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Electrical Earthing: Overcoming Grid Resistance in Restricted and Highly Resistive Soil Environments

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Abstract

In this paper, optimization software was used in the design of an earthing system for a substation located in a restrictive and highly resistive soil area. The software could not obtain the required grid resistance and to overcome this, the grid resistance were further reduced through the contributing part of the earth rods using soil enhancing materials. The final results obtained met the touch and step voltage criteria as well as the required grid resistance.

Keywords: Optimization, substation, grid resistance, soil, enhancement.

1.0 Introduction

Earthing has now become an important aspect of electrical power system [1-3]. Proper earthing is a measure of the degree of safety in the system. For an earthing system to be regarded as providing protection to personnel in a system it must satisfy the touch and step voltage criteria apart from having a low grid resistance. Obtaining a low grid resistance is a function of two factors; these are the layout of the site and the soil resistivity of the site. The earthing system of a power installation plays a pivotal role in providing a safe environment for personnel and avoiding damage to equipment, particularly during fault conditions. Interest in earthing has been rekindled in recent years due to injuries, equipment damage and factors that have increased the external environmental effect of power faults.

The importance of effective earthing is outlined as follows [4]:

i. Reduce the risk of human exposure to the danger of critical electric shock due to touch or step voltages produced in a fault condition.

ii. Provide means to carry and dissipate electric currents into earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

iii. Provide grounding for lightning impulses and the surges occurring from the switching of power installation equipment, which reduces damage to equipment and cable.

iv. Provide a low resistance for the protective relays to sense and clear ground faults, which improves protective equipment performance, particularly at minimum fault.

Due to rapid urban development, the layout available for the location of substation is becoming limited. This had made the requirement for a low grid resistance rather difficult. With this difficulty in mind, an earthing designer often resorts to all manner of methods in order to attain a low grid resistance. In this paper we designed a safe and efficient substation earthing grid using conventional practices [5] for a restricted (limited land area) and highly resistive soil (soil with high electrical resistivity $> 100\Omega m$) environments. This practice if followed will help the earthing designer to overcome the associated problems thus saving cost and time.

This paper briefly discusses the methods required to make a proper soil resistivity evaluations in restricted layouts. It also covers some of the procedural aspects of substation grid design in details. The goal is to design a safe and effective earthing grid system, to evaluate and to simulate grid conductor sizing, enhancement methods for vertical rods, touch and step voltage criteria, and grid resistance which will help earthing designer to adopt a good earthing practice and avoid the unconventional practices which is a common practice in Nigeria [6].

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2.0 Safety Criteria – The Touch and Step Voltage

The maximum tolerable voltages for step and touch can be calculated empirically for body weights of 50kg and 70kg using (1), (2), (3) and (4) respectively [5],

$$E_{touch,50} = (1000 + 1.5C_S\rho_s)\frac{0.116}{\sqrt{t_s}} \tag{1}$$

$$E_{touch,70} = (1000 + 1.5C_S\rho_s)\frac{0.157}{\sqrt{t_s}} \tag{2}$$

$$E_{step,50} = (1000 + 6C_S\rho_s)\frac{0.116}{\sqrt{t_s}} \tag{3}$$

$$E_{step,70} = (1000 + 6C_S\rho_s)\frac{0.157}{\sqrt{t_s}} \tag{4}$$

where,

$$C_S = 1 - \frac{0.09\left(1-\frac{\rho_{soil}}{\rho_s}\right)}{2h_s+0.09} \tag{5}$$

where $E_{touch,x}$ is the touch voltage limit (V) for a body of weight x kg, $E_{step,x}$ is the step voltage limit (V), C_s is the surface layer derating factor, ρ_s is the resistivity of the surface material (Ω.m), t_s is the maximum fault clearing time (s)

The choice of body weight (50kg or 70kg) depends on the expected weight of the personnel at the site. Typically, where women are expected to be on site, the conservative option is to choose 50kg.

3.0 Validation of Safety Criteria

The minimum conductor size capable of withstanding the adiabatic temperature rise associated with an earth fault is given as,

$$A = i^2t\sqrt{\left(\frac{\frac{\alpha_r\rho_r 10^4}{TCAP}}{\ln\left[1+\left(\frac{T_m-T_a}{K_0+T_a}\right)\right]}\right)} \tag{6}$$

where A is the minimum cross-sectional area of the earthing grid conductor (mm^2), i^2t is the energy of the maximum earth fault (A^2s), T_m is the maximum allowable (fusing) temperature (°C),T_a is the ambient temperature (°C), α_r is the thermal coefficient of resistivity (°C^{-1}), ρ_r is the resistivity of the earthing conductor (μΩ.cm), $K_0 = \left(\frac{1}{\alpha_r} - 20°\text{C}\right)$, $TCAP$ is the thermal capacity of the conductor per unit volume(Jcm^{-3}°C^{-1})

The earthing grid resistance with respect to remote earth is given as,

$$R_g = \rho_{soil}\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right] \tag{7}$$

where R_g is the earthing grid resistance with respect to remote earth (Ω), ρ_{soil} is the soil resistivity (Ω.m), L_T is the total length of buried conductors (m), A is the total area occupied by the earthing grid (m^2), h is the depth of burial (m)

The maximum grid current I_G is calculated by using,

$$I_G = I_gD_f \tag{8}$$

where,

$$I_g = I_{k,e}S_f \tag{9}$$

$$D_f = \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{\frac{-2t_f}{T_a}}\right)} \tag{10}$$

$$T_a = \frac{X}{R}\cdot\frac{1}{2\pi f} \tag{11}$$

I_g is the symmetrical grid current , D_f is the decrement factor, t_f is the duration of the fault (s), T_a is the dc time offset constant , $\frac{X}{R}$ is the X/R ratio at the fault location, f is the system frequency (Hz), S_f is the current division factor, $I_{k,e}$ is the worse case symmetrical earth fault current.

The maximum GPR is calculated by,

$$GPR = I_GR_g \tag{12}$$

where, R_g is the earthing grid resistance.

The mesh voltage E_m is the maximum touch voltage within a mesh of an earthing grid and is given as,

$$E_m = \frac{\rho_{soil}K_mK_iI_G}{L_M} \tag{13}$$

where,

$$K_m = \frac{1}{2\pi}\left[\ln\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right] + \frac{K_{ii}}{K(h)}\ln\left[\frac{8}{\pi(2n-1)}\right] \tag{14}$$

$$K_i = 0.644 + 0.148n \tag{15}$$

and

$$L_M = L_c + L_R \tag{16}$$

For grids with few or no earthing electrodes (and none on corners or along the perimeter):

$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_r}{\sqrt{L_x^2+L_y^2}}\right)\right] L_R \tag{17}$$

For grids with earthing electrodes on the corners and along the perimeter:

where, ρ_{soil} is the soil resistivity (Ω.m), K_m is the geometric spacing factor, K_i is the irregularity factor, L_M is the effective buried length of the grid, L_C is the total length of horizontal grid conductors (m),$L_R$is the total length of earthing electrodes / rods (m), D is the spacing between parallel grid conductors (m),h is the depth of buried grid conductors (m), d is the cross-sectional diameter of a grid conductor (m), $K(h)$is a weighting factor for depth of burial = $\sqrt{1+h}$, $K_{ii}$is a weighting factor for earth electrodes /rods on the corner mesh and is $K_{ii} = 1$ for grids with earth electrodes along the grid perimeter or corners and $K_{ii} = \frac{1}{2n^{\frac{n}{2}}}$ for grids with no earth electrodes on the corners or on the perimeter, n is a geometric factor

The geometric factor n is calculated as ,

$$n = n_a \times n_b \times n_c \times n_d \tag{18}$$

where,

$$n_a = \frac{2L_c}{L_p} \tag{19}$$

$$n_b = 1 \text{ for square grids, or otherwise } n_b = \sqrt{\frac{L_p}{4\sqrt{A}}} \tag{12}$$

$$n_c = 1 \text{ for square and rectangular grids, or otherwise } n_c = \left[\frac{L_x L_y}{A}\right]^{\frac{0.7A}{L_x L_y}} \tag{21}$$

$$n_d = 1 \text{ for square, rectangular and L-shaped grids, or otherwise } n_d = \frac{D_m}{\sqrt{L_x^2+L_y^2}} \tag{22}$$

where, L_p is the length of grid conductors on the perimeter (m), L_x and L_y are the maximum length of the grids in the x and y directions (m), D_m is the maximum distance between any two points on the grid (m)

The maximum allowable step voltage E_S is calculated using

$$E_S = \frac{\rho_{soil} K_S K_i I_G}{L_S} \tag{23}$$

where,

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{n-2})\right] \tag{24}$$

where, K_s is the geometric spacing factor.

Now that the mesh and step voltages are calculated, compare them to the maximum tolerable touch and step voltages respectively. If: $E_m < E_{touch}$, and $E_s < E_{step}$ then the earthing grid design is safe.

If not, however, then further work needs to be done. Some of the things that can be done to make the earthing grid design safe:

Redesign the earthing grid to lower the grid resistance (e.g. more grid conductors, more earthing electrodes, increasing cross-sectional area of conductors, etc). Once this is done, re-compute the earthing grid resistance and re-do the touch and step potential calculations. Limit the total earth fault current or create alternative earth fault return paths. Consider soil treatments to lower the resistivity of the soil. Greater use of high resistivity surface layer materials

While considering soil treatment the following expression can be used [7-8].

$$R_g = \left(\frac{1}{R_m} + \frac{1}{R_r}\right)^{-1} \tag{25}$$

where,

$$R_m = \rho_{soil}\left[\frac{1}{L_m} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right] \tag{26}$$

and

$$R_r = \frac{\rho_{em}}{2\pi L_r}\left(\ln\left(\frac{4L_r}{r}\right) - 1\right) + \frac{(\rho_{soil} - \rho_{em})}{2\pi L_r}\left(\ln\left(\frac{4L_r}{d}\right) - 1\right) \tag{27}$$

If the pit is partially filled then R_r becomes,

$$R_r = \frac{\rho_{em}\rho_{soil}}{2\pi(H\rho_{soil} + (L_r - H)\rho_{em}}\left(\ln\left(\frac{4L_r}{r}\right) - 1\right) + \frac{H\rho_{soil}(\rho_{soil} - \rho_{em})}{2\pi L_r(H\rho_{soil} + (L_r - H)\rho_{em}}\left(\ln\left(\frac{4L_r}{D}\right) - 1\right) \tag{28}$$

If the earth rods are more than one, the earth electrode resistance $R_{n_{rods}}$ for such number of earth rods n_{rods} can be computed using,

$$R_{n_{rods}} = \frac{R_r}{n_{rods}}\left(2 - e^{-0.17(n_{rods}-1)}\right) \tag{29}$$

In that case R_g becomes

$$R_g = \left(\frac{1}{R_m} + \frac{1}{R_{n_{rods}}}\right)^{-1} \tag{30}$$

4.0 Examined Grid Configuration

The earthing grid design to be carried out will be performed with all the safety criteria in mind as well as cost minimization, thus ETAP® [9] a substation earthing grid designer will be used. The design is for a 7.5 MVA, 33/11 kV substation at Abraka, Delta State.

The input data for such design is the site's available area, soil resistivity, surface layer parameters and the transformer's fault parameters. Fig 1 shows the available area where the earthing gird is to be installed. Due to the small area, only two soil resistivity readings where carried out. Table 1 shows the soil resistivity values and the apparent resistivity. The transformer's fault current, and the surface area parameters is as shown in table 2.

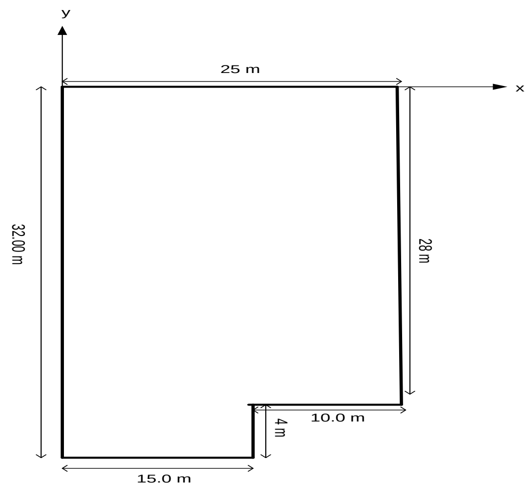

Fig.1: Available Grid area

Table1: Site Soil Profile

Spacing (a) m	R (Ω)	ρ_{soil} (Ωm)
5	10.56	331.75
10	4.68	294.05
Apparent resistivity $\rho_a = 312.9\ \Omega m$		

Table 2: System Parameters

Total fault current	2.230kA
Maximum Grid Current	2.258kA
Reflection Factor K	-0.863
Surface Layer Derating Factor C_s	0.923
Decrement Factor D_f	1.013

The input parameters were used in the Grid Earthing Module of a computer programme ETAP® and the results are shown in Tables 3 – 5.

Table 3: Grid Configuration

Parameters		
Conductor size		70 mm^2
Grid depth		0.5m
Grid Length	L_x long	25 m
	L_x short	15 m
	L_y long	32 m
	L_y short	28 m
Number of conductors in directions	X	4
	Y	3
Separations in directions	X	12.5 m
	Y	10.67 m

Table 5: Touch and Step Voltage

Results		Values
Grid Resistance R_g		5.664 Ω
Earth Potential Rise EPR		12790.2 $Volts$
Touch Potential	Tolerable	1534.5 $Volts$
	Calculated	1505.8 $Volts$
	Calculated	98.1%
Step Potential	Tolerable	5471.8 $Volts$
	Calculated	900.9 $Volts$
	Calculated	16.5%

Table 4. Rod Data

Diameter cm	Length m	Optimized Number of Rods	Arrangement
2	10	22	Rods throughout grid area

As seen in Table 5, the touch and step voltage criteria have been met. But the grid resistance is 5.664 Ohms. This value is higher than the recommended value of 1.0 Ohms. To reduce the grid resistance further we recommend that soil enhancing material like, ERICO's GEM be used only with the earth rods. In this case the grid conductor length is maintained.
The grid conductor resistance can be computed using (26) thus,

$$R_m = 312.3\left[\frac{1}{182} + \frac{1}{\sqrt{20*(25x28+4x15)}}\left(1 + \frac{1}{1+.5\sqrt{20/(25x28+4x15)}}\right)\right] = 6.59\Omega \qquad (31)$$

A hole of diameter 20 cm is drilled to a depth of 3.64 meter and fully filled with ERICO's GEM whose electrical resistivity is 0.2 Ohms-meter. The earth rod resistance for a single earth rod is computed using (27) thus,

$$R_r = \frac{1}{2\pi*3.64}(0.2[\ln(1.0/0.02)] + 312.3[\ln(8*3.64/1.0) - 1]) = 32.42\Omega \qquad (32)$$

To obtain a very low earth rod resistance we need 40 earth rods arranged in a rod bed configuration as shown in fig. 2. Table 6 replaces, table 4 in the redesign procedure. The earth rod resistance of such configuration is computed using (29) thus,

$$R_n = \frac{32.42}{40}\left(2 - e^{-0.17(40-1)}\right) = 1.62\Omega \qquad (33)$$

The new grid resistance R_g is obtained by using (30) thus,

$$\boldsymbol{R_g} = \left(\frac{\mathbf{1}}{\mathbf{6.59}} + \frac{\mathbf{1}}{\mathbf{1.62}}\right)^{\mathbf{-1}} = \mathbf{1.30}\Omega \qquad (34)$$

Table 6: Rod Data (Redesigned)

Diameter cm	Length m	Optimized Number of Rods	Arrangement
2	3.64	40	Rods throughout grid area

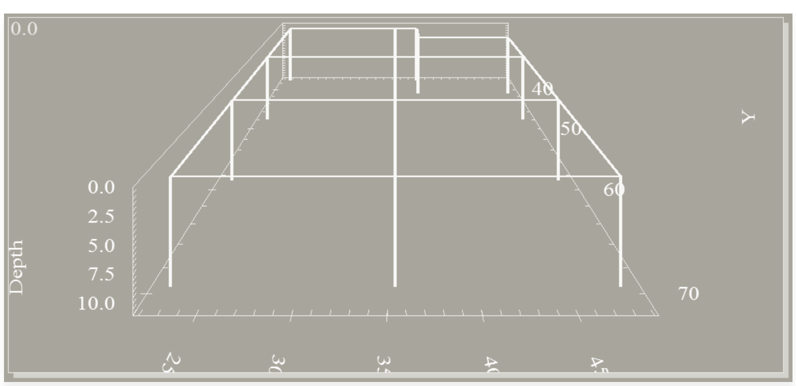

Fig. 2: Earthing Grid Design for 7.5 MVA 33/11 kV Injection Substation

5.0 Conclusion

Earthing grid design for substations is a very complex process especially if it is done on restrictive and highly resistive soil environment. In this paper a very simple procedure that enabled us to combine the grid conductor resistance as computed from ETAP® with a simplify method of reducing the earth rod resistance of vertically installed earth rods to give the desired grid resistance. The method presented eliminates the rigorous and unconventional practices usually carried out by earthing designers and allows us to perform an optimal earthing grid design on substations subject to technical and safety constraints that ensures that the twin safety criteria are not violated.

References

[1] Tabarabaei, N.N and Mortezaeei (2010) "Design of Grounding Systems in Substations By ETAP" IJTPE Vol.2, No.1, pp 45-49

[2]Unde, M.G and Kushare, B.E (2012) "Grounding Grid Performance of Substation in Two Layer Soil – A Parametric Analysis" IJESET Vol. 1, No. 2, pp 69-76

[3]Ashwani, K and Hans, R.S (2010) "Grounding System for High Resistivity Limited Area Substations in Hilly Region of Himachal Pradesh" 16th National Power System Conference, 15th-17th December, 2010, pp 516-522

[4]Osama, E.G and Hanan, M.A (2010) "Earth Surface Potentials and GPR for Grids Having Different Conductors Distributions Buried in Different Layer Soil Structures" proceedings of the 14th International Middle East Power System Conference (MEPCON'10),Cairo University, Egypt. December 19th – 21st ,2010, paper ID 229.

[5] ANSI/IEEE Std. 80-1986 "IEEE Guide for Safety in AC Substation Grounding" IEEE, New York.

[6]Ubeku, E.U and Odiase, F (2009) "Substation Earthing Grid Safety Analysis" IJEPE 3(5), pp 262-267.

[7] Nithiyanathan, K and Elavenil (2011) "GYMGRID Based Effective Earthing Design Model for Subtation" IJCAES Vol.1, No. 3, pp314-346

[8]Abdulrehman, A.A; Yasin, k; Nazar, H.N and Muhammad, I.Q (2010) "Grounding Pit Optimization for Uses in High Resistivity Areas" www.geema.org/documentos/1289821735D4qNY9yw1Dd84HZ6.pdf

[9] ETAP www.etap/com