EARTHING PRACTICE – Additional
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The object of an earthing system in a substation is to provide under and around the substation a surface which shall be at a uniform potential and near zero or absolute earth potential as possible. The provision of such a surface of uniform potential under and around the sub station ensures that no human being in the sub station is subject to shock or injury on the occurrence of a short circuit or development of other abnormal conditions in the equipment installed in the yard.

1. It stabilizes circuit potential with respect to ground and limit the overall potential rise.
2. It should protect the life and property from over-voltage.
3. It should provide low impedance path to fault current to ensure prompt and consistent operation of protective devices during the ground faults.
4. it should keep the maximum voltage gradient along the surface inside and around the substation within safe limits during ground faults.

EARTHING SYSTEM:

The earthing system meeting the above requirements comprises an earthing mat buried horizontally at a depth of about half-a meter below the surface of ground and ground rods at suitable points. All non-current carrying parts contribute little towards lowering the ground resistance. The earth mat is connected to following in a substation:

1. The natural point of each system through its own independent earth.
2. Equipment framework And other non-current carrying parts.
3. The earth point of lightning arresters, capacitive voltage transformers, voltage transformers, coupling capacitors and the lightning down conductors in the substation through their permanent independent earth electrode.
4. Substation fence.

The earthing system installation shall strictly comply with the requirements of latest edition of Indian electricity rules, relevant Indian standards and applicable course of practices.

PARAMETERS AFFECTING THE DESING OF EARTHING MAT:

Several variable factors are involved in the design of earthing mat conductor.Therefore, earthing mat for each substation has to designed individually usually. The earthing mat has to be designed for the site conditions to have a low overall impedance and a current carrying capacity consistent with the fault current magnitude. The parameter listed below influence the design of earthing mat:

- Magnitude of fault current;
- Duration of fault;
- Soil resistivity .
- Resistivity of surface material;
- Shock duration;

- Material of earthing mat conductor and
- Earthing mat geometry.

DESIGN PROCEDURE:

The following step are involved in the design of earthing mat:
1.The substation layout plan should be finalized before the design of earthing mat is taken up. From the proposed layout of the substation, determine the area to be covered by the earthing mat.
2. Determine the soil resistivity at the substation site. The resistivity of the earthing varies within extremely wide limits, between 1 and 10,000 ohmmeters. The resistivity of the soul at many station site as been found to be non-uniform. Variation of resistivity of soil with depth is more predominant as compare to variation with horizontal distances. Wide variation of resistivity with depth is due to the stratification of earth layers. In some sites, resistivity variation may be gradual, where stratification is not abrupt. A highly refined technique for the determination of resistivity of homogeneous soil is available.

MEASUREMENT OF EARTH RESISTIVITY:

In the evaluation of earth resistivity for substations and generation stations, at least direction shall be chosen from the center of the station to cover the whole site. This number shall be increased for very large station site of it, the test result obtained at various locations show a significant difference, indicating √variations in soil formation.

PRINCIPLE OF TEST:

Wenner's four-electrode method is recommended for these types of field investigations. In this method electrodes are driven in to the earth along a straight line at equal intervals. A current I is passed through the two outer electrodes and earth as shown in fig. And the voltage difference V, observed between the two inner electrode. The current I flowing in to the earth produces an electric field proportional to its density and to the resistivity the soil. The voltage V measured between the inner electrode is, therefore, proportion to the field. Consequently, the resistivity will be proportional to the ratio of the voltage to the current, i.e., R. the following equation holds for:

$$\rho = \frac{4 S \pi R}{1 + \frac{2s}{\sqrt{S^2 + 4 C^2}} - \frac{S}{\sqrt{S^2 + e^2}}} \quad \text{----------------------------------(1)}$$

where

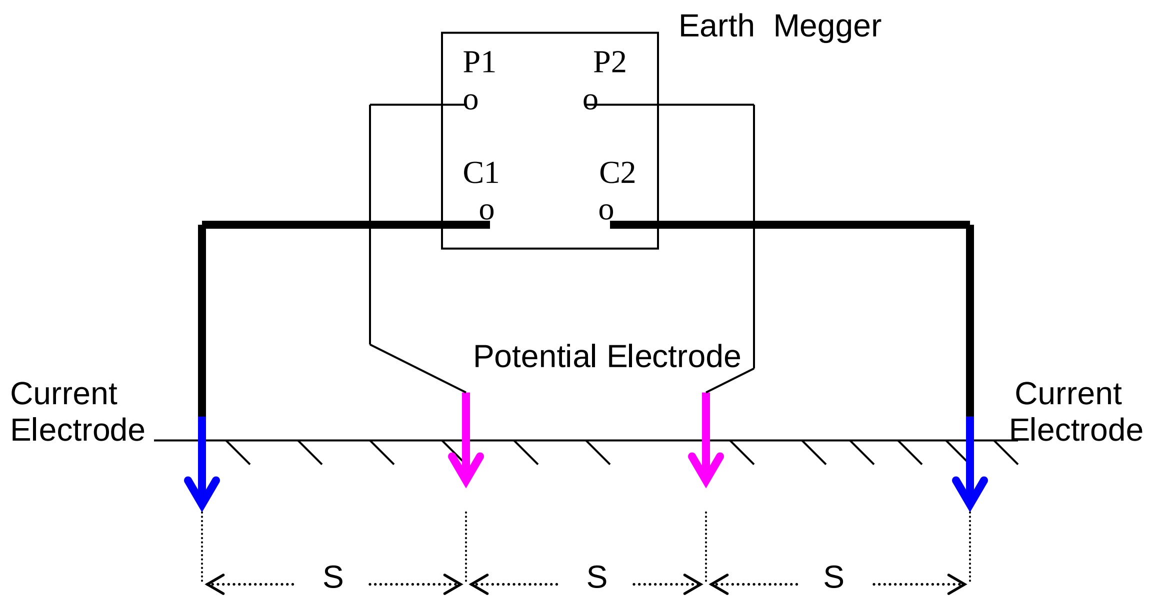
ρ = resistivity of soil in Ohm-meter,

s = distance between two successive electrodes in meters,
R = ratio of voltage to current or electrode resistance in Ohms,
e = depth of burial of electrode in the ground is negligible compare to the spacing between the electrodes, then,

$\rho = 2 \pi \ S R$ ------------------------------ (2)

Test Procedure

Four electrodes are driven in to the earth along a straight line at equal intervals, S. the depth of electrode in the ground shall be of the order of 10 to 15 cm. The megger is placed on a steady and approximately level base. The four electrodes are connected to the instrument terminal as shown in fig. (1) be



Connection for a four – terminal Earth Megger

After proper connections, range appropriately selected and by cranking the megger at prescribed speed (135 rev/min). Resistivity is calculated by substituting the value of "R" thus obtained in the equation No.(2). Incase depth of barrier is more than $1/20^{th}$ of the spacing, e.g. (1) should be used instead of (2).

Determine the maximum ground fault current:

Fault current at the substation is determined from the system studies. A correction factor is applied to the fault current thus determined to take care of future growth of the system. Value of this correction factor is usually of the order of 1.2 to 1.5. However, in practice 40ka for 400kv system and for 220/132kv systems are generally adopted for design purposes.

Duration of fault:

For the design of earthing mat, the practices regarding assumption of duration of fault differ from the country to country. In India, the short time rating of most of the equipment is based on 1.0 sec.duration of fault. Therefore 1.0sec. may be adopted as the duration of fault in the calculations to determine the size of conductor of earth mat. For the purpose of determining the safe step and mesh potentials a duration of 0.5 sec.may be adopted.

Determining the size of Earth Mat

a) Size based on Thermal Stability The thermal stability is determined by the following formula as per IEEE 80-1986

$$A_C^2 = \frac{I_f.(t_c.\lambda_r.\rho_r.10^4/T_{cap})}{l_n\{1+(T_m-T_a)/(K_0+T_a)\}} \quad \text{-------------------------------(3)}$$

T_{cap} =Thermal Capacity factor in joule /cm^3 /^{o}C as per IEEE table

=4.184SH.SW

Where SH is sp.heat in cal/gm/^{o}C,SW sp wt in gm/cm^{3}of Material.

t_c =Time of current flow, in seconds

ρ_r = resistivity of ear thing mat conductor at ref. Temperature $T_{r, in}$ μΩ/ cm^3

A = conductor X-section in mm^2

I_f = rms value of symmetrical fault current in KA

λ_r = co-efficient of linear expansion of earthing conductor

T_r = ref.temperature for material constant in degrees Celsius(C ^{o})

T_m = maximum temperature in Celsius(C ^{o}) for joints (welded or bolted)

Ta = ambient temperature in degrees Celsius (^{o}C)

$$K_o = \frac{1}{\lambda_r} - Tr$$

Let us take a case of design with parameters as under:-

I_f = symmetrical fault current 25KA

t_c =Duration of fault current 1sec

ρ =soil resistivity of substation area 161Ω-meter

A_e=area of the main earthmat

Length of main earthmat 70 mtr.

Breadth of main earthmat 56 mtr.

A_s= Area of satellite earthmat 8526 sq.meter

Length of satellite earthmat 98mtrs.

Breadth of satellite earthmat	87mtrs.
h.depth of buried conductor	0.5mtr.
l_t= thickness of surface material	o.15mtr.

<u>The values of Various Constants in the Equation applicable to MS Steel rod are</u> : -

T_{cap} = $4.184 x S_h x S_w$ Sh(Sp.heat MS rod)=0.114K Cal./Kg/ ^oC,
Sw (Sp.Weight)=7.86gm/cc

t_c =1.0 , in seconds

ρ_r = 0.00423 at 20^o centigrade

α_r = **0.00423 at ref.20 ºC** temperature

Tr = ref.temperature for material constant in degrees celcius(C ^{o})

Tm = 620 maximum allowed temp. in degrees celcius(C ^{o}) welded joint

Ta = 50 ºC temperature in degrees celcius(^{o}C)

I_g = 25KA rms value of current in Kamps.(KA)

Ko = 1/0.00423-20 =216

Hence substituting the value in equation-3 above for rod type ground conductor the area Ac works out as 304 sq. mtr. Therefore, dia of rod material is ;
Dia=$\sqrt{}$(4x304)/ π=19.6mm.

To standardize the size of ground conductor a uniform corrison allowance of 0.12mm per year is considered for life of substation as 40 yrs.
A corrosion allowance to diameter= 40x0.12x2mm, i.e. 9.6 mm
The diameter of the gournd conductor after considereint the corrison effect shall be selected from;
D>=(19.67+9.6)mm or 29.6 mm
The diameter of the ground conductor was selected as 32mm.

Mechanical Ruggedness of Conductor

The mechan consideration are important from ruggedness point of view.It is considered that width to thickness ratio of steel flat for ground mat conductor should be 7.5 such that thickness of the flat is not less than 3mm.Ground mat conductor comprising steel rod having a dia not less than 5 mm .The standard sizes of conductor are :-

1) 10 x6 mm^2
2) 20 x6 mm^2
3) 30 x6 mm^2
4) 40 x6 mm^2
5) 50 x6 mm^2
6) 60 x6 mm^2
7) 50 x8 mm^2
8) 65 x8 mm^2
9) 75 x12 mm^2

Corrosion

In soil steel corrodes 6 times faster than copper. The extent of corrosion depends upon properties of soil.Some have conflicting properties and appear to be corrosive while other appear opposite.A fair degree of co-relation has been found between resistivity of soil and corrosion.This relationship called as corrosivity is indicated below.

SOIL RESISTIVITY and CORROSION

Range of soil resistivity (Ohm-metre)	**Class of Soil**
Less than 25	Severly corrosive
Between 25 – 50	Moderatly corrosive
Between 50 – 100	Mildly corrosive
Above 100	Very mildly corrosive

Determination of Maximum Grid Current

Design of maximum Grid current I_G is given by the following equation :

$$I_G = C_P \,.D_f \,.\, I_g$$

Where

I_G = Maximum Grid Current in Amps

C_P = Corrective projection factor for relative increase of fault Current during s/s lifespan

I_g = Symmetrical grid current in Amp rms

S_f= Current Division Factor depends on fault location

S_f is dependant on a)lacation of fault b)Station earth Mat resistance c)Burried pipes and cables in vicinity and connected to station earthing system d)O/H ground wire or Neutral conductor.

S_f is computed by deriving the equivalent representation of O/H grount wire ,neural etc connected to earthing mat and then solving the equivalent to determine the fraction of Fault current which flows into the mat andearth and through the ground wire or neutral.

$$S_f = \frac{\text{Combined eq. Resistance of O/H wire as seen from Fault}}{\text{Combined eq. Resistance of O/H wire as seen from Faul t+Stn ground Resistance to remote earth}}$$

I_0=Zero sequence fault current.

$$I_{0 \text{ for L-L-ground fa}} \quad \frac{E\,X_2}{\dfrac{X_1(X_0 + X_2) + X_2.X_0}{E}}$$

$I_{0 \text{ for L-ground fault}} = \frac{}{X_1 + X_2 + .X_0}$

Where E = phase to neutral voltage

The value of X_1, X_2, $.X_0$ the sequence reactance are computed looking into the ststem from point of fault.

Calculation of current division factor (Sf) for earthing system with lines as part of earthing system.

It is considered that a portion of the fault current is diverted through the overhead shield wire of the transmission lines.

The self impedance, Z_{gi} of the overhead ground wire is calculated by the following expression:

$$Z_{gi}=r_e+0.000988f+j0.0028938fx\log_{10} (D_e/GMD)$$

$\sqrt{ts}$

R_e= is resistance of overhead ground wire.

F= is the system frequency.

D_e= is the equivalent depth of the earth return and is given by, $D_e=658.4\sqrt{(p/f)}$;p is the soil resistivity and

GMD= is self GMD of the earthwire and is given by GMD=0.7253xra;ra is the radius of the overhead ground wire.

For,

R_e = 3.375ohms/Km, f=50 Hz., p=161 ohm mtr. And

R_a=9.45x10-3 mtr.

D_e=1181.46mtr. GMD=0.003427 m

The self impedance, Z_{gi}=3.4244+j0.8 ohms=3.5517ohm.

The equivalent impedance of the overhead ground wire for each line, Z_a is calculated as follows ;

$Z_a= (0.5Z_{gi} +\sqrt{(Z_{gi}.R_i)})$

Where R_i is the impedance of remote earth of the tower (10 Ohm assumed)

With the above values of Z_{gi} and R_i

Z_a=7.689Ohms.

As five lines are terminating at the substation, the combined equivalent impedance

Z_{eq}=7.689ohm/5=1.538 Ohms

$S_f=Z_{eq}$ IIR_G

S_f=(1.538x1.17)/(1.538+1.17)=0.6645

The maximum grid current, IG=Sf.(3I_o)=$S_f.I_f$

Or I_G=0.6645x25kA=16.613kA.

Calculation of permissible Touch and Step Potential

Touch potential and step potential has been calculated based on formulae given:

$E_{touch}=(1000+1.5 x C_s X \rho_s).(0.116/\sqrt{t_s})$
$E_{step}=(1000+6.0 x C_s X \rho_s).(0.116/\sqrt{t_s})$

Resistivity of Surface Layer (ρ_s)

Crushed rock is used as a surface layer in sub-station for following reasons

a) It provides high resistivity surface layer
b) It serves as impedant to the movement of reptiles & likely hazards caused by them are averted.
c) It does not allow formation of pool of oil in the event of oil from oil cooled /insulated equipments in sub-station
d) It discourages lower the growth of weeds.
e) Retention of moisture in underlying soil and helps maintain resistivity of sub soil at lower value.
f) Step potential is reduced.

A crushed rock 15-20 cm is spread on entire switch yard to minimize touch potential to minimum values.

The resistivity of rock – crush is as under

Type of Rock	Range of Resistivity	Av. value of resistivity (Ohm – meter)
Morain Gravel	1000 –10,000	3000
Boulder gravel	3000 –30,000	15,000
Lime stone		5000
Primary Rock (Gries,Granite etc.)	10,000-50,000	25,000

Calculation of resistance of the Earthing Grid.

Grid resistance mainly depends on the areas covered by the grid the spacing of the grid the soil resistivity of the substation area. Lots of empirical formulae are available to calculate the grid resistance. Following expression has been used to calculate the grid resistance.

$$Rc=\rho\left[\frac{1}{LM}+\frac{1}{\sqrt{(20xA_e)}}\left\{1+\frac{}{1+h\sqrt{20/A_e}}\right\}\right]$$

Where

A_e= is the area of the ground mat.

h= is the depth of the buried conductor

LM=is the length of the total buried conductor

<u>Touch and Step Potential</u>

The Touch (mesh) potential is regarding rise of potential of grounded equipment and its structure to a value which is not dangerous to equipment and human life in the sub – station.The equation is :-

$$E_m = \frac{P\, K_m\, K_i\, I_{G\ main}}{L_M}$$

Where

K_m = is spacing factor for mesh voltage

K_i = is the correction factor for grid geometry

L_M= is effective length of the burried earthing conductor

K_m , K_i and L_M are given by IEEE Standard 80

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

D is the grid spacing

d is diameter of the earthing conductor (in metres)

K_{ii} is the corrective weighing factor that adjusts for the effects of inner conductors on the corner mesh

K_h is the corrective weighting factor that emphasizes the effects of grid depth.

n is the effective number of parallel conductor.

The grid is designed with the ground rods along the perimeter, hence by (IEEE Standard 80);

$K_{ii} = 1$

$K_h = \sqrt{(1+h/h_o)}$; h_o= 1m (grid reference depth)

$n=n_a, n_b, n_c, n_d$

For rectangular grid of the design as considered,

$n_a=2.L_C/L_P$

$n_b=1$, $n_C=1$ and $n_d=1$

L_C = is the total length of the conductor in the horizontal grid in meters.

L_P = is the peripheral length in meters.

K_i= is given by the following expression;
K_i=0.644+0.148.n

$$L_M = L_C + \left[1.55 + 1.22 \left\{ \frac{L_r}{\sqrt{(L_x^2 + L_Y^2)}} \right\} \right] . L_R$$

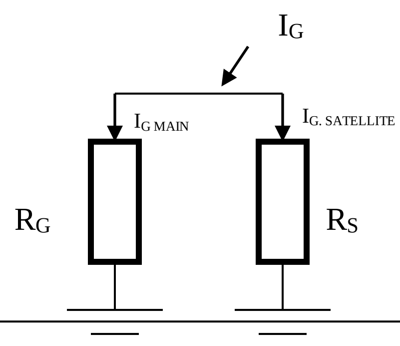
Where
L_x = is the maximum length of the grid in X- direction in meters.
L_y = is the maximum length of the grid in Y- direction in meters
L_r = is the length of each ground rod in meters and
L_R = is the total length of all ground rods in meters.

Design of the Main Earthmet
Total number of 3m long rod (electrodes) with a spacing of 8mtrs. With 125 rods in the Main Earthmet. Grid spacing 8 mtrs.
So, L_r= 3m and L_R =3x125=275 m
L_x=70m, L_y=56 m
L_P=2(70+56)=252m
L_c=70x7+56x10=1056m

Therefore,
L_M=1653m
Na=2x1056/252=8.38
n= $n_a.n_b.\ n_c.n$
=8.38.1.1.1=8.38
K_i=0.644+0.148.8.38
=1.884
K_h=1.225

Even with grid spacing of 2.5mtr., the potential attained is more than the tolerable touch potential hence the design of main earth was not possible without considering an auxiliary earthmat also known as auxiliary satellite earthmat. This was to increase the area w.r.t. touch potential.

The idea of auxiliary earthmat is to provide a parallel earthmat as per drawing given below:-



DIVISION OF PART OF IG THROUGH SATELLITE MAT

$$\mathbf{IGmain = IG.} \left(\frac{\mathbf{Rs}}{\mathbf{RG+Rs}} \right)$$

And

$$\mathbf{IG\ satellite = IG} \left(\frac{\mathbf{RG}}{\mathbf{RG+RS}} \right)$$

The resistance of the satellite ground mat.

$$\mathbf{RS = p_s} \left[\frac{1}{L_{MS}} + \frac{1}{\sqrt{(20xA_s)}} \left\{ 1 + \frac{1}{1+h_s\sqrt{(20/A_s)}} \right\} \right]$$

Where
A_s= is the area of the satellite ground mat.
H_s= is the depth of buried conductor in satellite ground mat.
L_{MS}= is the length of the total buried conductor in satellite ground mat.

Calculated values of grid resistances for main earthmat and satellite earthmat.

The value of the soil resistivity of the satellite mat, ps=50ohms-meter grid spacing for the satellite mat is considered as 3.5m and 125 numbers 3m long rod electrodes has been laid under the satellite earthmat.

With the parameters given above, the value of grid resistances for the main earthmat and satellite earthmat;

R_G=1.2276 ohm and RS=0.248 ohms
I_{Gmain} =2792 Amps and
$I_{G\ satellite}$=13821 Amps.

The main earthmat has been designed with the grid spacing, D=8m
For D=8m, Km=0.355

$$E_m = \frac{(161).\ (0.355).(1.884).2792)}{\quad} \text{ volts}$$

1653

or E_m=182 volts< 845 volts (E_{touch})
The attainable step potential is calculated by the following expression [1];

$$E_s = \frac{p.K_s.K_i.I_G}{L_s}$$

Where
K_s= is the spacing facto for step voltage.
K_i=is the correction factor for grid geometry and
L_s=is the effective length of L_C+L_R for step voltage in meters.
$L_s=0.75.L_C+0.85L_R$

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

L_s=(0.75).(1056)+(1.884).(375)m=1111.0m

K_s=0.395

$$E_s = \frac{(161).(0.395).(1.884).(2792)}{1111} \text{ volts}$$

or E_s=30 Volts <2887 Volts (E_{step})

Etransferred=$I_G.R_G$=(2830).(1.2276) Volts=3474 Volts

So, the design of themain earthmat is safe w.r.t. touch and step potential.

Calculation of permissible Step Potential for the Satellite Earthmat.

The permissible and attainable step potential are calculated based on the same formulae as considered in the design of the main earthmat.

$E_{step}=(1000+6.0xC_sxP_s).(0.116/\sqrt{t_s})$

C_s=1 for the satellite earthmat.

$E_{step.s}=(1000+6.0x1x50).(0.116/\sqrt{0.5})$=213.26Volts

Calculation of attainable step potential for satellite earthmat.
The satellite mat was laid at a depth of 1m with grid spacing of 3.5m.

$L_{s.s.}$=(0.75).(5071)+(0.85).(375)m=4122m

$h_{a.s}$=2x5071/370=27.4

$n_s=n_{a.s}.n_{b\ .s}.n_{.e.s}.n_{d.s}.$

=27.4.1.1.1=27.4

$K_{i.s.=}$0.644+0.148.27.4=4.699

$$K_{.s.s}= \frac{1}{\pi}\left(\frac{1}{2x1} \quad \frac{1}{3.5+1} \quad \frac{1}{3.5} \quad (1\text{-}0.527.4\text{-}2) \right)$$

=0.268

$$E_{s.s}= \frac{(50).(0.268).(4.699).(13821)}{4122} \text{Volts}$$

$E_{s.s}$=211Volts<213.26Volts ($E_{step.s}$)

So, it was found that the design of the satellite earthmat was safe even without considering the surface material (gravel).