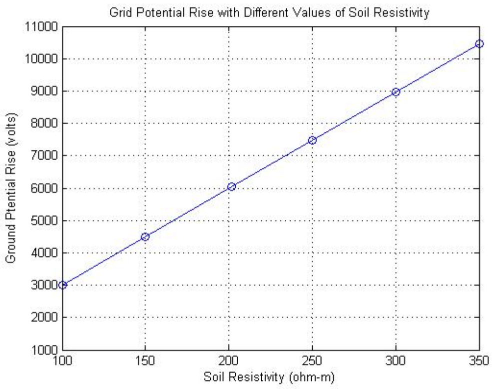

Figure 6: Earth potential rise with different values of soil resistivity

❖ In above graph Red colour indicates the permissible values & blue colour indicates the actual calculated values.

Table 3: Input Constant values referred for design calculations

Parameters	Symbol	Value	Units
Ambient temperature	Ta	45	°c
Maximum allowable temperature	Tm	450	°c
Time of flow of Fault current	tc	1s	Sec
Fault duration time	ts	0. 5s	Sec
Thermal coefficient of resistivity	αr	0. 0032	
Resistivity of conductors	ρr	20. 1	μΩ/cm
Resistivity of substation soil	ρ	201. 8	Ωm
Resistivity of surface material	ρs	2500	Ωm
Thermal capacity factor	TCAP	3. 931	j/cm³/°c

Depth of burial conductor	h	0. 6	m
Reference depth of grid	ho	1	m
Conductor spacing	D	7	m
Diameter of grid conductor	d	34	mm
Length of one earth rod	Lr	3	m

Table 4: Output results of Grid Construction Design

Parameters	**Symbol**	**Value**	**Units**
Earth conductor size	A	793. 1	mm^2
Maximum grid current	I_G	20	kA
Earth resistance	Rg	0. 301732	Ω
Earth potential rise	GPR	6034. 633	Volts
Spacing factor for mesh voltages	Km	0. 380395	
Spacing factor for step voltages	Ks	0. 352793	
Touch voltage criteria	Etouch	648. 7258	Volts
Step voltage criteria	Estep	2103. 00	Volts
Maximum attainable step voltage (Actual step voltage)	Es	389. 6783	Volts
Maximum attainable mesh voltage(Actual touch voltage)	Em	374. 1747	Volts
Total length of earth conductor in switch yard	LT	34405. 5	m

The main electrical properties of an earthing system are:

- Earthing resistance
- Earth surface potential distribution
- Current carrying ability

The most favorable earth surface potential distribution concepts have horizontal earth electrodes, especially meshed ones, whose surface potential can be controlled easily. The potential distribution of vertical electrodes is the most unfavorable, with high values of touch potential. On the other hand, vertical electrodes can easily reach low earthing resistance with stable values, largely independent from seasons. Vertical electrodes are also used in combination with horizontal ones in order to reach lower values of earthing resistance. . The results obtained here can be referred for safe earth grid design of 400 kV substations. Graphs represents the Reference & Actual calculated values of step potential, touch potential & ground resistance (Rg) with different values of soil resistivity between 100 - 350 Ω meter

6 CONCLUSION

This paper has a focus on design of 400 kV AC substation earthing system. The results for earthing system are obtained by computational method & MATLAB programming. For earthing conductor and vertical earth electrode, mild steel is referred and step by step approach for design of substation earthing system is presented. When high voltage substations are to be designed, step and touch voltages should be calculated and values must be maintained as per specified standards. Importance to be given to the transfer of Ground Potential Rise (GPR) under fault conditions to avoid dangerous situations to the public, customers and utility staff. The calculated values of step, mesh voltages and ground resistance (R_g) obtained for 400 kV substations are respectively 389.6783 Volts and 374.1747 Volts and 0.3017 Ω which are within the permissible limits.

- R.M.S. value of fault current is 31.5 kA for 132 kV substations and for 400 kV substations it is to be taken 50 kA to enhance safety
- In general we spread 150 mm crushed rock as a surface layer of resistivity 3000 Ω m for limiting the touch & step potentials but for 400 kV voltage levels use of granite or other gravels of higher resistivity as a surface layer can reduce the risk of possible high touch & step potentials

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