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OPTIMAL DESIGN ANALYSIS OF SUBSTATION GROUND GRID MESH

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Abstract

Substations are grounded by means of earth-embedded electrodes in order to provide safety during normal or fault conditions. Electric substations are effectively grounded to guarantee the proper operation of electrical devices, minimize the likelihood of flash-over during transient conditions as well as dispel lightning strokes. A structure is termed grounded if it is electrically bonded to earth-embedded metallic frames. The earth-embedded metallic frames provide a conducting pathway of electricity to the earth and it is called a ground grid system. Substation ground grid mesh is comprised of vertical and horizontal conductors as well as vertical rods buried beneath the substation ground. Electric current flow through the human body is hazardous. Therefore, ground grid systems should be designed such that the likely electric body current in an operator or passer-by should not exceed the standard defined limits under any foreseeable harmful circumstances and as well provide protection of equipment. The objective of this study is to determine substation, safe ground grid system parameters as well as the cost-effectiveness of designing substation ground grids by comparing the IEEE Std. 80-2000/2013 and the Finite Element Method (FEM). ETAP 16.0 Power Tool is employed in carrying out this analysis. The substation expected maximum short circuit current is stated. The design analysis using both methods is presented separately and suggestions are made with reference to the most cost effective and safest method for the effective designing of the substation ground grid system.

Keywords: ETAP, Finite element Method, IEEE Std. 80-2000, Ground grid system, Max. Fault Current.

1.0 INTRODUCTION

Effective grounding of electric power substations are not only for the security of personnel but also to provide protection of equipment. An effective ground grid system will enhance the reliability of equipment and also reduce the possibility of damage resulting from fault currents and lightning. The main purpose of a ground grid system is to provide a low-impedance electrical contact connection between an electrical system neutral and the earth [1]. A standard substation ground grid system comprise of ground rods, ground mat and more earth-embedded metallic frameworks.

Hypothetically, for a three-phase system, the potential of the neutral should correspond to that of the earth. Thence, power system operators and by-standers are safe whenever they come in contact with metallic structures affixed to the system neutrals. Regrettably, the grounding system impedance to earth is consistently a finite number. Therefore, during fault conditions, the potential of grounded structures may turn out to be divergent at different points on the earth. Substantially, substation ground grid system must be designed to restrict the ground potential rise (GPR) to a tolerable value for any probable fault condition and also to restrain the step and touch potentials within and around the substation to tolerable values.

Typically, the effectiveness of a substation ground grid system is determined from a number of parameters such as: the soil resistivity in the precinct and the geometry of the ground grid area. Figure 1. Illustrates a single transformer substation facility. The power system as shown in Figure 1, is vulnerable to short circuit faults within the substation facility or along the transmission lines. Hence, design analysis of a substation ground grid system should address the issue of deducing the soil resistivity, maximum GPR, touch and step voltages computation. Being the major component of the power system grounding structures, ground grids should be designed to ensure the safety of the overall grounding system and should also be cost effective [2].

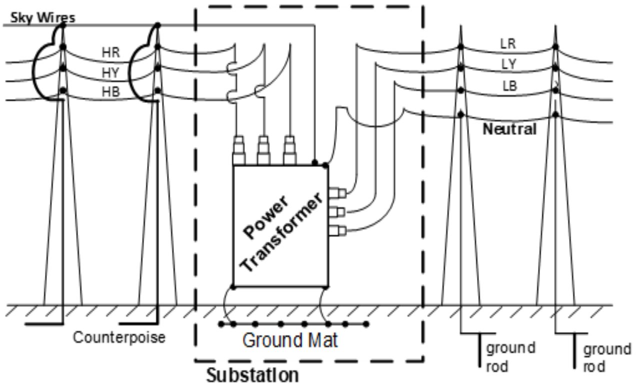

Figure 1: Substation Grounding Structures [1]

There are quite a few studies in the area of optimal design of substation grounding system for very high fault current. In [2], the performance of substation grounding system was expounded with regards to the different grounding parameters. This was done to ascertain the most effective parameters needed to achieve cost-effective and safe design. The study was centered on a program, based only on IEEE Std. 80-2000. In [3], grounding system optimization study was conducted on a 275/150kV substation using CYMGRD software. The methods employed in the design were not stated. [4], proposed a method for overcoming the shortcomings associated with a 500kV substation grounding system. IEEE Std. 81-2013 was employed in extracting ground grid mesh from the designated site of the study. IEEE Std. 80-2000 in ETAP-12 was exclusively used in analyzing the system optimization. [11], presented an optimized ground grid mesh design for a 132/33kV substation facility with an expected maximum fault current of less than 40kA. [5], analyzed a substation ground grid system using a MATLAB programme. The safety standard met by the developed programme was not stated.

The Finite Element Method of ETAP ground grid system module was used in combination with Sverak's variable space technique by [12], for the design and optimization of substation ground grid system. [13], introduced a transient methodology for investigating the effect of lightning on ground grid operation under normal and optimized conditions. The best values of mesh sizes required for the ground grid under varying conditions were obtained using Genetic algorithm. The study was implemented using ATP-EMTP and Genetic algorithm. The Simulated Annealed (SA) algorithm was presented by [14] for obtaining optimization results for substation grounding system. SA algorithm was used in different soil condition; uniform soil, two-layer vertical soil and two-layer horizontal soil.

This paper presents the design analysis of a substation ground grid system with an expected maximum short circuit current of 45 kA such that the touch and step potentials are held within tolerable limits. The optimal design analysis is executed using the IEEE Std. 80 and the Finite Element Method (FEM) respectively. Both methods are analogized with regards to safety and cost-effectiveness.

1.1 Soil Resistivity Measurement

The fundamental procedure in grounding system design is to ascertain the soil model in the substation vicinity. A number of field test can be used to establish the soil model. The most widely used is the Wenner method. The basis for determining soil resistivity when selecting substation location is to secure a location with the lowest resistance. Measuring soil resistivity after selecting a site will provide the relevant details needed to design and build an effective grounding system that will meet the desired ground resistance requirements. Soil composition is a factor that affects soil resistivity. Soil is scarcely homogenous and its resistivity differs geographically and at varying depths.

The moisture contents of soil which varies seasonally and in accordance with the depth of the water table, is a factor that also affects soil resistivity. Logically, it is assumed that soil resistivity decreases with an increase in moisture content and vice versa. Numerous techniques have been developed for measuring soil resistivity. The major techniques referenced by international standards includes:

(i) The Wenner Four-Pin Method
(ii) The Schlumberger-Palmer Method
(iii) The Central Electrode Arrangement
(iv) The Dipole-Dipole Method
(v) The Lee Method
(vi) The Square Arrangement

The Wenner Four-Pin Method is most frequently used in practice because of the simplicity of its application. It entails the placing of four short rods into the ground at equal distance apart, as shown in Figure 2. A source current is injected between the outer electrodes and the voltage between the inner electrodes are documented.

The source current I and the estimated voltage V are related to the soil resistivity. This relationship is derived as follows. Assume the depth of the probe, b << a. the two exterior probes can be adjudge as point current sources of current I and –I, separately located on the earth surface [1]. The voltage V(x) at distance x from the probe injecting current I into the earth is computed as follows:

$$V(x) = \frac{\rho I}{2\pi x} - \frac{\rho I}{2\pi(3a - x)} \qquad (1)$$

The voltage of both inner probes are V(a) and V(2a), respectively. Therefore, the voltage between both inner probes is given as:

$$V = V(a) - V(2a) = \frac{\rho I}{2\pi a} \qquad (2)$$

Therefore, the soil resistivity ρ is given as:

$$\rho = 2\pi a \frac{V}{I} \qquad (3)$$

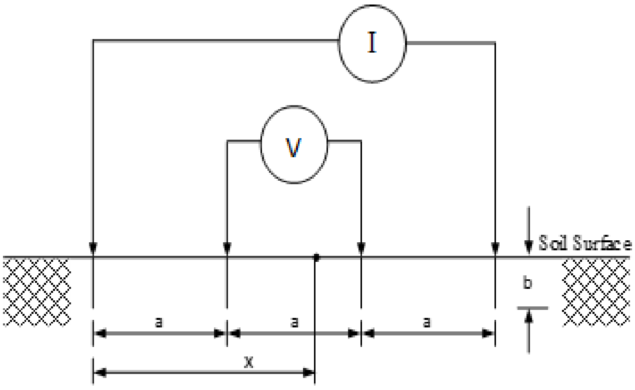

Figure 2: Wenner Four-Pin Method [6]

In a homogenous soil, the Wenner four-pin arrangement should be able to provide uniform soil resistivity regardless of the distance of separation a. For non-homogeneous soil, which is most common, the apparent soil resistivity which is dependent on the distance of separation a will be presented.

The minimal ground resistance value offered by a ground grid embedded in a soil of uniform resistivity, can be gotten from the resistance expression of a circular metal plate, which is applicable to square shaped grids [7].

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} \qquad (4)$$

R_g is the substation ground resistance (Ω), ρ is the soil resistivity (Ω-m) and A is the ground grid area (m^2)

For a square-shaped ground grid, the maximal ground resistance value can be derived [7] as given in equation (5)

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L} \qquad (5)$$

where, L is the gross length (m) of grid conductors.

Equation (5) may be applied with practical accuracy for square grids embedded in the soil at depths less than 0.25 meters, for ground grids earth-embedded between a range of 0.25-2.5 meters, a correction factor was introduced by [8], to account for the variation in the depth of the earth-embedded grid, and the expression for the ground resistance is given in equation (6).

$$R_g = \rho\left[\frac{1}{L} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right] \qquad (6)$$

where, h is the depth (m) of earth-embedded grid.

[9], presented an expression in equation (7) for deriving earth-embedded ground grid resistance in a soil of uniform resistivity. Equation (7) is effective for multiple-grid systems, and may be simplified for an isolated grid, without ground rods.

$$R_g = \frac{\rho}{\pi L}\left(\ln\frac{2L}{\sqrt{2rh}} + K_1\frac{L}{\sqrt{A}} - K_2\right) \qquad (7)$$

where h is the depth (m) of earth-embedded conductors, and r is the radius of the conductors (m).

K_1 and K_2 in equation (7) can only be obtained through the use of graphs. [10], presented expressions for deriving K_1 and K_2 as shown in equations (8) and (9).

$$K_1 = 1.84\sqrt{\frac{ab}{2}}\left[\frac{1}{a}\ln\left(\frac{a + \sqrt{a^2+b^2}}{b}\right) + \frac{1}{b}\ln\left(\frac{b + \sqrt{a^2+b^2}}{a}\right) + \frac{a}{3b^2} + \frac{b}{3a^2} - \frac{\left(a^2+b^2\right)^{3/2}}{3a^2b^2}\right] \qquad (8)$$

$$K_2 = ln\frac{4(a+b)}{b} + 2K_1\frac{(a+b)}{\sqrt{ab}} - ln\frac{\left(a+\sqrt{a^2+\left(\frac{b}{2}\right)^2}\right)}{\left(\frac{b}{2}\right)} - \frac{1}{2}\,ln\frac{(b/2)+\sqrt{a^2+(b/2)^2}}{-(b/2)+\sqrt{a^2+(b/2)^2}} \qquad (9)$$

where b is the length (m) of the long side of the grid, a is the length (m) of the short side. These expressions applies to a limited group of rectangles, with an 8:1 peak length to width ratio. Equation (6) is considered the best available expression thus far and it is recommended by the IEEE Std. 80.

1.2 Voltage Limits/Standards

Substation ground grid system proffer a finite resistance to fault currents. Ground resistance of a substation grid is expected to be very low, and it ranges from 1Ω large substations and between 1Ω-5Ω for distribution substations. Grounded equipment at substations are expected to operate at near zero ground potential under normal conditions. Under fault conditions, fault current that is conducted into the earth causes the grounding grid potential to rise with respect to remote earth. This rise in grounding grid voltage is referred to as ground potential rise (GPR). The GPR is proportional to the magnitude of the ground grid resistance and the fault current.

The mesh voltage and the step voltage are essential design parameters that are dependent the GPR and ground resistance values. The touch voltage is the potential difference between the GPR and the surface potential at the point where an individual is standing, while touching a grounded structure. The maximum touch voltage within a substation facility is known as mesh voltage. Consequently, the critical limit to the amount of shock energy that a human body can absorb is dependent on factors like body weight. The predominant physiological effects of electric current on the human body are muscular contraction, coma, fibrillation of the heart, respiratory nerve clot and burning. The fibrillation threshold of the human body ranges from 60-100mA [10]. The tolerable fault current duration by most persons is expressed in equation (10).

$$(I_B)^2 t_s = S_B \tag{10}$$

$$I_B = \sqrt{S_B / t_s} \tag{11}$$

where I_B is the current (A) flowing through the body, t_s is the duration (s) of current flow and S_B is the tolerable energy shock constant. $\sqrt{S_B}$ has a value of 0.116 for a body weight of 50kg and 0.157 for body weight of 70kg.

$$\text{50kg person:} I_B = 0.116/\sqrt{t_s} \tag{12}$$

$$\text{70kg person:} I_B = 0.157/\sqrt{t_s} \tag{13}$$

Typically, the top soil layer of substations are covered with crushed rocks which offer high resistivity below the feet of substation personnel. Assume an overly large depth of crushed rock layer, will equate the footing resistance value R_{foot} as $3\rho_s$, where, ρ_s is the crushed rock layer's resistivity. The contact resistance between the feet and the substation surface is greatly increased by the crushed rock layer, thereby reducing the amount of current flowing through the body of a substation operator or a bystander. The safe limits of the touch and step voltages are defined as shown below.

$$E_{touch} = (R_B + 0.5R_{foot}) * I_B \tag{14}$$

With $R_B = 1000\Omega$, and $R_{foot} = 3\rho_s$, as shown in equation (14), touch potential for a 50kg and 70kg body weight, can be written as:

$$E_{touch50} = (1000 + 1.5\, C_s\, \rho_s) \frac{0.116}{\sqrt{t_s}} \tag{15}$$

$$E_{touch70} = (1000 + 1.5\, C_s\, \rho_s) \frac{0.157}{\sqrt{t_s}} \tag{16}$$

The safe limit for step voltage is given as:

$$E_{step} = (R_B + 2R_{foot}) * I_B \tag{17}$$

$$E_{step50} = (1000 + 6\, C_s\, \rho_s) \frac{0.116}{\sqrt{t_s}} \tag{18}$$

$$E_{step70} = (1000 + 6\, C_s\, \rho_s) \frac{0.157}{\sqrt{t_s}} \tag{19}$$

The factor C_s account for the crushed rock layer that is spread on top of the substation soil, and its resistivity is different from the substation soil resistivity. It application of the C_s compensate for the finite thickness of the surface layer of the crushed rock. The C_s factor and its derivation form a major aspect of substation ground grid design and is expressed as shown in equation (20).

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \tag{20}$$

Where, C_s is the surface layer derating factor, ρs is resistivity of the surface layer material (Ωm), h_s is thickness of the surface layer (m) and ρ is the soil resistivity (Ωm).

The mesh potential, for square ground grids with square meshes, is calculated as given in equation (21).

$$E_m = \frac{\rho I_G K_m K_i}{L} \tag{21}$$

where, I_G is the maximum ground grid current (A), L is the total conductor length, K_m is the spacing factor for the mesh voltage and it is given as:

$$K_m = \frac{1}{2\pi}\left[\ln\left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{K_{ii}}{K_h}\ln\frac{8}{\pi(2n-1)}\right] \tag{22}$$

D is the spacing (m) between parallel conductors, h is the depth (m) of earth-embedded grid conductors, d is the grid conductors diameter (m), and n is the number of parallel conductors in any one direction. K_i is the asymmetrical factor, which accounts for some errors introduced by the presumptions made in deriving K_m, K_{ii} is the weighting factor for earth electrodes per rods on the mesh intersection and K_h is the weighting factor for depth of embedded conductor.

$$K_h = \sqrt{(1 + h)} \tag{23}$$

$$K_i = 0.644 + 0.148 * n \tag{24}$$

$$K_{ii} = \frac{1}{(2n)^{2/n}} \tag{25}$$

The step potential may be calculated as:

$$E_{step,\ max} = \frac{\rho I_G K_s K_i}{L} \qquad (26)$$

The spacing factor K_s for step potential is given as:

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}\left(1 - 0.5^{n-2}\right)\right] \qquad (27)$$

In cases of rectangular ground grids having square meshes, the value of n could be modified as shown in equations (28a) – (28b).

When calculating mesh potential, n is given as:

$$n = \sqrt{n_A n_B} \qquad (28a)$$

where, n_A is the amount of conductors connected in parallel along one of the coordinate axis, and n_B is the amount of conductors connected along the other axis.

When calculating step potential, n is given as:

$$n = \max.\ (n_A, n_B) \qquad (28b)$$

The recommended limits for the application of these equations are given in equations (29a) - (29c).

$$0.25m \leq h \leq 2.5m \qquad (29a)$$

$$d < 0.25m \qquad (29b)$$

$$D > 2.5m \qquad (29c)$$

2.0 DESIGN METHOD

The optimal design analysis of a substation grounding grid system with an expected maximum short circuit current of 45 kA is considered in this study. Based on the IEEE Std. 80 and the Finite Element Method, the substation grounding system was designed using ETAP 16.0 software. The under listed problems must be addressed when analyzing a substation grounding grid system.

(i) Evaluation of soil resistivity
(ii) GPR computation
(iii) Computation of step and touch potential
(iv) Safety analysis

The general ground grid system design procedure as outlined above involves some specific test stated below and presented in figure 3.

Step 1: carry out soil resistivity measurement around the vicinity of the substation facility.

Step 2: establish the soil parameters from step 1

Step 3: collate and prepare required data for the interconnected power system.

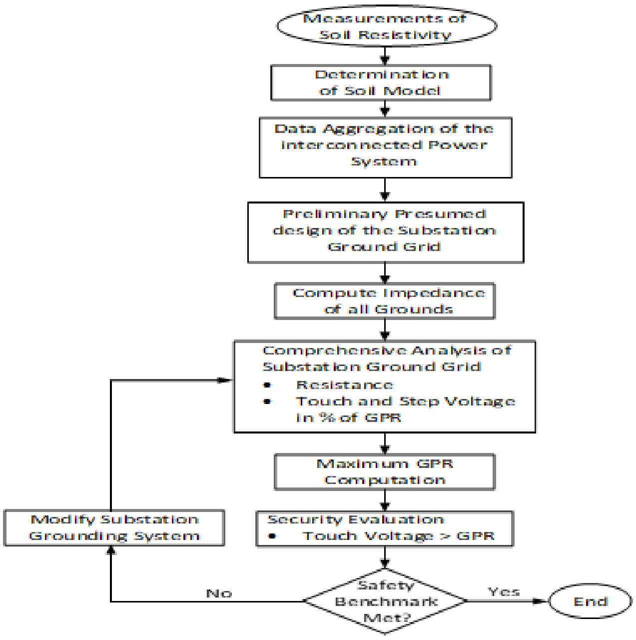

Figure 3: Substation Grounding System Design Procedure

Step 4: assume a preliminary ground grid design for the substation.

Step 5: determine the impedance of all the system grounding structures, such as: substation ground resistance, tower footing resistance.

Step 6: carry out a comprehensive analysis of the substation grounding system in order to ascertain the ground resistance, maximum step voltage, and maximum touch voltage as a percentage of GPR.

Step 7: determine the system maximum short circuit current (fault current) and computationally determine the maximum GPR (or maximum earth current).

$$I_g = 3S_f * I_o \qquad (30)$$

$$GPR = I_g * R_g \qquad (31)$$

Step 8: conduct a safety assessment of the system. Precisely, compute the maximum step voltage and maximum touch voltage in volts. Verify if these values are within standard tolerable limits. If yes, the procedure terminate here. Otherwise, modify the system design and perform steps 6, 7 and 8 again.

3.0 SYSTEM ANALYSIS

ETAP 16.0 is used for the design and simulation of the ground grid system using IEEE Std. 80 Method and FEM method respectively. In both cases, the GPR value will be kept less than the tolerable values of step and touch potentials because it will be ensured that the calculated step and touch potentials do not exceed their safety limits. The ETAP 16.0 grounding grid system module have the provision for performing analysis using both IEEE Std. 80-2000 method and the Finite Element Method (FEM).

3.1 Case Study A: IEEE Method

The IEEE std. 80-2000 method in ETAP analyses ground grid system in three different ways; ground grid configuration for normal simulation, optimized number of conductors, and optimized number of rods and conductors, with each generating varying parameters. A maximum short circuit current value of 45kA and fault clearing time of 0.5 sec. is taken into account.

Table 1: Ground grid input parameters for normal simulation, optimized number of conductor and optimized number of rods and conductors

Parameters		**IEEE 80-2000 Config. for Normal Simulation**	**IEEE 80-2000 Config. for Optimized No. of Conductors**	**IEEE 80-2000 Config. for Optimized No. of Rods & Cond.**
Length of Grid	x-axis	92	92	92
	y-axis	92	92	92
Number of Conductors	x-axis	30	6	6
	y-axis	30	6	6
Conductors Depth (m)		1.8	1.8	1.8
Conductor Size (mm^2)		120	120	120
Type of Conductor		Copper	Copper	Copper
Number of Rods		90	90	80
Type of Rod		Copper	Copper	Copper
Rod Diameter		2	2	2
Length of Rods		10	10	10
Total cost of Design ($)		64,200.00	20,040.00	19,040.00

Table 2: Output result of the IEEE Std. 80-2000/2013

Method IEEE 80-2000/2013	**Touch Voltage (V)**	**Step Voltage (V)**	**GPR (V)**	**Ground Resistance (Ω)**
Config. for Normal Simulation	1591.5	1182.7	21764.5	0.482
Config. for Optimized No. of Conductors	2641.4	522.7	23314.0	0.516
Config. for Optimized No. of Rods & Cond.	2820.8	552.2	23432.3	0.519

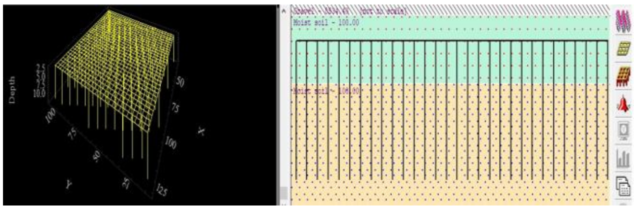

Figure 4: Grid Mesh and Soil Modeling using ETAP-16.0

3.2 Case Study B: Finite Element Method (FEM)

The Finite Element method happens to be one of the most reliable methods of finding ground grid resistance. The ground resistance found using FEM is usually fairly close to the actual value, when compared to the ones calculated using conventional measurement methods. The input parameters of the proposed substation ground grid design with expected maximum short circuit current value of 45kA and fault clearing time of 0.5 sec. are shown in Table 3.

Table 3: Ground Grid Input Parameters for FEM

Parameters		**FEM Method**
Length of Grid (m)	x-axis	92
	y-axis	92
Number of Conductors	x-axis	30
	y-axis	30
Conductors Depth (m)		2.8
Conductor Size (mm^2)		120
Number of Rods		42
Type of Rod		Copper
Rod Diameter (cm)		4
Length of Rods (m)		10
Total cost of Design ($)		59,400.00

Table 4: Output Result of the FEM Analysis

Method	**Touch Voltage (V)**	**Step Voltage (V)**	**GPR (V)**	**Ground Resistance (Ω)**
Finite Element Method	2653.3	974.1	19815.9	0.439

The substation ground grid design analysis is performed in order to evaluate the most effective and economical method, comparing between the IEEE method and Finite Element Method. Based upon results obtained from case study A and case study B. IEEE 80-2000/2013 configuration for optimized number of rods and conductors is taken into account owing to the lower cost of design as compared to the other two configurations.

Table 5: Results Comparison

Method	**Touch Voltage (V)**	**Step Voltage (V)**	**GPR (V)**	**Ground Resistance (Ω)**
FEM Method	2653.3	974.1	19815.9	0.439
IEEE 80-2000/2013	2820.8	552.2	23432.3	0.519

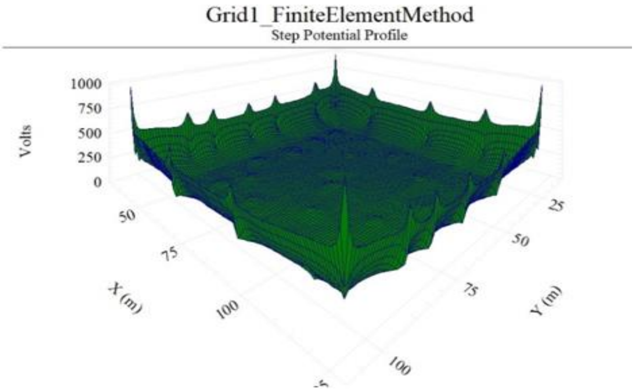

Figure 5: Step Potential Profile

Shown in figures 5, 6 and 7 are graphs for Step, Touch and Absolute Potential profile. The peak touch and step voltages are clearly observed at the corners of the ground grid system voltage profile. In order to bring the maximum touch and step voltages within their tolerable limits, they should be elevated at the corners as shown in figures 5, 6 and 7.

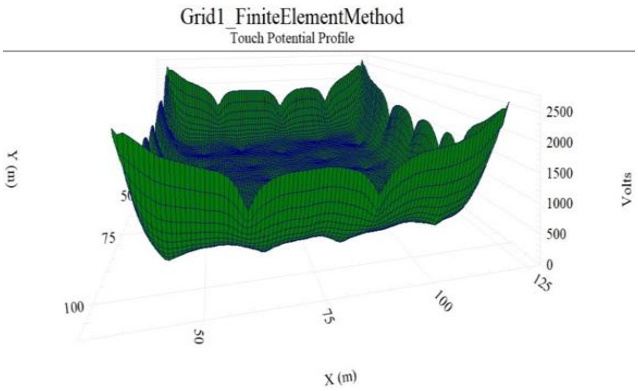

Figure 6: Touch Potential Profile

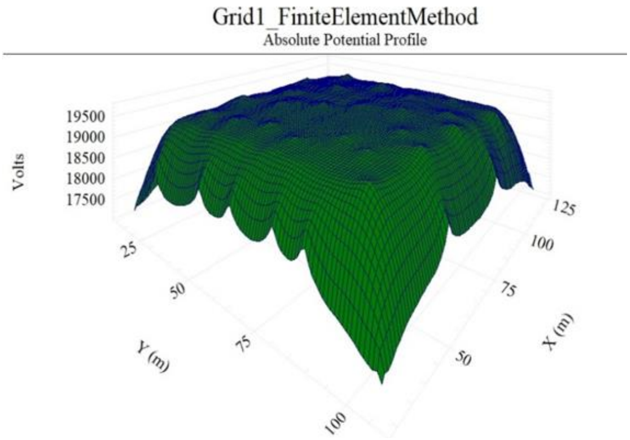

Figure 7: Absolute Potential Profile

Upon comparison of both methods, the number of conductors required for designing the ground grid structure is more, using FEM compared to that of the IEEE method. The required number of rods is more using the IEEE method unlike that by FEM. Again, as shown in Table 1 and Table 3. The reason behind the increased cost by FEM result from the incorporation of a high number of conductors and rods (5940m) used for executing the ground grid structure as opposed to that of IEEE method (1904m). The surface area of the horizontally laid conductors and the diameter of the vertical rods are more in mesh designed by FEM.

Finally, the ground grid structure design using FEM is found to be more effective with a ground resistance (R_g) value of 0.439Ω when compared to that of IEEE method with a ground resistance (R_g) of 0.519Ω. This indicate that case study B (FEM) will permit a higher dissipation of short circuit current. This study has succinctly shown that ground grid design using FEM is functionally more effective than the IEEE 80-2000/2013 method, though less cost effective.

4.0 CONCLUSION

The results presented in this study shows a substation ground grid system design with expected short circuit current of 45kA. Both FEM method and IEEE 80-2000/2013 method were analyzed using ETAP-16.0 software in order to determine the tolerable safe limits of the different design parameters; step voltage, touch voltage, GPR and ground resistance. The ground grid design procedure is iterative, based on analysis and successive refinement of the grounding system until the safety conditions are met. It can be concluded from obtained results that FEM method showed a high effectiveness in dissipating more fault current when compared to IEEE method. But, the IEEE 80-2000/2013 method proved to be cost effective as opposed to FEM method.

Degradation in ground grid mesh often occurs after eight to ten years, with various potentials surpassing their safety limits. Proper ground grid system design is essential to accommodate new system requirements as well as ground grid mesh degradation. Ground grid mesh design using FEM method will ensure a more durable grounding system that can effectively withstand excessive fault currents.

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