ISSN 2056-5860

DESIGN OF GROUNDING SYSTEM FOR A.C. SUBSTATIONS WITH CRITICAL CONSIDERATION OF THE MESH, TOUCH AND STEP POTENTIALS

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ABSTRACT

Substations are a vital part of the electric power system and therefore require properly designed grounding systems to ensure protection of persons working in the vicinity of earthed facilities from danger of electric shock, safeguard of equipment against unnecessary breakdowns and maintain steady functioning of the entire electrical system. When electricity is generated remotely and there are no return paths for earth faults other than the earth itself, there is often a risk that earth faults can cause dangerous voltage gradients in the earth around the site of the fault (called ground potential rises). In other words, someone standing near the fault can receive a dangerous electrical shock owing firstly to the presence of a dangerous potential difference between the earth and a metallic object that a person is touching and secondly the presence of another dangerous voltage gradient between the feet of a person standing on earth. The objective of designing a safe grounding system is to provide easy and shortest path to the flow of fault currents without exceeding the operation and equipment limits and therefore adversely affecting the continuity of service. This paper proposes a suitable grounding system design for alternating current (A.C.) substations based on the relevant IEEE Standards and International best practices. The paper elaborates the step-by-step calculations necessary to determine the values of the mesh, touch and step potentials suitable for a good grounding system model for the A.C. electrical substation. The proposed design ensures protection of substation personnel from danger and affords safe operation of the entire substation facilities and increased overall system reliability.

Keywords: Earthing, Grounding systems, Soil Resistance, Soil Resistivity, Substation.

INTRODUCTION

An electrical substation is a subsidiary of an electricity generation, transmission and distribution system where voltage is transformed from high to low or the reverse using transformers [IEEE STD-80,1986; MTU, n.d.]. A substation may include transformers to change voltage levels between high transmission voltages and lower distribution voltages, or at the interconnection of two different transmission voltages. Between the generating station and consumer, electric power may flow through several substations at different voltage levels. Because of the possibility of direct lightning strokes, switching surges, etc. grounding must be done to protect passers-by, the substation equipment and electrical personnel within the vicinity from dangers arising from or outside the power system.

When designing and installing a vital subsystem of the electrical power system such as the substation, proper grounding is a necessity [Al.Nami etal, 2014]. Different soils have different grounding resistivity, it is advisable therefore to always consider grounding resistivity variations while designing for grounding systems. A good grounding arrangement provides a low-impedance path for fault and lightning-induced currents to flow through earth thus ensuring maximum safety from electrical system faults and lightning. A properly installed grounding system helps to safeguard equipment and buildings from damages resulting from unintentional fault currents and lightning surges as well as protects human lives against any potential danger [Fluke, n.d].

A good grounding system is necessary for an electrical substation for the following reasons [Open Electrical, 2017; IEEE Std., 2000; MTU, n.d.]:

i. To ensure safety to personnel in the substation against electric shocks;
ii. To provide the ground connection for connecting the neutrals of star connected transformer winding to earth (neutral earthing);
iii. To provide a path for discharging the charge between phase and ground by means of earthing switches;
iv. To discharge the over voltages from overhead ground wires or the lightning masts to earth. To provide ground path for surge arresters;
v. To provide earth connection to structures and other non-current carrying metallic objects in the substation (equipment earthing).

As shown in Figure 1 is a typical earth mart used in a substation grounding system.

Figure 1. Typical Substation Earth Mart [Study Electrical, 2014]

A safe grounding design thus serves two main objectives [Open Electrical, 2017]:

1. To carry the electric currents into earth under normal and fault conditions without exceeding operating and equipment limits or adversely affecting continuity of service.
2. To ensure that the person in the vicinity of grounded facilities is not exposed to the danger of electric shock.

When designing an extensive grounding system therefore, it is advisable to locate the area of lowest soil resistivity in order to achieve the economical grounding installation. It is essential to determine the soil resistivity and maximum grid currents to design a substation grounding system. The touch and step voltages are directly proportional to these values. Underestimating them may cause the design to be unsafe.

The paper therefore proposes a suitable grounding system design that accords with the relevant IEEE Standards and International best practices. The paper describes the step-by-step calculations necessary to determine the values of the mesh, touch and step potentials appropriate for a good grounding system model for an A.C. electrical substation. The proposed design ensures protection of substation personnel from danger and affords safe operation of the entire substation facilities and therefore increased system reliability. Figure 2 shows a typical path for an earth fault current.

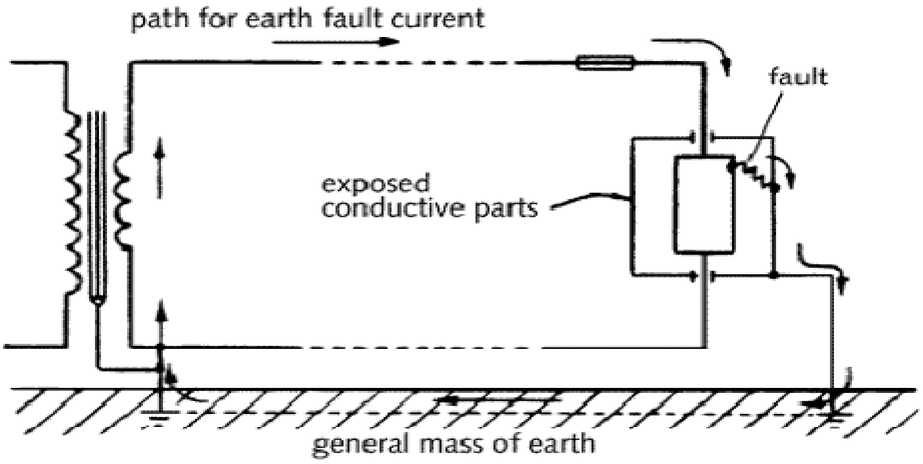

Figure 2. Path for earth fault current (shown by arrows)

Seven Common Electrical Grounding Design Mistakes

Electrical grounding designs fail due to common mistakes some of which are [E&S Grounding Solutions, n.d.]:

i. Using Concrete and Other Ground Enhancement Materials
ii. Using Undersized Ground Wires
iii. Using a Water Pipe as a Grounding Electrode
iv. Bonding to a Water Pipe at any Point in the System
v. Using Building Steel for Grounding
vi. Improper Bonding to Gas Pipes
vii. Believing that Crushed Rock Eliminates Hazardous Step & Touch Voltages

MATERIALS AND METHODS

The study undertakes a step by step manual calculation approach to designing a grounding system suitable for alternating current substations. In the course of the design, three types of voltages were considered. These were:

- Touch Voltage: This is the difference in potential between the surface potential and the potential at an earthed equipment whilst a man is standing and touching the earthed structure.
- Step Voltage: This is the potential difference developed when a man bridges a distance of 1m with his feet while not touching any other earthed equipment.
- Mesh Voltage: This is the maximum touch voltage that is developed in the mesh of the earthing grid.

The step-by-step approach deployed in the design of grounding system for A.C. Substations in the study is as follows:

Step 1: Resistivity Measurement [Open Electrical, 2017]

Soil resistivity is a measure of how much the soil resists the flow of electricity. An understanding of the soil resistivity and how it varies with depth in the soil is necessary to achieve a good grounding system design for an electrical substation, or for lightning conductors. Owing to the fact that soil quality may vary greatly with depth and over a wide lateral area, estimation of soil resistivity based on soil classification provide only a rough approximation. Actual resistivity measurements are required to fully qualify the resistivity and its effects on the overall transmission system.

Different methods are available for soil resistivity measurement. However, the Wenner four-pin method (Figure 3) developed by Dr. Frank Wenner of the US Bureau of Standards in 1915 is the most widely used and the most accurate method of testing soil resistivity. The method uses four

electrodes which are embedded to the ground in straight line. Two of these electrodes are for current injection and two for voltage measurement. The two outer electrodes are current electrode and the two inner electrodes measure voltage drop due to resistance of soil path when current is passed between the outer electrodes.
The resistance can be measured and resistivity calculated according to the formula:

$$\rho = 2\pi AR \quad (1)$$

Where:
ρ = Soil resistivity (Ω-m)
π = Constant (3.1426)
A = Distance between the electrodes (m)
R = Resistance (Ω) measured from the test instrument
Four probes are inserted in a straight line, equidistant from one another into the soil area being tested. The distance between the earth ground probes should be at least three times greater than the depth into which the probes are inserted into the soil. The earth ground tester then generates a constant current which flows through the two outer ground probes (C1 and C2) and the develops potential difference which is measured between the two inner ground probes (P1 and P2). The resistance measured by the tester is used to calculate the soil resistivity according to equation (1).

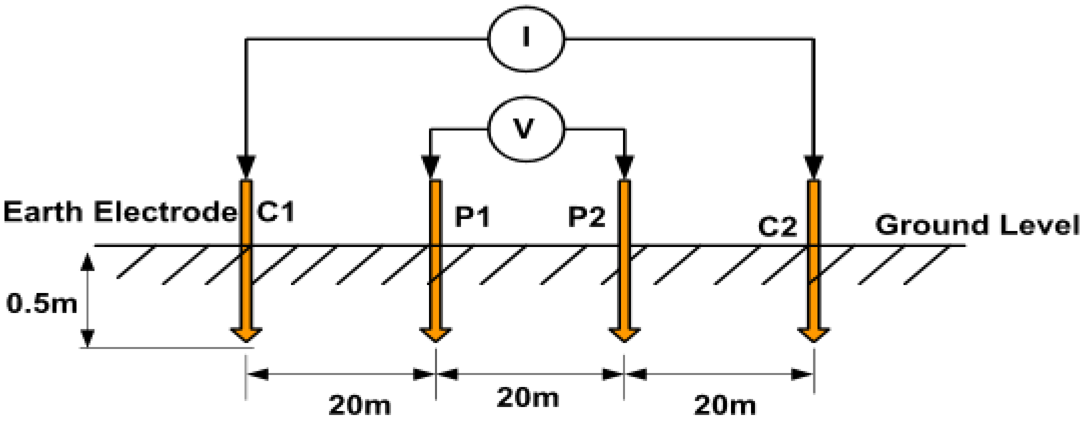

Figure 3. The Wenner Four-Pin Method

The resistivity properties of the soil where the earthing grid will be laid is an important factor in determining the earthing grid's resistance with respect to remote earth. Soils with lower resistivity lead to lower overall grid resistances and potentially smaller earthing grid configurations can be designed (i.e. that comply with safe step and touch potentials). It is good practice to perform soil resistivity tests on the site. A detailed discussion on the interpretation of soil resistivity test measurements is found in IEEE Std 80 Section 13.4 [Open Electrical, 2017].

Sometimes it is impossible to conduct soil resistivity tests such that an estimate must suffice. When estimating soil resistivity, it is advisable that one errs on the side of caution and select a higher resistivity. The IEEE Std 80 Table 8 gives some guidance on range of soil resistivities based on the general characteristics of the soil (i.e. wet organic soil = 10 Ω.m, moist soil = 100 Ω.m, dry soil = 1,000 Ω.m and bedrock = 10,000 Ω.m) [Open Electrical, 2017; Shah and Bhasme, 2014].

Earthing Grid Conductor Sizing
It is necessary to determine the minimum size of the earthing grid conductors in order to ensure that the earthing grid will be able to withstand the maximum earth fault current. In other words, we want to be sure that the earth grid conductors do not start melting during the worst case earth fault [Open Electrical, 2017; Shah and Bhasme,2014].

The minimum size of the earthing grid conductor is obtained by re-arranging IEEE Std 80 Equation 37 as follows:

$$A = \sqrt{\left(i^2 t \left(\frac{\frac{\alpha_T \rho_T \times 10^4}{TCAP}}{\ln\left[1 + \left(\frac{T_m - T_a}{K_o + T_a}\right)\right]} \right) \right)} \qquad (2)$$

Where

A = maximum cross-sectional area of the earthing grid conductor (mm^2)

$i^2 t$ = energy of the maximum earth fault (A^2s)

T_m = maximum allowable (fusing) temperature (^oC)

T_a = ambient temperature (^oC)

α_T = thermal coefficient of resistivity ($^oC^{-1}$)

ρ_T = resistivity of the earthing conductor ($\mu\Omega$.. Cm)

K_0 = a constant denoted by ($\frac{1}{\alpha_T} - 20^o C$)

$TCAP$ = the thermal capacity of the conductor per unit volume ($Jcm^{-3o}C^{-1}$)

The values of the material constants: T_m, α_T, ρ_T and $TCAP$ for common conductor materials are as stipulated in Table 1 of IEEE Std 80.

Touch and Step Potential Calculations [Open Electrical, 2017]

When electricity is generated remotely and there are no return paths for earth faults other than the earth itself, there is a risk that earth faults can cause dangerous voltage gradients in the earth around the site of the fault (called ground potential rises) [Open Electrical, 2017]. This means that someone standing near the fault can receive a dangerous electrical shock due to:

- Touch voltages - there is a dangerous potential difference between the earth and a metallic object that a person is touching
- Step voltages - there is a dangerous voltage gradient between the feet of a person standing on earth

The earthing grid helps to dissipate fault currents to remote earth and reduce the voltage gradients in the earth. The touch and step potential calculations are performed in order to assess whether the earthing grid can dissipate the fault currents so that dangerous touch and step voltages cannot exist [Open Electrical, 2017].

Step 2: Surface Layer Materials [Open Electrical, 2017]

Applying a thin layer (0.08m - 0.15m) of high resistivity material (such as gravel, blue metal, crushed rock, etc) over the surface of the ground is commonly used to help protect against dangerous touch and step voltages. This is because the surface layer material increases the contact resistance between the soil (i.e. earth) and the feet of a person standing on it, thereby lowering the current flowing through the person in the event of a fault [Open Electrical, 2017].

IEEE Std 80 Table 7 gives typical values for surface layer material resistivity in dry and wet conditions (e.g. 40mm crushed granite = 4,000 Ω.m (dry) and 1,200 Ω.m (wet)).

The effective resistance of a person's feet (with respect to earth) when standing on a surface layer is not the same as the surface layer resistance because the layer is not thick enough to have uniform resistivity in all directions. A surface layer derating factor needs to be applied in order to compute the effective foot resistance (with respect to earth) in the presence of a finite thickness of surface layer material. This derating factor can be approximated by an empirical formula as per IEEE Std 80 Equation 27:

$$C_s = 1 - \frac{0.09(1 - \frac{\rho}{\rho_s})}{2h_s + 0.09} \tag{3}$$

Where:

C_s = Surface layer derating factor

ρ = Soil resistivity (Ω.m)

ρ_s = Resistivity of the surface layer material (Ω.m)

h_s = Thickness of the surface layer (m)

This derating factor will be used later in Step 5 when calculating the maximum allowable touch and step voltages.

Step 3: Earthing Grid Resistance [Open Electrical, 2017; Shah and Bhasme, 2014]

IEEE Std 80 offers two alternative options for calculating the earthing grid resistance (with respect to remote earth): (1) the simplified method and (2) the Schwarz equations. Only the Schwarz equations, however, is considered in this work.

The Schwarz equations are a series of equations that accurately model the effect of earthing rods/electrodes. According to IEEE Std 80, Schwarz equations are usually written as:

$$R_g = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} \tag{4}$$

Where:

R_g = Earthing grid resistance with respect to remote earth (Ω)

R_1 = Earth resistance of the grid conductors (Ω)

R_2 = Earth resistance of the earthing electrodes (Ω)

R_m = Mutual earth resistance between the grid conductors and earthing electrodes (Ω)

The grid earthing electrode and mutual earth resistances are expressed as:

$$R_1 = \frac{\rho}{\pi L_c}\left[\ln\left(\frac{2L_c}{a'}\right) + \frac{k_1 L_c}{\sqrt{A}} - k_2\right]$$

$$R_2 = \frac{\rho}{2\pi n_r L_r}\left[\ln\left(\frac{4L_r}{b}\right) - 1 + \frac{2k_1 L_r}{\sqrt{A}}\left(\sqrt{n_r} - 1\right)^2\right]$$

$$R_m = \frac{\rho}{\pi L_c}\left[\ln\left(\frac{2L_c}{L_r}\right) + \frac{k_1}{\sqrt{A}} - k_2 + 1\right]$$

Where ρ = Soil resistivity (Ω.m)

L_c = Total length of buried grid conductors (m)

a' = $\sqrt{r.2h}$ for conductors buried at depth h metres and with cross-sectional radius r metres, or simply r for grid conductors on the surface

A = Total area covered by the grid conductors (m^2)

L_r = Length of each earthing electrode (m)

n_r = Number of earthing electrodes in area, A

b = Cross-sectional radius of an earthing electrode (m)

k_1 and k_2 = Constant coefficients depending on the geometry of the grid

The coefficient, k_1 can be approximated by the following:

- For depth, $h = 0$: $k_1 = -0.04\frac{L}{R} + 1.41$
- For depth, $h = \frac{1}{10}\sqrt{A}$: $k_1 = -0.05\frac{L}{R} + 1.20$
- For depth, $h = \frac{1}{6}\sqrt{A}$: $k_1 = -0.05\frac{L}{R} + 1.13$

The coefficient, k_2 can be approximated by the following:

- For depth, $h = 0$: $k_2 = 0.15\frac{L}{R} + 5.50$
- For depth, $h = \frac{1}{10}\sqrt{A}$: $k_2 = 0.10\frac{L}{R} + 4.68$
- For depth, $h = \frac{1}{6}\sqrt{A}$: $k_2 = 0.05\frac{L}{R} + 4.40$

Where in both cases, $\frac{L}{R}$ is the length-to-width ratio of the earthing grid.

Step 4: Maximum Grid Current [Open Electrical, 2017]

The maximum grid current is the worst case earth fault current that would flow via the earthing grid back to remote earth. To calculate the maximum grid current, you firstly need to calculate the worst case symmetrical earth fault current at the facility that would have a return path through remote earth (call this $I_{k,e}$). This can be found from the power systems studies or from manual calculation. Generally speaking, the highest relevant earth fault level will be on the primary side of the largest distribution transformer (i.e. either the terminals or the delta windings).

Current Division Factor

It is assumed that not all of the earth fault current will flow back through remote earth. A fraction of the earth fault current may have local return paths (e.g. local generation) or there could be alternative return paths other than remote earth (e.g. overhead earth return cables, buried pipes and cables, etc). Therefore a current division factor S_f must be applied to account for the proportion of the fault current flowing back through remote earth.

Computing the current division factor is a task that is specific to each project and the fault location and it may incorporate some subjectivity (i.e. "engineering judgement"). In any case, IEEE Std 80 Section 15.9 has a good discussion on calculating the current division factor. In the most conservative case, a current division factor of $S_f = 1$ can be applied, meaning that 100% of earth fault current flows back through remote earth. The symmetrical grid current I_g is calculated by:

$$I_g = I_{k,e} S_f$$

Decrement Factor

The symmetrical grid current is not the maximum grid current because of asymmetry in short circuits, namely a dc current offset. This is captured by the decrement factor, which can be calculated from IEEE Std 80 Equation 79:

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

Where D_f is the decrement factor

t_f is the duration of the fault (s)

T_a is the dc time offset constant

The dc time offset constant is derived from IEEE Std 80 Equation 74:

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

Where:

$\frac{X}{R}$ is the X/R ratio at the fault location

f is the system frequency (HZ)

The maximum grid current, I_G is lastly calculated by:

$$I_G = I_g D_f$$

Step 5: Touch and Step Potential Criteria [Open Electrical, 2017]

One of the objectives of a safe earthing grid is to protect people against lethal electric shocks in the event of an earth fault. The magnitude of ac electric current (at 50Hz or 60Hz) that a human body can withstand is typically in the range of 60 to 100mA. The maximum tolerable voltages for step and touch scenarios can be calculated empirically from IEEE Std 80 Section 8.3 for body weights of 50kg and 70kg:

Touch Voltage Limit – This is the maximum potential difference between the surface potential and the potential of an earthed conducting structure during a fault (due to ground potential rise):

- 50Kg Person: $E_{Touch.50} = (1000 + 1.5 C_s \rho_s)\frac{0.116}{\sqrt{t_s}}$
- 70Kg Person: $E_{Touch.70} = (1000 + 1.5 C_s \rho_s)\frac{0.157}{\sqrt{t_s}}$

Step Voltage Limit – This is the maximum difference in surface potential which can be experienced by a person bridging a distance of 1 metre with the feet without contact to any earthed object:

- 50Kg Person: $E_{Step.50} = (1000 + 6 C_s \rho_s)\frac{0.116}{\sqrt{t_s}}$
- 70Kg Person: $E_{Step.70} = (1000 + 6 C_s \rho_s)\frac{0.157}{\sqrt{t_s}}$

Where:

E_{Touch} = The Touch Voltage Limit (V)

E_{Step} = The Step Voltage Limit (V)

C_s = The Surface Layer Derating Factor (As calculated in Step 2)

ρ_s = The Soil Resistivity (Ω.m)

t_s = The Maximum Faulty Clearing Time (s)

The choice of body weight (50Kg or 70Kg) depends on the expected weight of the Personnel at the Site. Typically, women are expected to be on site, the conservative option is to choice 50Kg.

Step 6: Ground Potential Rise (GPR) [Open Electrical, 2017]

Normally, the potential difference between the local earth around the site and remote earth is considered to be zero (i.e. they are at the same potential). However an earth fault (where the fault current flows back through remote earth), the flow of current through the earth causes local potential gradients in and around the site. The maximum potential difference between the site and remote earth is known as the ground potential rise (GPR). It is important to note that this is a maximum potential difference and that earth potentials around the site will vary relative to the point of fault.

The maximum GPR is calculated by:

$$GPR = I_G R_g$$

Where:

GPR = The Maximum ground potential rise (V)

I_G = The Maximum grid current (A) found earlier in Step 4

R_g = The Earthing grid resistance (Ω) found earlier in Step 3

Step 7: Earthing Grid Design Verification [Open Electrical, 2017]

In order to verify that the earthing grid design is safe for touch and step potential, the value of the maximum GPR calculated must be compared with the touch and step voltage limits. If the maximum GPR calculated above does not exceed either of the touch and step voltage limits (from Step 5), then the grid design is safe. However if it does exceed the touch and step voltage limits, then some further analysis is required to verify the design, namely the calculation of the maximum mesh and step voltages as per IEEE Std 80 Section 16.5.

Mesh Voltage Calculation

The mesh voltage is the maximum touch voltage within a mesh of an earthing grid and is derived from IEEE Std 80 Equation 80:

$$E_m = \frac{\rho_s K_m K_i I_G}{L_M}$$

Where:

ρ_s = The Soil resistivity (Ω.m)

I_G = The Maximum grid current (A) found earlier in Step 4

K_m = The Geometric spacing factor (See below)

K_i = The Irregularity factor (See below)

L_M = The Effective buried length of the grid (See below)

Geometric Spacing Factor, K_m

The geometric spacing factor, K_m is calculated from IEEE Std 80 Equation 81:

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

Where:

D = The Spacing between parallel grid conductors (m)

h = The Depth of buried grid conductors (m)

d = The Cross-sectional diameter of a grid conductor (m)

K_h = A Weighting factor for depth of burial = $\sqrt{1+h}$

K_{ii} = A Weighting factor for earth electrodes/rods on the corner mesh

Usually,

K_{ii} = 1 for grids with earth electrodes along the grid perimeter or corners

$K_{ii} = \frac{1}{2n^{n/2}}$ for grids with no earth electrodes along the grid perimeter or corners

n = A geometric factor (See below)

Geometric Factor, n

The geometric factor, n is calculated from IEEE Std 80 Equation 85:

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

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

Usually,

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

Where:

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

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

Where:

L_c = Total length of horizontal grid conductors (m)

L_p = The length of grid conductors on the perimeter (m)

A = Total area of the grid (m^2)

L_x and L_y = The Maximum length of the grids in the X and Y directions (m)

D_m = The Maximum distance between any two points on the grid (m)

Irregularity Factor, K_i

The irregularity factor, K_i is calculated from IEEE Std 80 Equation 89:

$K_i = 0.644 + 0.148n$

Where n is the geometric factor derived above.

Effective Buried Length, L_M

The effective buried length, L_M is determined as follows:

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

$$L_M = L_c + L_R$$

Where:

L_c = The total length of horizontal grid conductors (m)

L_R = The total length of earthing electrodes/rods (m)

For grids with earthing electrodes along the grid perimeters or corners:

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

Where:

L_c = The total length of horizontal grid conductors (m)

L_R = The total length of earthing electrodes/rods (m)

L_r = The length of each earthing electrode/rod (m)

L_x and L_y are the maximum length of the grids in the X and Y directions (m)

Step Voltage Calculation

The maximum allowable step voltage is calculated from IEEE Std 80 Equation 92:

$$E_s = \frac{\rho_s K_s K_i I_G}{L_S}$$

Where:

ρ_s = The soil resistivity (Ω.m)

K_s = The geometric spacing factor (see below)

K_i = The irregularity factor (as derived above in the Mesh Voltage Calculation)

I_G = The maximum grid current (A) found earlier in Step 4

L_s = The effective buried length of the grid (see below)

Geometric Spacing Factor, K_s

The geometric spacing factor, K_s based on IEEE Std 80 Equation 81 is applicable for burial depths between 0.25m and 2.5m:

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

Where:

D = The spacing between parallel grid conductors (m)

h = The depth of buried grid conductors (m)

n = A geometric factor (as derived above in the Mesh Voltage Calculation)

Effective Buried Length, L_s

The effective buried length, L_s for all cases can be calculated by IEEE Std 80 Equation 93:

$$L_s = 0.75 L_c + 0.85 L_R$$

Where:

L_c = The total length of the horizontal grid conductors (m)

L_R = The total length of earthing electrodes/rods (m)

A simple algorithm for designing a grounding system for an electrical substation is presented in Figure 4.

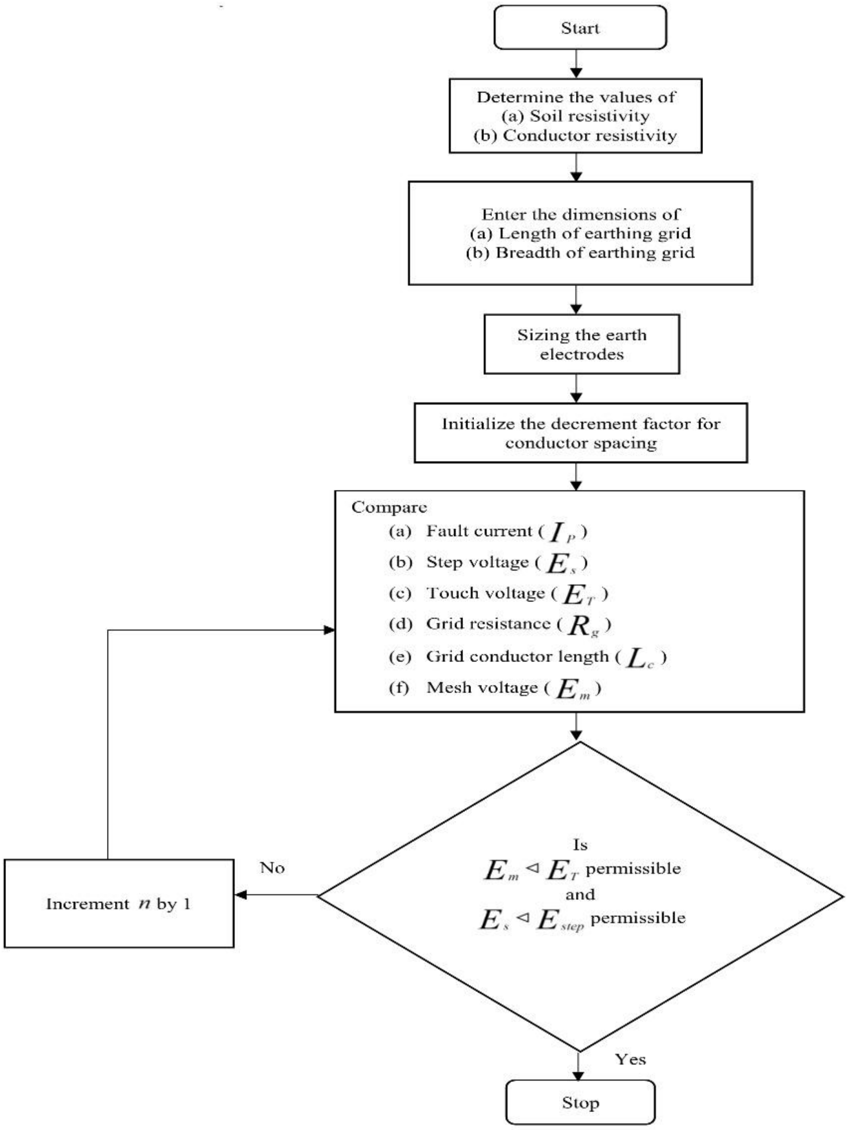

Figure 4. Algorithm for designing a grounding system for a typical A.C. Substation [Arjunsingh et al., 2012; Ubeku and Odiase, 2009]

ASCERTAINING THE SAFETY OR OTHERWISE OF THE COMPLETED EARTHING GRID DESIGN

Having determined the values of the mesh and step voltages, these determined values can now be compared with the values of both the maximum tolerable touch and step voltages respectively as follows:

If $E_m < E_{Touch}$ and $E_S < E_{Step}$, it can be deduced that the earthing grid design is safe.

In other words, to check if the design is safe or not, we perform the following check:

Now compare GPR < Etouch voltage

If yes then design is safe

If GPR > E touch

Then Find E mesh and E Step

Now compare E mesh < E touch

If yes then

Compare E step actual < E step

Permissible if yes then design is safe

Otherwise, modify by increasing or decreasing spacing of conductor, length of conductors.

Calculate again.

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 include:

- 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 (see Step 3) 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

RESULTS AND DISCUSSION

In the event that the grid design fails to meet the tolerable touch voltage requirements, it is advisable to reduce the available ground fault current. Owing to the fact that this is not always practicable, however, the grid is usually modified by changing any or all of the following: grid conductor spacing, total conductor length, grid depth, addition of ground rods, etc. in order to achieve the required conditions. Earthing resistance and earth surface potential distribution are the main parameters characterizing electrical properties of the earthing system. Electrical parameters of the earthing system depend on both soil properties and earth electrode geometry. Soil properties are characterised by earth resistivity, which changes over a wide range from a few m up to few thousand m, depending on the type of ground and its structure, as well as its humidity. As a result, it is difficult to calculate an exact value of earthing resistance. All relationships describing earthing resistance are derived with the assumption that the ground has a homogenous structure and constant resistivity. Ideally, the earth surface potential should be flat in the area around the earth electrode. This is important for protection against electric shock, and is characterised by touch and step voltages. Rod electrodes have a most unfavourable surface potential distribution, while meshed electrodes have a much flatter distribution.

The behaviour of the earthing system for high transient currents should be considered. Very high current values diminish earthing resistance due to the strong electric field between the earth electrode and the soil, while fast current changes increase earthing impedance due to earth electrode inductance. The earthing impedance is, in this case, a superposition of both these events.

CONCLUSION AND RECOMMENDATION

This paper has successfully proposed a grounding system design suitable for A.C. Substations that accords with the relevant IEEE Standards and International best practices. To accomplish this, rigorous calculations were carried out to determine the applicable values of the mesh, touch and step potentials. The proposed design ensures protection of substation personnel from danger and affords safe operation of the entire substation facilities and increased system reliability. A complete grounding system might include only one earth electrode, an entire group of electrodes with a grounding grid, or anything in between and beyond. The earth electrodes from any of these types of systems can have their resistance to remote earth determined. Therefore, it is advisable that these variations be considered when assessing soil resistivity. To help ensure expected grounding system resistance values are achieved throughout the year, worst-case soil resistivity values should be considered when designing the grounding electrode system.

The paper recommends an effective and periodic maintenance program to ensure continuity exists throughout the grounding system. The grounding system should also be regularly inspected using an approved ground-testing instrument to test electrical resistance and continuity. That way, the system would remain effective and ensure that the electrical system functions properly and uninterruptedly.

Conflicting Interests

The author declares that no conflicting interests exist.

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