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Comparison between Earthing System Designing Parameters for Different Types of Soil Resistivity Area and Minimization of Limitation

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Abstract: ***This paper presents the design of safe, reliable and effective earthing system designing for different types of soil resistivity area. Also present the calculation of parameters and comparison between their parameters. Know very well that substation soil resistivity is very important factor for earthing system designing. According to soil characteristics(soil resistivity, soil structure and soil model)designed the earthing system of AC substation. This paper mainly focuseson the soil resistivity. Earthing system provides the low resistance path for fault current therefore when designing earthing system it is advisible to locate the area with lowest soil resistivity in order to achieve the economical and effective earthing system. If any case low resistivity area is not available, can managed with other types of soil but for high resistivity soil area to attain low ground grid resistance may be difficult and costly. This paper also discuss about minimization of this difficulty without change the soil characteristic.***

Keywords: Grid resistance, ground grid design, ground potential rise (GPR), ground rod, Earth pit, soil resistivity, current division factor, step potential, touch potential

1. Introduction

The 'earthing' means connecting of non-current carrying parts of electrical equipments (such as transformer tank, circuit breaker operating box and pole structure etc.) and neutral point of the supply system (such as neutral of star connected transformer) to the general mass of earth(soil) in such a manner that all unwanted and fault current suppressed in earth without enters in human body and healthy equipments.Earthing system is the system where electrical connection of earth conductors and earth electrodes which placed vertically and horizontally in contact with soil and some distance below of ground level. Main purpose of earthing system is to provide low resistance path for safe passage of fault current to enable to operate protective and control devices and also provide safety to personnel and substation equipments.

In any substation, a good designed earthing system plays an important role and required considerable attention while designing because without this mal-operation and non operation of control and protective devices and security of substation equipments and personnel are also not sure.

Field data (For three different type soil resistivity) obtained from different types of soil area. Substation data collected from the 220KV substation, Rampur, Jabalpur(MP).

Various standard equation and methodology used-
- IEEE std 80-2000, "IEEE guide for safety in AC Substation grounding"
- IEEE std 81-2012 "IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System"
- IS:3043 "Code of practice of earthing"

2. Objective of Earthing System

All the objective of earthing system is very important not only tha protection of personnel and equipments but also for optimal operation of whole power system (control, protective and communication system.)

Following objective of earthing system:-
- The earthing system provides a low resistance path for fault current (comes from the non current carrying part of equipments due to earth fault and insulation failure) to provides protection for substation equipments and personnel.
- Earthing system provides ground connections for grounded neutral system (star connected transformer).
- Earthing system provides discharge path for lightning Arrestors, protective gaps and other similar devices which provides safety of equipments and personnel against lightning and surges.
- Earthing system provides low resistance grid relative to remote area prevents the dangerous ground potential rises (touch and step potential).
- Earthing system also provides a reference and ground potential for electronic, communication and instrumentation system. Also used for reduction of noise.

3. Terminology

Standard terms are very important for understanding of earthing system designing:-
- **Earth**:- The general(conductive) mass of soil, whose electric potential is conventionally taken as zero.
- **Earthing**:-Earthing is achieved by electrically connecting of earth electrodes which placed in intimate contact with the soil and some distance below ground level.
- **Earthing electrodes**:- A conductor placed inside the earth and contact with a soil, is called earthing electrode. It is used

for collecting fault current from faulty circuit and dissipate ground current into earth.

- **Earthing conductor**:-Earthing conductor provides electrical connections of earthing terminal of equipments with earhing electrodes (grid) to pass the fault current from faulty circuit to earthing.
- **Earth grid**: A system of earthing electrodes which placed below ground level and consists vertical and horizontal inter connections of electrodes in a pattern over specified area to provide common ground for electrical devices and structure.
- **Earthing system**:- Whole assembly of earthing, earthing conductors and earth grid is called earthing system.
- **Earth resistance**:-The resistance offered by the earth electrodes to flow of current into the ground is known as earth resistance. Earth resistance between earth electrode, grid or system and remote earth(having zero potential). Earth resistance should be as low as possible and should not exceed the following limits (show in table-1):-

Table 1: Permissible earth resistance value[5]

Particulars	Permissible resistance
Large substations	0.5Ω
Major substations	1.0 Ω
Small substations	2.0 Ω
Tower foot	8.0 Ω

- **Step potential**:-Step potential is the potential difference between the feet of a person standing or spacing between one step on the floor of substation, during the flow of fault current in earthing system
- **Touch potential**:-Touch potential is a potential difference between the hand touching the faulted structure and feet of person standing on substation floor.

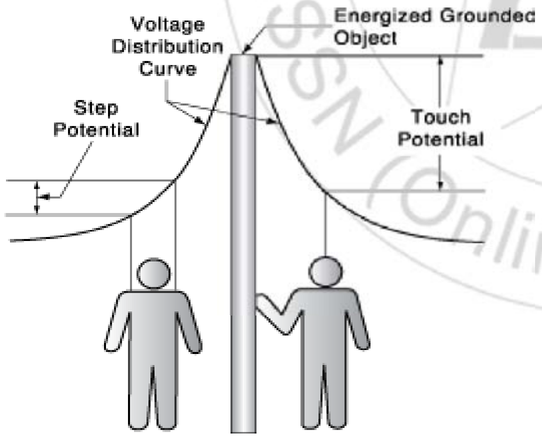

Figure 1: Step and touch potential

- **Ground potential rise:-**The maximum ground potential within substation earthing may attain relative to away ground point assumed to be at the potential of remote earth.
- **Mesh potential:-** The maximum touch potential within substation earthing grid.

4. Design Procedure of Earthing System

Field data collection

- Layout of area.
- Soil model investigation.
- Soil resistivity test.
- Surface material selection.
- Surface material resistivity.

Substation data collection:-

- Maximum fault current.
- Fault clearing time.

Parameters calculations:-

- Conductor size.
- Touch potential criteria.
- Step potential criteria.
- Grid resistance.
- Maximum grid current
- Ground potential rise (GPR).
- Actual touch potential.
- Actual step potential.

Verification:-

- It must actual step and touch potential lower than step and touch potential criteria.
- Grid resistance must lower than 1 Ω.

5. Soil Characteristics

Detailed investigation of soil resistivity is essential for design of earthing system. Boring test samples and other geological investigations are used for the resistivity investigation of substation site for determining the general soil composition and degree of homogeneity. These investigations provide useful information such as presence of various layers and nature of soil material and range of resistivity at substation site. Range of resistivity for different types of soil show in table-2[1]

Table 2: Range of resistivity

Types of soil	Average resistivity
Wet soil	10
Moist soil	10^2
Dry soil	10^3
Rock soil	10^4

First investigate the model of soil. Basically two types of soil model:-

- Uniform soil model.
- Non-uniform soil model.

Non-uniform soil model also classified in two types:-

- Two layer soil model.
- Multi-layer soil model.

Soil model investigation is the most difficult part to obtained apparent resistivity. Main objective of soil model is a good approximation of the actual soil. Soil resistivity varies horizontally and vertically, depending on the soil stratification. Seasonal variations may occur in soil resistivity due to varying weather conditions (as high resistivity in summer season and low resistivity in rainy season).

Uniform soil model and two layer soil model are most commonly used resistivity model. When there is a moderate variation in apparent resistivity should be used uniform soil model. For homogenous soil condition the uniform soil may be give accurate result. In practice, homogenous soil conditions very rarely occurred. If there is a large variation in measured apparent resistivity, the uniform soil model is not yield accurate results. In such instances a non-uniform soil model may be required. Two layer soil models are often a good approximation of many soil structures while multilayer soil models may be used for complex soil conditions. The two layer soil model consists of an upper layer of finite depth and lower layer of infinite depth with different resistivity. There are various methods to determine an equivalent two layer soil model from apparent resistivity obtained from field tests. In some instances a two layer soil model can be approximated by graphical inspection of a plot graph between apparent resistivity versus depth or apparent resistivity versus probe spacing from wenner four pin measurements. In some instances the variations in soil resistivity may exhibit minimums and maximums such that an equivalent two layer model may not give an accurate results. In such instances a different soil model, such as a multilayer soil model, may be required. Computers programs available to the industry may also be used to derive a two layer soil model and multilayer soil model. Typical resistivity for different types of soil show in table-3[3].

Table 3: Typical resistivity for different types of soil

Types of soil	Probable value	Range value
Light clay	5	Depends on areas
Clays	10	5 to 20
Marls	20	10 to 30
Porous limestone	50	30 to 100
Porous sandstone	100	30 to 300
Compact limestone	300	100 to 1000
Clay slates	1000	300 to 3000
Granite	1000	300 to 3000
Rock	2000	1000 upwards

5.1 Soil resistivity measurements

Soil resistivity is very important factor for earthing system designing so more attention required while measuring soil resistivity. The resistivity of soil varies appreciably with depth and also horizontally, it is often desirable to use an increased range of probe spacing on order to obtain an accurate value of resistivity. Due to more probe spacing, the source current penetrates more in both vertical and horizontal directions.

Several techniques are available for measuring soil resistivity. The wenner four pin methods[2] is most commonly used technique as show in figure-

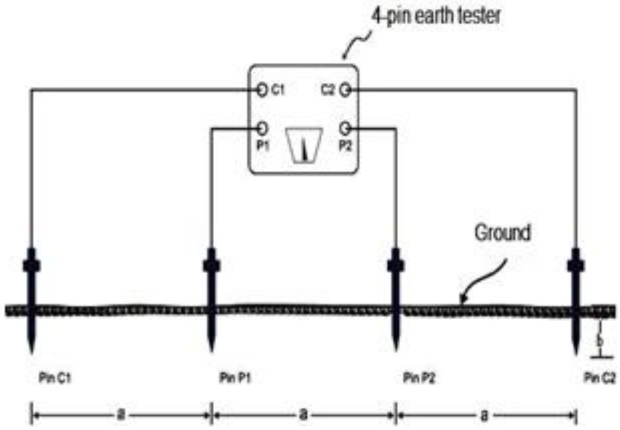

Figure 2: Wenner four-pin method

In wenner four pin method four probes are used therefore it is called four pin method. Four probes are buried into the earth with depth ‘b’ at equal distances ‘a’ apart along a straight line. Outer probes used for flowing known current while inner two probes used for measured voltage and divide the value voltage and current then get the value of resistance ‘R’. By means of four pin earth tester can measured direct value of resistance ‘R’ then get the value of apparent resistivity by equation-

$$\rho_a = \frac{4aR}{1+\frac{2a}{\sqrt{a^2+4b^2}}-\frac{a}{\sqrt{a^2+b^2}}} \qquad (1)$$

Where

ρ_a is the apparent resistivity of soil in Ω-m
R is the reading of earth tester in Ω
a is the probe spacing in m
b is the depth of buried probe in m

If ‘b’ is small compared to ‘a’, then equation can be reduced to

$$\rho_a = 2\pi a R \qquad (2)$$

The approximate uniform soil resistivity may be obtained by taking an arithmetic average of the measured apparent resistivity data as shown in Equation

$$\rho_a(av) = \frac{\rho_{a1}+\rho_{a2}+\rho_{a3}+\rho_{a4}+\cdots\rho_{an}}{n} \qquad (3)$$

where

$\rho_{a1}, \rho_{a2}, \rho_{a3}, \rho_{a4}, \ldots \rho_{an}$ is the measured apparent soil resistivity for different probe spacing

n is the number of measurements

Three different types of soil area are tested for the comparison and get following data-

- For the convenience assumed uniform soil resistivity model.
- Soil resistivity values-
  Type-1 soil resistivity (ρ_1=80Ω-m)
  Type-2 soil resistivity (ρ_2=445Ω-m)
  Type-3 soil resistivity (ρ_3=1450Ω-m)

For the soil resistivity measurements used the 4-pin earth tester which gives the direct reading of resistance(R) and for calculation used equation 2 and 3[2].

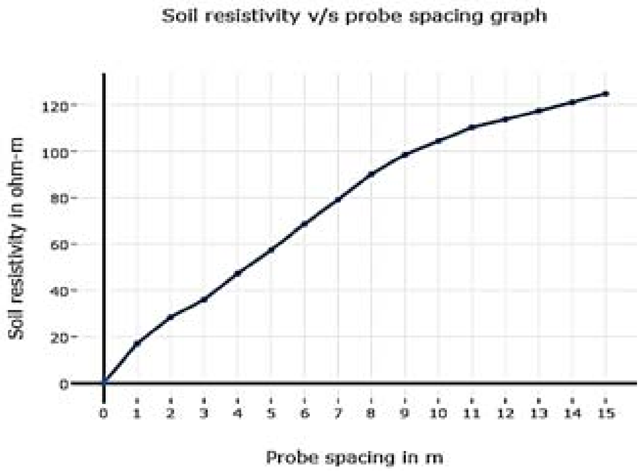

Figure 3: Apparent soil resistivity curve for type-1 soil

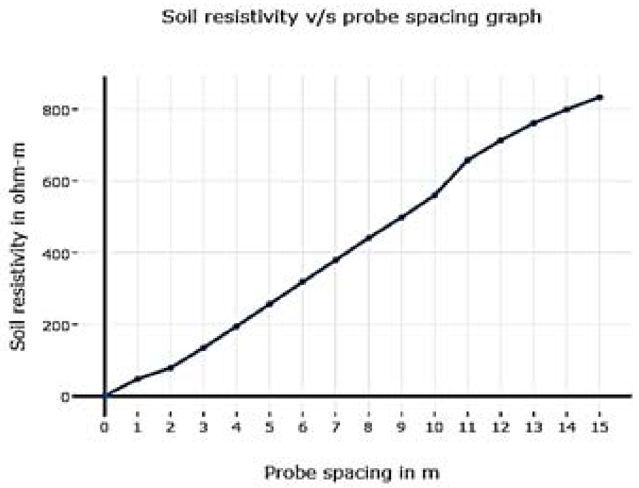

Figure 4: Apparent soil resistivity curve for type-2 soil

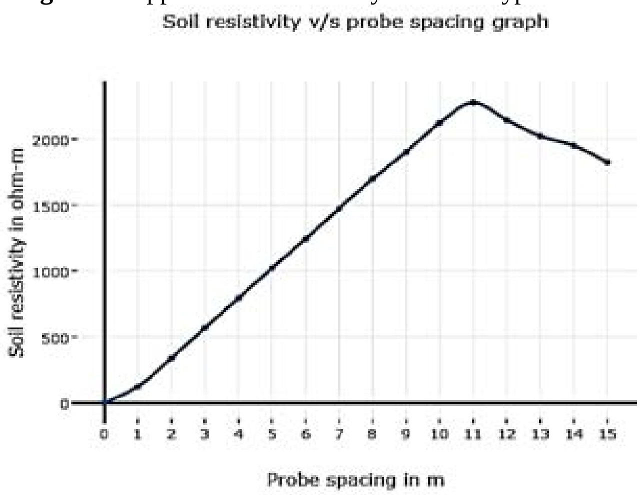

Figure 5: Apparent soil resistivity curve for type-3 soil

Soil resistivity v/s probe spacing graph for different types of soil show in fig.-3,4 and 5.

6. Details of Earthing System Items

If the value of earth resistance found more than permissible value, the same shall have to be improved by way of drilling of bore (earth pit) and installed GI pipes. Earth pit bore filled with black cotton soil (low resistivity soil) free from boulders and harmful mixture. These GI pipes are welded with M.S. flats by making mesh frame and cutting of pipes as also making holes in the pipe for water seepage which show in figure-5 clearly. The earth pit is to be connected with equipment and earth mat at least two points with M.S. flats.

Dimensions of earth pit[7]- Show in fig.-6
Height- 3 meters
Length- 1.5 meters
Width- 1.5 meters

Different size of GI pipes used[7]-
4 Nos of 40 mm diameters
3 Nos of 75 mm diameters
1 of 200 mm diameters

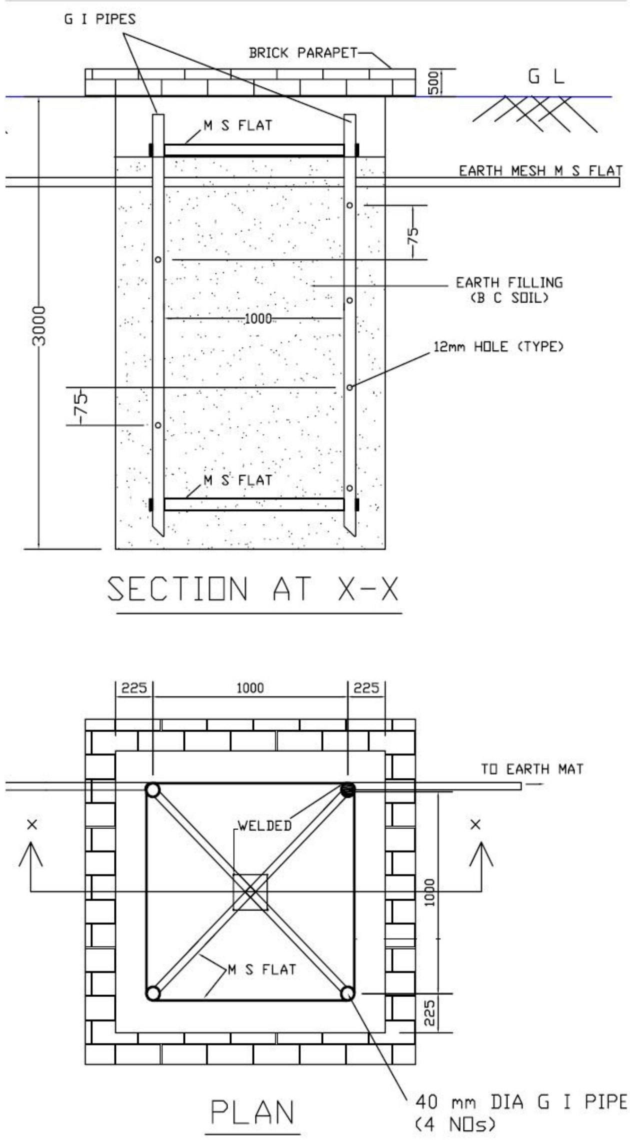

Figure 6: Details of earth pit[7]

6.1 Earthing system items details

Earthing system items such as earthing conductor, earthing electrodes and GI pipes details show in table-4

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Table 4: Earthing system items details[7]

Item	Size	Material
Main earthing conductor	75x8 mm M.S. flats (in 220 & 132 kv yard) 65x8 mm M.S. flats (in 33 kv yard)	Mild steel
Earthing of equipment structureRaiser	50x6 mm flats	Mild steel
Earthing electrodes (rod type)	25 mm dia& 3 m long	Mild steel (hot dip galvanized)
GI pipes	40mm dia, 3m long & 4 mm thick	Galvanized iron

7. Mathematical Description of Parameter

Conductor size:- Minimum conductor size equation is mentioned below-

$$A = I\frac{1}{\sqrt{\left(\frac{TCAP*10^{-4}}{t_c\rho_r\alpha_r}\right)\ln\left(\frac{K_o+T_m}{K_o+T_a}\right)}}$$

Where

I is the rms current in kA

A is the conductor cross section in mm²

Tm is the maximum allowable temperature in°C

Ta is the ambient temperature in°C

Tr is the reference temperature for material in°C

α_o is the thermal coefficient of resistivity at 0 °C in 1/°C

α_r is the thermal coefficient of resistivity at reference temperatureTrin 1/°C

ρ_r is the resistivity of the ground conductor at reference temperatureTrin Ω -cm

Ko =1/ α o or (1/ α r) – Tr

Tc is the duration of current in s

$TCAP$ is the thermal capacity per unit volume

- **Step potential criteria:-** The maximum step and potential of any place of the earthing grid should not exceed the limits defined as follow-

The tolerable step potential criteria[1,6]-
For 50 kg body weight-

$$E_{step\ 50} = (1000 + 6C_s * \rho_s)\frac{0.116}{\sqrt{t_s}}$$

For 70 kg body weight-

$$E_{step\ 70} = (1000 + 6C_s * \rho_s)\frac{0.157}{\sqrt{t_s}}$$

- **Touch potential criteria**:- Similarly as step potential criteria touch potential criteria defined as follow-

The tolerable touch potential criteria-
For 50 kg body weight-

$$E_{step\ 70} = (1000 + 1.5C_s * \rho_s)\frac{0.116}{\sqrt{t_s}}$$

For 70 kg body weight-

$$E_{step\ 70} = (1000 + 1.5C_s * \rho_s)\frac{0.157}{\sqrt{t_s}}$$

Where

$Estep$ is the step voltage in V

$Etouch$ is the touch voltage in V

Cs is the derating factor of surface layer material

ρ_s is the resistivity of the surface material in Ω·m

t_s is the duration of shock current in seconds

- **Grid resistance**:- Grid resistance or earth resistance should be as low as possible and should not exceed the permissible value which show in table-2. Grid resistance defined as follow-

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

Where

Rg is the substation ground resistance in Ω

P is the soil resistivity in Ω·m

A is the area occupied by the ground grid in m²

L_T is the total buried length of conductors in m

h is the depth of the grid in m

- **Maximum grid current[1,6]**:- This is defined as follow-

$$I_G = D_f * S_f * I_f$$

Where

I_G is the maximum grid current in A

D_f is the decrement factor

I_f is the rms value ground fault current in A

S_f is the fault current division factor

- **Ground potential rise(GPR)[1,6]:-** GPR is already defined in terminology and GPR calculated as follows-

$$GPR = R_G * I_g$$

- **Actual step potential:-** Already defined in terminology and calculated as follows-

$$E_s = \frac{\rho * K_i * K_s * I_G}{L_s}$$

Where

ρ is soil resistivity in Ω-m

E_s is step voltage between point in V

K_s is spacing factor of step voltage

K_i is correct factor for grid geometry

L_s is effective buried conductor length for step potential in m

- **Actual touch potential:-**Maximum touch potential attained by grid is called mesh voltage. Already defined in terminology and calculated as follows-

$$E_m = \frac{\rho * K_i * K_m * I_G}{L_m}$$

Where

E_m is mesh voltage at the center of corner mesh in V

K_m is spacing factor for mesh voltage

L_m is effective buried length for touch potential in m

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8. Comparison of Parameters

Various parameters are used for the calculations of earthing system designing but some parameters are confirmed the safety level of earrthing system designing such as grid resistance, actual step potential and actual touch potential.

Here we discuss about all parameters but compare only major parameters.

Different parameters for different types of soils are show in table-

Table 5: Different parameters of soil type-1

Parameters	Value	Unit
Soil resistivity(ρ)	80	Ω-m
Surface layer derating factor(C_s)	0.74	-
Division factor (S_f)	0.55	-
Grid resistance (R_g)	0.1854	Ω
Maximum grid current (I_G)	16.5	kA
GPR	3059.1	v
Tolerable step potential (E_{step})	3376.65	v
Tolerable mesh potential (E_{touch})	1010.68	v
Actual step potential (E_s)	310.06	v
Actual mesh potential (E_m)	182.68	v
Safety	Best	

Table 6: Different parameters of soil type-2

Parameters	Value	Unit
Soil resistivity (ρ)	445	Ω-m
Surface layer derating factor (C_s)	0.77	-
Division factor (S_f)	0.18	-
Grid resistance (R_g)	1.0135	Ω
Maximum grid current (I_G)	5.4	kA
GPR	5570.1	v
Tolerable step potential (E_{step})	3504.54	v
Tolerable mesh potential (E_{touch})	1042.66	v
Actual step potential (E_s)	564.45	v
Actual mesh potential (E_m)	332.57	v
Safety	Acceptable (not good)	

Clearly show in the table-5 that for soil type-1 the safety level is best because all criteria and permissible value fulfilled according to verification of designing such as-

- Actual mesh potential (168.68) much lower than tolerable mesh potential(1010.68)
- Actual step potential (310.06) much lower than tolerable step potential (3376.65)
- Grid resistance value also much lower than 1Ω
- Therefore safety level is best.
- In the table-6 for soil type-2 the safety level is only acceptable because here one criteria is not full filled and other fulfilled, they are-
- Actual mesh potential (332.57) much lower than tolerable mesh potential(1042.66)
- Actual step potential (564.45) much lower than tolerable step potential (3504.54).

Table-7: Different parameters of soil type-3

Parameters	Value	Unit
Soil resistivity (ρ)	1450	Ω-m
Surface layer derating factor (C_s)	0.86	-
Division factor (S_f)	0.06	-
Grid resistance (R_g)	3.3613	Ω
Maximum grid current (I_G)	1.8	kA
GPR	6050.3	v
Tolerable step potential (E_{step})	3888.21	v
Tolerable mesh potential (E_{touch})	1140.25	v
Actual step potential (E_s)	613.08	v
Actual mesh potential (E_m)	361.22	v
Safety	Worst	

- Grid resistance value slightly more than 1Ω which is only acceptable but not well according to safety purpose. Therefore safety level only acceptable not good.
- Similarly in the table-7 for soil type-3 the safety level is worst because here one criteria is not full filled and other fulfilled, they are-
- Actual mesh potential (360.22) much lower than tolerable mesh potential(1138.58)
- Actual step potential (613.08) much lower than tolerable step potential (3888.21)
- Grid resistance value more than 1Ω which is not acceptable.

Therefore safety level is worst.

Graphical representation also show in graphs-

- Figure-7 Mesh potential curve
- Figure-8 Step potential curve
- Figure-9 Grid resistance curve

9. Minimization of Limitations

Several types of techniques are available for minimization of limitation such as-

- **Decreasing ground grid spacing[4]**- This method is good for the large area substation and worst for small area substation with high resistivity because in small substation higher potential gradient in outer side of the perimeter of grid. This technique is not feasible for the completely installed substation. This is more expensive technique but effective for the reducing grid resistance. Commonly 3-7 meters grid spacing is used in india.

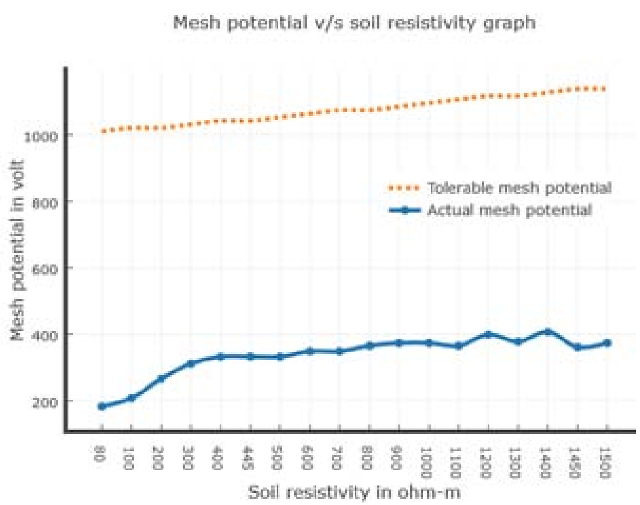

Figure 7: Mesh potential curve for different soil resistivity

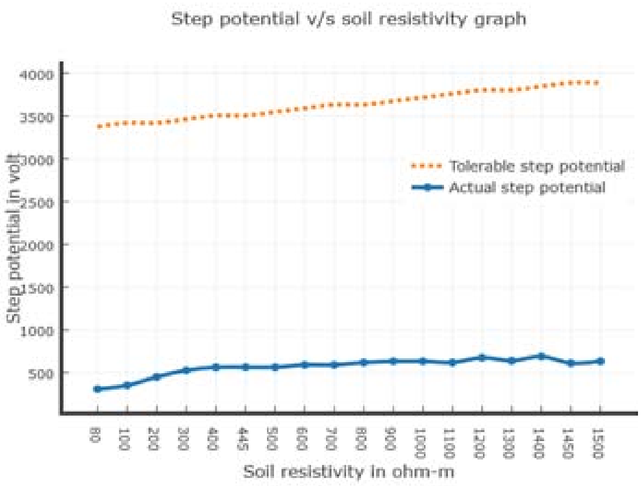

Figure 8: Step potential curve for different soil resistivity

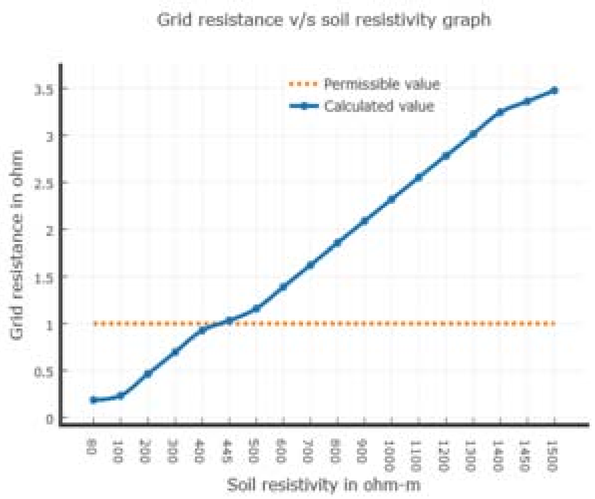

Figure 9: Grid resistance curve for different soil resistivity

- **Boring earthing pits**- This technique is best for the completely installed substation. This technique is more effective than others techniques for reducing the grid resistance therefore this technique are used in mostly substation in india. More details about earth pits already mention in above sections.

- **Using longer and more ground rods**- By this technique effective metallic area is increased, thus resistance decreases. This technique also help for lowering the potential gradient but not feasible for the completely installed substation.

- **Decreasing fault clearing time[4]**- By decreasing the fault clearing time managed the tolerable step and touch potential. This is done by using fast speed relay and fast tripping circuit breaker. By this method cannot reduce the grid resistance value.

- **Decreasing current division factor**- Current division factor defined as divert the amount of fault current flowing through the grid by other means. This is done by connecting overhead ground wires of transmission lines or by decreasing the tower footing resistances. Sometimes near tower footing high potential gradient occur therefore this technique is rarely used and if used then required more attention. By this method cannot reduce the grid resistance value.

- **Using high resistivity surface layer material[4]**-This technique is rarely used. Commonly black gravel (2800-3500 Ω-m) is used in india. Surface layer material increased the contact resistance between soil and human feet therefore low potential rise. If much higher resistivity surface material or high thicker layer (more than 5 inch) is used then can managed allowable step and touch potential.

Commonly used technique is boring the earth pits within substation in india. In 220 kV substation used this technique.

In above sections clearly show that for soil type-2 and soil type-3 the calculated value is higher than permissible value of grid resistance. For reducing the grid resistance value used the boring earth pits technique. Here we used different numbers of earth pits and get following result and show in fig.-10.

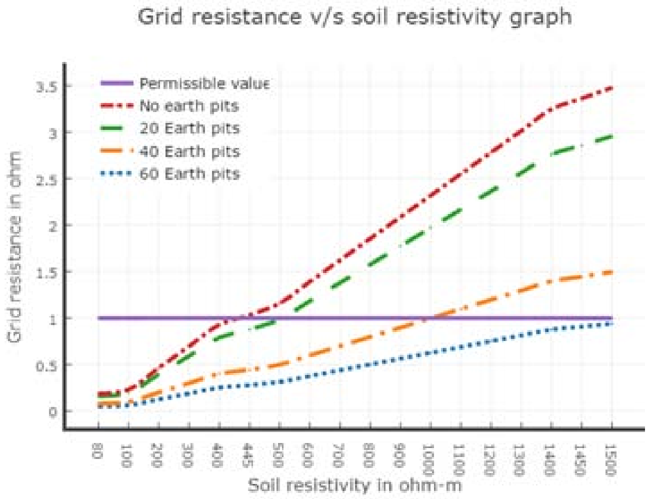

Figure 10: Grid resistance curve for different soil resistivity with modification

10. Conclusion

It provides guidance for designing a safe and reliable substation earthing system for different types of soil resistivity. For low resistivity area very easily safe and economically earthing system achieved and not required more attention therefore always suggest choosing the low resistivity area. For high resistivity area unlike the low resistivity area, to achieve the safe, reliable and economical earthing system is difficult and required considerably attention. This paper also discussed about various alternatives to achieve low grid resistance and safe step and touch potential.

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