International Journal of Electrical and Power Engineering 3 (5): 262-267, 2009
ISSN: 1990-7958

Substation Earthing Grid Safety Analysis

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Abstract: This study presents a user interactive computer program for the design and configuration arrangement of a 33/11 kV substation earthing grid system within restricted areas such as the cases of Benin city injection substations. The study is aimed at the creation of awareness on safe substation earthing grid system design. The provision of earthing systems is not only for the protection and proper functioning of substation equipments, but also for the safety of personnel during earth faults and lightning strikes. Standard expressions taken from IEEE 80 and 2000 are used in writing an interactive programme for the simulation of touch, step and mesh potentials of substation earthing grid, which are the most important factors for personnel safety in and around substations. The interactive program follows an algorithm that gives the final design configuration and the total required conductor length that satisfied the criterion for safety.

Key words: Earthing system, touch potential, grid configuration, interactive program, personnel safety

INTRODUCTION

Substation earthing grid systems are required to perform satisfactorily under steady-state and transient conditions. The effects of an improper or faulty earthing arising from unconventional practices as being practice in Nigeria can range from erratic operation of electrical and electronic systems to death and injuries to Personnel (Conroy and Richard, 1993).

Before now the design and the subsequent implementation of substation earthing was a trial and error procedure. The recent years has shown the development of computer-based tools for the design and performance analysis of substation earthing grid systems. The aim is to compute accurately earthing behaviour under steady and transient conditions without first burying the conductors. There are two approaches in using a computer in the design, simulation and analysis earthing systems: the user-interactive approach and the electromagnetic field approach (Grcev and Amutovski, 1996).

The user-interactive approach involves the development of a design algorithm based on standard earthing equations and design procedures. A computer program is then written using software. Optimum design parameters like the total length requirements and configuration settings are then obtained by the iterative procedure of the design algorithm.

Two distinct methods exits in the field approach: domain-type and boundary-type. Domain-type formulation is the direct solution of the differential equation governing the field. The Finite Difference (FDM) and Finite Element (FEM) (Vu *et al*., 2007; Yan and Jiangjun, 2005) as well as the Method of Moments (MoM) methods are the most commonly used domain-type methods. The boundary-type formulation is the solution of boundary integral equations, on which the Boundary Element Method (BEM) is based (Dragan, 2006).

The purpose of this study is to describe a user-interactive computer-based approach written in MATLAB software for the design and configuration arrangement of a substation earthing systems that will meet the touch and step potential criterion for safety in and around substations.

Grid safety parameters: Body current is the current, which flows through a human body that completes an electrical circuit path. The most common physiological effects of electric current on the body, stated in order of increasing current magnitude, are perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage and burning. The permissible limit of body current is depended on the current magnitude and its duration on the body and is computed using the expression (IEEE SD 80-1986):

$$I_b = \frac{k}{\sqrt{t}} \tag{1}$$

The Eq. 1 is valid for shock durations within 0.3-3 sec. Currents and times, which yields values below this constant will not cause ventricular fibrillation to 99.5% of the people who encounter them.

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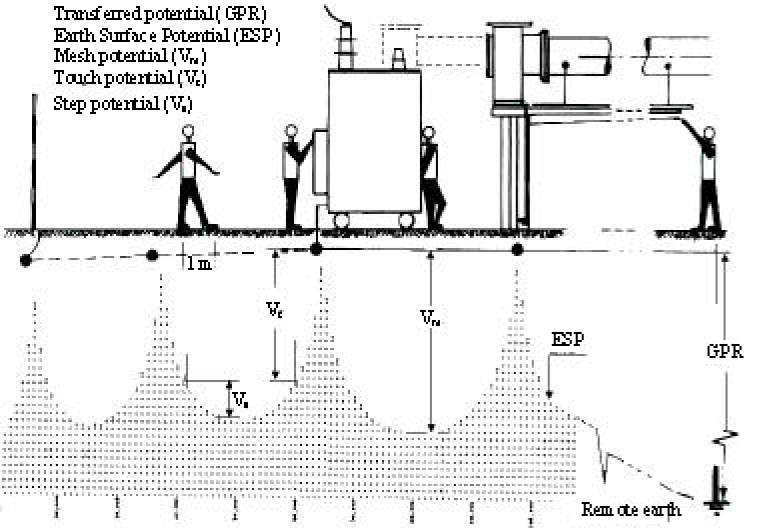

Fig. 1: Illustration of the touch and step potentials (Markowska and Wiater, 2003)

The substation earth grid is used as an electrical connection to earth at zero potential reference. This connection however is not ideal due to the resistivity of the soil within, which the earth grid is buried. During typical earth fault conditions, the flow of current via the grid to earth will therefore, result in the grid rising in potential relative to remote earth to which other system neutrals are also connected. This produces potential gradients within and around the substation ground area.

Touch potential as illustrated in Fig. 1 is the voltage between the energized object and the feet of a person in contact with the object (Markowska and Wiater, 2003). It is equal to the difference in voltage between the energized object and a point some distance away. It should be noted that the touch potential could be nearly the full voltage across the earthen object if that object is earthen at a point remote from the place, where the person is in contact with it. Touch potential can be expressed as:

$$V_{t50} = (1000 + 1.5C_s \rho_s) \frac{0.116}{\sqrt{t_s}} \qquad (2)$$

$$V_{t70} = (1000 + 1.5C_s \rho_s) \frac{0157}{\sqrt{t_s}} \qquad (3)$$

Step potential as illustrated in Fig. 1 is the voltage between the feet of a person standing near an energized earthen object. It is equal to the difference in voltage given by the voltage distribution curve between two points at different distances from the earth electrode. A person could be at risk of injury during a fault simply by standing near the earthing system point:

$$V_{s50} = (1000 + 6C_s \rho_s) \frac{0.116}{\sqrt{t_s}} \qquad (4)$$

$$E_{s70} = (1000 + 6C_s \rho_s) \frac{0.157}{\sqrt{t_s}} \qquad (5)$$

where, C_s is the reduction factor for derating the nominal value of surface layer resistivity ρ_s with a thickness of h_s laid on a native soil of resistivity ρ_{soil} and could be assigned as follows:

$$C_s = 1 - 0.106 \left[\frac{1 - \frac{\rho_{soil}}{\rho_s}}{2h_s + 0.106} \right] \qquad (6)$$

The mesh potential is defined as the potential difference between the center of an earthing grid mesh and a structure earthen to the buried grid conductors. This is effectively a worst-case touch potential. The mesh potential of an earth grid is computed using:

$$V_m = \frac{\rho_{soil} K_m K_{im} I_g}{L} \qquad (7)$$

where, K_m and K_i are the spacing and corrective factors, respectively for the mesh voltage and are computed using:

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

Table 1: Likely grid potential rise of 33/11 kV injection substations using a Zero sequence (Z_0) and positive sequence (Z_1) impedance of 12.6 and 6.3 Ω, respectively

Substation	Rated (mVA)	Fault current $I_g = \frac{3V_l}{\sqrt{3}(2Z_1 + Z_0)}$	Measures grid resistance (R_g) Ω as at 12/2/09	Grid potential rise ($0.6\,I_g \bullet R_g$)
Ugbowo	7.5	2268.2	25.20	34295
Nekpen-nekpen	7.5	2268.2	32.44	44148
Etete	7.5 and 15	2268.2	15.35	20890
Siluko	7.5 and 15	2268.2	21.04	28634
Ikpoba Dam	7.5	2268.2	12.87	17515
Guiness	7.5	2268.2	27.19	37003
GRA	7.5	2268.2	43.12	58683

$$K_i = 0.65 + 0.172n_m$$

Where:

I_g = RMS value of current (kVA)
L = Total length of buried conductors (m)
D = Adjacent conductor spacing (m)
h = Depth of burial of grid conductors (m)
d = Diameter of grid conductors (m)
n_m = Number of adjacent conductors

According to Cho and Oo (2008), the IEEE 80-1986 and IEEE 80-2000 standards uses the maximum mesh voltage as the touch voltage and this usually exists at the corner mesh. Modern earthing system design is based on the touch and step potential criteria as it helps in attaining an efficiently designed earthing system, which limits earth voltages due to Earth Potential Rises (EPR) within earthen equipment during earth faults. The Earth Potential Rise (EPR) of an earthen equipment under earth fault conditions must be limited so that touch and step potential limits are not exceeded and is controlled by keeping the earth electrode Resistance (R_C) of the equipment earthing system as low as possible.

Grid potentials rise of existing substations: a case study: In densely populated cities and towns the 33/11 kV injection substations are installed in restricted land mass of approximately, 20×20 m and the required grid resistance is 10 Ω or less depending on the local soil conditions. An assessment of grid resistance of six injection substations in Benin was carried and Table 1 shows the likely Grid Potential Rise (GPR) if an earth fault had occurred.

The high value in the grid resistances in some of these injection substations may be due to high soil resistivity and unconventional practices, where the same configuration is used undermining the soil topology.

MATERIALS AND METHODS

In the field of substation earth grid system design, grid design optimization means to find an earth grid configuration system, which is able to safeguard those people that are working or walking in and around the earthen installations and on the other hand has minimal cost. The basic design quantities of the earth grids are the grid Resistance (R_g), the Grid Potential Rise (GPR), touch potential (V_t), step potential (V_s) and the cost of the earth grid system design. These mentioned quantities depend on the grid parameters, such as the available grid area and the soil resistivity.

Substation earth grid design starts from the resistivity of the local soil. A reasonable and accurate estimation of the soil resistivity is the fundamental for an earthing system design. Soil resistivity has seasonal values and knowledge of this helps in designing a good and effective earthing systems. There are established techniques for measuring the local soil resistivity. Where, it becomes very hard to perform these measurement local soil resistivity data must be consulted. In Benin, soils a worse-case value of 400 Ωm, which is an average value during the drying season should be assumed.

For a given square or rectangular grid area, where the side lengths are L_a and L_b, respectively the conductor length requirement without earth rod can be computed from:

$$L_T = L_a\left(\frac{L_a}{D_a} + 1\right) + L_b\left(\frac{L_b}{D_b} + 1\right) \qquad (9)$$

For a square grid $L_a = L_b$ thus:

$$D_a = \frac{L_a}{2^n} \qquad (10)$$

Where, n = 0, 1, 2,......... a decrementing factor for conductor spacing. Where,

L_T = The total conductor without earth rods
D_a, D_b = Side conductor spacing, respectively

Using the step and touch potential criteria the minimum conductor length requirements necessary to keep the maximum touch potential within the earthen

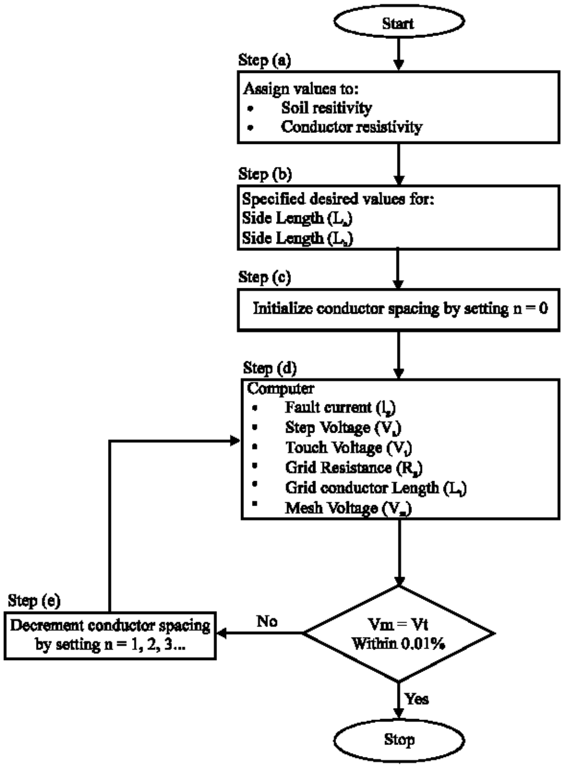

Fig. 2: Block diagram of simulation procedure

substation below the safe limits is computed by equating the mesh and touch potentials. Thus, for 50 kg person the minimum conductor length is:

$$L_{t(50)} > \frac{K_m K_i \rho I_g \sqrt{t_s}}{\left(116 + 0.174 C_s \rho_s\right)} \qquad (11)$$

Similarly, for a 70 kg person the minimum conductor length is:

$$L_{t(70)} > \frac{K_m K_i \rho I_g \sqrt{t_s}}{\left(157 + 0.235 C_s \rho_s\right)} \qquad (12)$$

Where, the grid fault current ignoring the substation resistance is giving as:

$$I_g = \frac{3V_{line}}{\sqrt{3}(2Z_1 + Z_{01})} \qquad (13)$$

The grid resistance is computed using:

$$R_g = \rho_{soil}\left[\frac{1}{L_i} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right] \qquad (14)$$

The product of the grid resistance and the fault current is the Grid Potential Rise (GPR) is computed using:

$$GPR = 0.6 I_g R_g \qquad (15)$$

Simulation technique: The substation earthing grid design was carried out according to the flow chart shown in Fig. 2, which is effected using a user interactive program written using MATLAB. The step by step procedure for the design is described below. Step (a) first of all, we assign values for soil resistivity, top-layer resistivity, conductor resistivity, depth of burial, fault duration step (b) the user interactive program allows us to enter the desired substation grid area dimensions for the design of the earth grid and also the line voltage and impedance parameters. Step (c) the user initializes the parallel conductor spacing. To begin with, the spacing is set to its maximum value. Step (d) the earth fault current, the cross-section of the conductors, length of conductor for specific grid configuration as well as the length requirement for the mesh voltage as well as the mesh voltage and touch voltage are computed. Step (e) the computed mesh voltage is compared with the touch voltage. If the difference between the two values is not within a margin of 0.01%, we decrement the spacing by a specific value, provided the spacing is not <1 and proceed to redo step (d) through and step (e), this iteration loop in the program, is repeated until the computed mesh voltage as well as the required length met the required criterion for safety.

RESULTS AND DISCUSSION

The earthing grid safety parameter curves of a uniform soil of resistivity 400 Ωm is shown in Fig. 3. The other input parameters are: $-\rho_s = 3000$; $t_f = 0.5$, $V_L = 33$ kV, $A = 400$ m^2, line voltage 33 kV with Zero sequence (Z_0) and positive sequence (Z_1) impedance of 12.6 and 6.3 Ω, respectively. The length of conductor required for the grid to meet the step and touch voltage criterion is 449 m, which can be configured into an 8×8 grid with a conductor length of 360 m and additional 32 perimeter vertical rods of 2.5 m each giving a grid resistance of 9.34 Ω.

Soil stratification cannot be rule out of earthing system design. There are cases where the top soil has a higher resistivity than the lower soil or the other way round. Figure 4 shows the safety parameter curves in a case, where the upper layer soil resistivity is taken as 400 Ωm with a thickness of 2 m and a lower layer resistivity of 120 Ωm.

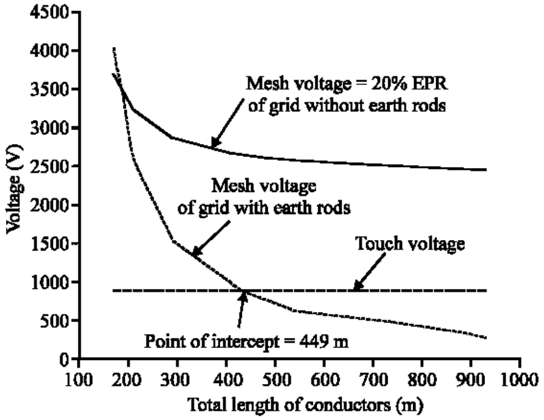

Fig. 3: Determination of the total required length using the safety parameter curves when ρ_{soil} = 400 Ωm

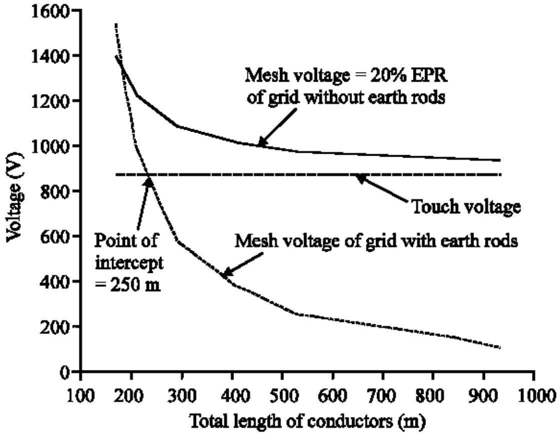

Fig. 4: Determination of the total required length using the safety parameter curves assuming a layered soil of top and bottom layers of 400 and 120 Ωm, respectively

The length of conductor required for the grid to meet the step and touch voltage criterion in this case is 250 m, which can be configured into a 4×4 grid with a conductor length of 200 m and additional 16 perimeter vertical rods of 5 m each giving a grid resistance of 3.75 Ω.

Figure 5 shows the safety parameter curves in a case where, the upper layer soil resistivity is taken as 400 Ωm with a thickness of 2 m and a lower layer resistivity of 600 Ωm. The length of conductor required for the grid to meet the step and touch voltage criterion in this case is 520 m, which can be configured into an 8×8 grid with a conductor length of 360 m and additional 81 evenly distributed vertical earth rods of 2.5 m each giving a grid resistance of 12 Ω, which is on a higher side.

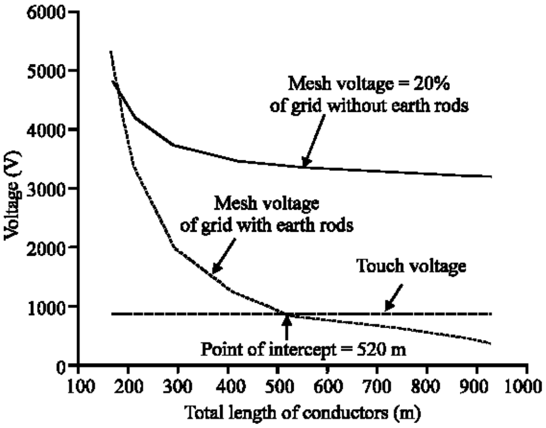

Fig. 5: Determination of the total required length using the safety parameter curves assuming a layered soil of top and bottom layers of 400 and 600 Ωm, respectively

CONCLUSION

Substation earthing grid design requires a simple, but accurate method to compute the parameters that guarantees the safety of personnel during earth faults. These parameters are the touch, step and mesh potentials as well as the grid resistance.

In this study, we present an interactive computer program that allows the computation of the total grid conductor length required for the earth grid to meet the step and touch potential criterion for safety. The interactive method versatility has allowed us to configure the grid according to the availability of land space and value of the native soil resistivity. Thus, the optimization procedures adapted has reduced the cost of materials, which could have being wasted with the unconventional methods as practice in Benin city, Nigeria.

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