OPTIMIZATION DESIGN OF GROUND GRID MESH OF 132/33KV SUBSTATION USING ETAP

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ABSTRACT

This paper presents ground grid mesh design analysis and optimization of a 132/33kV substation. Ground grid mesh is made up of horizontal and vertical conductors connected with vertical rods buried under substation ground. The function of this structure is to effectively dissipate extremely high current generated in the system. The objective of this study is to determine the cost effective and safe ground grid mesh parameters by comparing mesh design analysis using IEEE and Finite Element Analysis (FEM) methods. The two methods are used differently to determine the ground grid mesh parameters, step & touch voltages, horizontal and vertical number of conductors, vertical numbers of rods, and final substation Resistance. Etap 12.60 software is used for the analysis. Firstly, expected maximum short circuit current of OHIA 132/33kV substation is determined. Secondly, analysis is performed to determine input and output parameters of grid mesh structure using IEEE and FEM methods. An optimized result of IEEE method is determined. Analysis of both results is shown in different tables and recommendation is given regarding the best method for the grid mesh design.

Keywords: ETAP, ground grid mesh, design, optimization, finite element method, short-circuit current

1. INTRODUCTION

Grounding system for transmission substation is very important for stability of power system. It is described as system of electrical connection to the general mass of earth. This system of electrical connection consists of components of electrical system and metal works associated with the equipment, apparatus and appliances. This system provides protection to personnel, equipment and buildings and must have the ability of carrying short circuit current into earth under normal and fault conditions without exceeding operating and equipment limits or adversely affecting continuity of service [1]. The earth must be treated as semi-conductors while the grounding electrode itself as a pure conductor. These factors make the design of a grounding system complex, not derived from a simple calculation or the random driving of a few rod into the soil [2]. Due to the difference in soil characteristics at each substation, ground grid design must be carefully done to gain acceptable safety limit of all the parameters [3]. An accurate assessment of

the site's soil condition is mandatory in other to determine the soil structure, type, depth and resistivity of each layer of the soil [1]. The primary requirement of earthing is to provide low earth resistance path for the dissipation of current in other to protect equipment personnel from excess current which may lead to equipment breakdown as well as loss of lives. If the resistance is high, more voltage drop will occur in mesh which will result in rise of mesh potentials [4]. A vertical rod is more effective electrode than a horizontal rod [3]. They discharge the grid current in the soil at sufficient depth thereby reducing soil resistance and Grid Potential Rise (GPR). With the presence of more ground rods, total length of conductors in the earth increases which causes decrease in step and mesh voltages. Ground rods are considered to be more effective way of reducing resistance of combine grounding system, actual mesh and step voltages whenever design modifications are necessary i.e. in actual practice [5]. There are three

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purposes of using grounding rods in a system grounding design. They are;

➢ To reach to the lower earth layers which are less affected by environmental factors such as temperature and moisture content,

➢ To protect the system operation as they are sited near surge arresters as close as possible to minimize the effectiveness of transient voltage.

➢ To ground the fence of the grounding region separately [6].

The main issues related to ground grid design and determination of optimum method for substation mesh design is presented in this paper. The objective of this paper is to design ground grid mesh of a 132/33kV substation with expected maximum short circuit of 26 kA such that the acceptable levels of step and touch potentials are held below their maximum permissible levels. The design analysis and optimization of grid mesh is carried out using two methods, Finite Element Analysis (FEM) and IEEE 80-2000. The two methods are compared to determine the most efficient and cost effective design for the proposed 132/33kV substation at Ohia. Latest Etap software 2014 version is used in the study.

2. DETERMINATION OF SOIL RESISTIVITY.

Soil resistivity is the key factor that determines what the resistance of the charging electrode will be and to what depth it must be driven to obtain low ground resistance. The resistivity of the soil varies widely throughout the world and changes seasonally. The lower the resistivity, the fewer the electrodes required to achieve the desired earth resistance value. Usually there are several soil layers with each having different resistivity which lead to non uniformity of the soil. Thus uniform soil is the soil that has one layer with constant value of resistivity [7]. Soil resistivity of a substation can be calculated using any of these four methods [8, 9]

➢ Wenner
➢ Four point
➢ Three point driven
➢ Schlumberger.

Among the four methods, schlumberger is the most commonly used as testing procedure is easier and stratification type whether the soil is horizontally or vertically stratified can easily be judged [21].
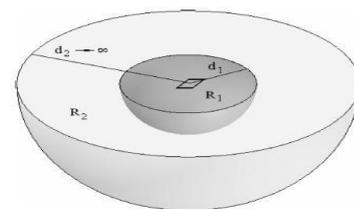
3. METHODS OF ANALYSIS

3.1 Finite Element Grounding Methods

Most recent studies about grounding analysis are based on finite element methods FEM . It is used to determine grounding resistance of a design or a grounded region. They give more accurate results compared to conventional ground methods . FEM is one of the more reliable methods of finding ground grid mesh resistance. The resistance found is fairly close to the actual value compared to the one calculated using the conventional measurement methods[10].

Old FEM methods are composed of current flow analysis by using grid potential set. After the current is computed, ground resistance can be found by dividing voltage by current. However, the short coming of this method is selecting the size of the model such as earth distance to be considered is starting from the grounding grid. Since analysis of each potential in the soil for a selected point is considered from grounding grid to the point [5]. New FEM methods are developed by researchers such that main disadvantage of old FEM method is overcome. In new FEM, modeling starts from the following steps;

❖ In the first step, researchers assume that grounding resistance is such a parameter that does not depend on potential or current in the grid except frequency cases other than power frequencies (50Hz or 60Hz).

❖ Second assumption is that the region is an infinite flat surface [11]

Fig 1 New finite element model of soil [15]

R_1 is the Resistance inside the semi-spherical surface, R_2 is the Resistance outside the semi-spherical surface, d_2 is the Distance from grid to the points where electrical potential goes to zero.

d_1 is the Distance from grid to the points where semi-spherical model of equipotent surface disturbs.

$$d_1 = \frac{D}{2} + 30 \qquad (1)$$

where D is the diagonal distance of grounding grid.

Resistance of grounding grid [R] is calculated from equation (2)

$$R = R_1 + R_2 \qquad (2)$$

Resistance outside the semi spherical surface R_2 is calculated using equation (3)

$$R_2 = \frac{\rho}{2\pi d_1} \qquad (3)$$

Determination of R_1 is not as simple as R_2. This is where finite element analysis exactly takes its place. Ingeneral R_1 can be calculated from dissipated power given in Eq. (4).

$$R_1 = \frac{(Voltage)^2}{Dissipated\ power} \qquad (4)$$

R_1 can be detailed by replacing the terms as in Eq. (5).

$$R_1 = \frac{(V_G - V_B)^2}{\int_v \frac{E^2}{\rho} dv} \qquad (5)$$

V_G is the potential in the grid, V_B is the potential in the boundary. d_1 And E is the Energy consume to do work From Eqs. (3) and (5), one can compute the grid resistance by Eq. (6).

$$R_g = \frac{(V_G - V_B)^2}{\int_v \frac{E^2}{\rho} dv} + \frac{\rho}{2\pi d_1} \qquad (6)$$

Finite Element Analysis can be also used to determine touch and step voltages. Once Rg is determined from FEM, step and touch voltages can be determined by the following steps.

Actual grid potential (V_{AG}) is determined by Eq. (7) by finite element analysis.

$$V_{AG} = R.I_G \qquad (7)$$

where I_G is actual fault current in A.

Actual boundary potential (V_{AB}) is determined by Eq. (8) by finite element analysis.

$$V_{AB} = R_2.I_G \qquad (8)$$

3.2 IEEE Methods of Grounding System Design.

IEEE 80-2000 describes four different methods of determining ground resistance R_g [12]. The methods are discussed hereunder.

3.2.1 Laurent-Niemann Method: The ground resistance is a function of the area covered by the substation and the soil resistivity in the substation region. Soil resistivity has a non-uniform nature and varies both vertically and horizontally in the earth region. R_g can be calculated using eqn. (9)

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \qquad (9)$$

where A is area covered by the substation in m^2, L_T is total buried length of conductors, ρ is the resistivity of soil.

$$L_T = L_t + n_R.h \qquad (10)$$

L_t is the total length of conductors in grid in meters., n_R is the number of grounding rods used in grid in meters., h is the depth of the grid in meters. [13]

3.2.2 Sverak Method: This method is an integrated form of Laurent-Niemann Method. Ground resistance at the surface of the soil is modified in order to improve the accuracy of the ground resistance R_g calculated. The work done in [14] observed significant effect of the grid depth on ground resistance and decided that this effect is large enough to be included into the equation Therefore, Eq. (9) is rearranged and the resultant Eq. (10) is obtained.

$$R = \rho\left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h(\sqrt{20/A})}\right)\right] \qquad (10)$$

Examining Laurent-Niemann and Sverak Equations, it can be easily understood that the resistance is directly proportional to resistivity and inversely proportional to total buried length of conductors and the following is observed. Increasing the area of grounding grid decreases the resistivity in the order of square root. Ground resistance decreases while using more conductors in grid design [14].

3.2. 3. Schwarz Method: This method is composed of three equations and one equation for merging the three.

$$R = \frac{R_1 R_2 - R_m^{\ 2}}{R_1 + R_2 - 2R_m} \qquad (11)$$

$$R_1 = \frac{\rho}{\pi L_t}\left[In\left(\frac{2L_t}{a'}\right) + \frac{K_1 L_t}{\sqrt{A}} - K_2\right] \qquad (12)$$

2a is the diameter of conductor in m. a' is the $\sqrt{2ah}$ for conductors buried at depth h.

K_1 and K_2 are the coefficients found by the following equations according to the value of grid depth (h).

$$R_2 = \frac{\rho}{2\pi n_R L_r}\left[ln\left(\frac{4L_r}{b}\right) - 1 \right. $$
$$\left. + \frac{2K_1 L_r}{\sqrt{A}}\left(\sqrt{n_R} - 1\right)^2\right] \qquad (13)$$

where L_r is the length of each rod in meters, b is the diameter of rod in meters,
n_R number of rods placed in area A.

The third variable in Schwarz Equation is given in Eq. (14). Rm is the combined ground resistance of the grid and the rod bed. Reference [16] has the necessary derivations to obtain Schwarz equations

$$R_m = \frac{\rho}{\pi L_t}\left[ln\left(\frac{2L_t}{L_t}\right) + \frac{K_1 L_t}{\sqrt{A}} + 1 - K_2\right] \qquad (14)$$

3.2.4 Thapar-Gerez Method: Thapar-Gerez formula is given in Eq. (15) and this formula is the integrated version of Eq. (10). In detail, an extra multiplication part is added to include the effect of grounding region shapes on calculated resistance.
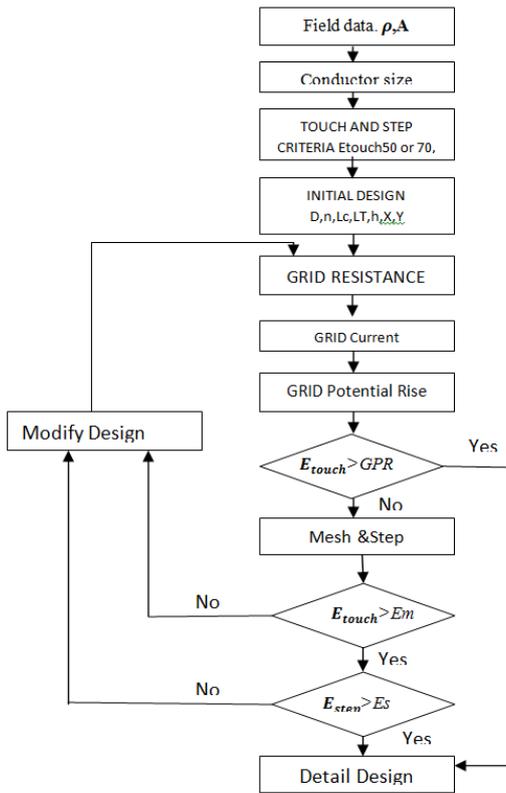
$$R = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right]$$

$$\times 1.52 \left[2ln \left(L_p \sqrt{\frac{2}{A}} \right) - 1 \right] \frac{\sqrt{A}}{L_p} \quad . (15)$$

Where L_P is the peripheral length of grid.

4. DESIGN PARAMETERS.

The proposed 132/33kV Ohia substation is fed from 330/132kV Alaoji grid station as shown in figure 2. Etap 12.6 software is used to design the network and also used to determine the expected maximum short circuit current. From fig 2, the maximum short circuit current at Ohia 132/33kV substation bus bar is 26.6kA. The grid mesh design is done manually to obtain the design parameters and the results verified using the software.

5. DESIGN METHODOLOGY

Step 1. Determine the following field data;

A. Area (A) of the substation using any of the following Square, Rectangular, Triangular, L- Shape, T-Shape methods.

B. soil resistivity of the site using any of the methods: Schlumberger, 3 point driven Rod, 4 point and wenner [8,9].

C. Maximum expected short circuit current and maximum clearing time using Etap 12 software.

Step 2.Determine the conductor cross sectional area $A_{mm}{}^2$ using equation 16.

$$A_{mm}{}^2 = I \times \sqrt{\frac{\frac{t_c \times \alpha_r \times \rho_r \times 10^4}{TCAP}}{ln\left[1 + \frac{(T_m - T_a)}{(K_0 + T_a)} \right]}} \quad (16)$$

Step3. Step potential (E_{step}) and touch potential (E_{touch}) using eqn(17-20)

$$E_{step_{50}} = (1000 + 6C_s(h_S K)\rho_s) \frac{0.116}{\sqrt{t_s}} \quad (17)$$

$$E_{step_{70}} = (1000 + 6C_s(h_S K)P_S) \frac{0.157}{\sqrt{t_s}} \quad (18)$$

$$E_{toch_{50}} = (1000 + 1.5C_s(h_S K)P_S) \frac{0.116}{\sqrt{t_s}} \quad (19)$$

$$E_{toch_{70}} = (1000 + 1.5C_s(h_S K)P_S) \frac{0.157}{\sqrt{t_s}} \quad (20)$$

Step 4. Determine the following; Depth of burial grid conductor, ground conductor spacing, crushed rock resistivity, Quantity of ground rod and calculate the number of conductors in X and Y axis and total length (L_t) of grid conductor using the eqn. 21, 22 and 23.

$$X = \frac{width}{D} \quad (21)$$

$$Y = \frac{length}{D} \quad (22)$$

$$L_t = Y \times length + X \times width \quad (23)$$

Fig 2: Alaoji substation network

Figure 3: Design procedure block diagram

Step 5; Determine the ground grid resistance using any of equation (9), (10), (11) and (15). The most commonly used are (10) and (15) equations, as testing procedure is easy and stratification type, whether the soil is horizontally or vertically stratified can easily be judged by this method.

Step 6: Determine the grid current (I_g) using eqn. 24.

$$I_g = 3S_f I_0 \qquad (24)$$

Step 7: Determine the grid potential rise (GPR) using equation (25)

$$GPR = I_g R_g \qquad (25)$$

Step 8:.If E_{touch} is greater than GPR then proceed to the detailed design otherwise go to step 9.

$E_{touch} > GPR$

Step 9: Determine the mesh and Step voltages using equations 26 and 27

$$E_{mesh} = \frac{PK_m K_{im} I_g}{L_t + 1.15 L_r N_r} \qquad (26)$$

$$E_{step\ cal.} = \frac{PK_i K_{is} I_g}{L_t + 1.15 L_r N_r} \qquad (27)$$

Step 10: If E_{touch} is greater than mesh voltage then proceed to step 11 and if not move to step 12.

Step 11: If E_{step} is greater than calculated step voltage then proceed to detail design step 13 otherwise move to step 12

Step 12: Output detailed design

6. GRID PARAMETERS FROM ETAP SOFTWARE

Ground grid input data is generated from Etap 12 Software after the simulation as shown in Appendix A which shows all the input parameters and constants that are used for the design of ground mesh. These are the System data, Soil data, Material constant, Rod data, Grid configuration and Cost of Design.

6.1 Case1. IEEE Method.

The ground grid system module in Etap 12.6 has the provision of performing analysis using IEEE 80-2000 methods in three different ways and each generate different parameters. Table 1 show the input ground grid parameters upon which modeling are done. It shows grid mesh data for normal simulation, Optimized number of conductors and optimized number of rods and conductors as shown in Figures: (4) through (7).

Table1: Grid mesh data for normal simulation, optimized number of conductors and optimized number of rods and conductor

Parameters		Grid Configuration for normal Simulation	Grid Configuration for Optimized no of cond.	Grid Configuration for optimized no of rods & conductors
Conductors Depth (ft)		6.00	6.00	6.00
Grid Length (ft)	Lx	300	300	300
	Ly	300	300	300
No of Conductors	X	18	13	6
	Y	18	13	6
Separation Length	X	17.6	25	60
	Y	17.6	25	60
Total no of Conductors		36	26	12
No of rods		75	75	123
Length in (ft)		32.80	32.80	32.80
Ground Resistance		0.518	0.518	0.480
Total Cost of Design		$2310.00	$1710.00	$966.00

The results of analysis using IEEE 80-2000 methods for normal simulation. The result of analysis for optimized number of rods and conductors is shown in Figure 6.

6.2 Case 2: FEM method.

This shows the design of grid mesh of the proposed substation with maximum expected short circuit of 27kA using Finite Element Analysis method. Table 2 shows the input parameters for the design.
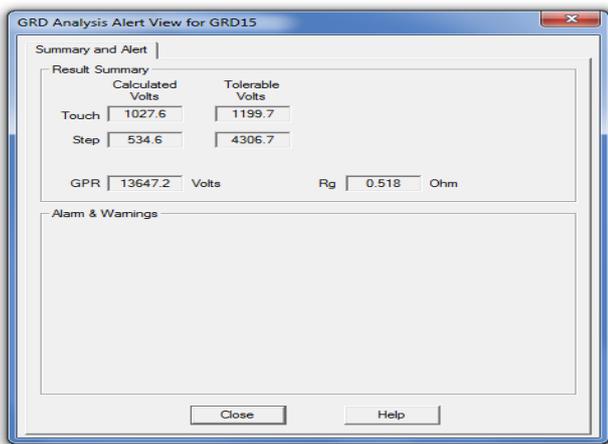
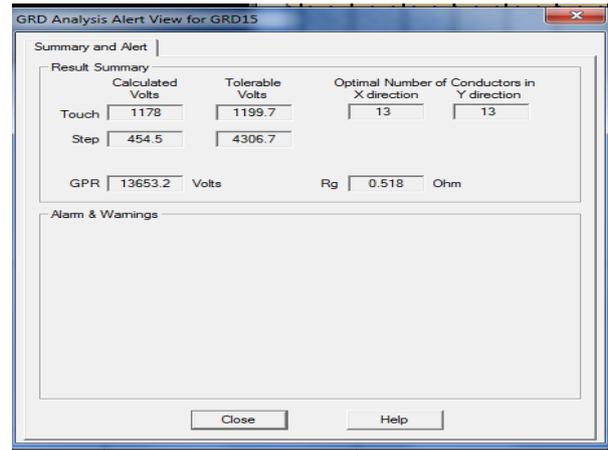Fig 4; Grid Configuration for Normal Simulation.

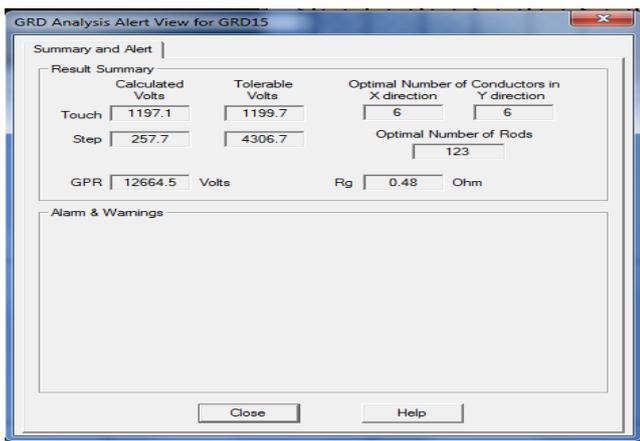Fig.5 Grid Configuration for Optimized Number of conductors.

Fig. 6 Grid Configuration for optimized number of rods and conductors.
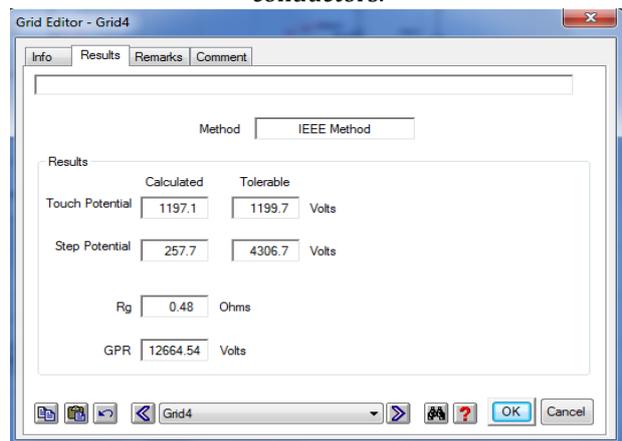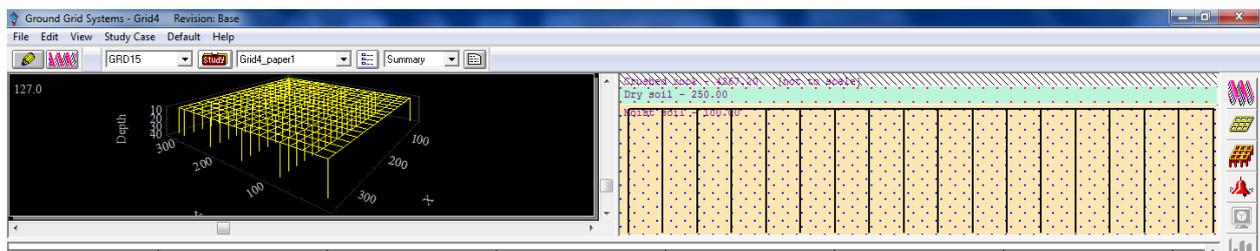

Fig7. Final result Using IEEE method

Fig; 3 Ground Grid Systems with different simulation.

Table 2: Input parameters

Parameters		FEM
Conductors Depth (ft)		8.00
Grid Length (ft)	Lx	300
	Ly	300
No of Conductors	X	15
	Y	15
S Separation Length	X	21.4
	Y	21.4
Total no of Conductors		30
No of rods		34
Length in (ft)		100
Rod Diameter		4inch
Ground Resistance		0.37Ω
Total Cost of Design		$1868

Figures 9, 10 and 11 shows different Touch, Step, Absolute potential after the simulation of design using FEM method.

Cases 1 and 2 are analyzed below. The analysis is performed to evaluate the most effective and economical ground grid mesh structure using IEEE method and FEM method. See appendix A and B for details of simulation results. The results of Case 1 and Case 2 have been presented and based upon these results, the two are compared in order to determine the most effective and cost effective method for ground grid mesh design.
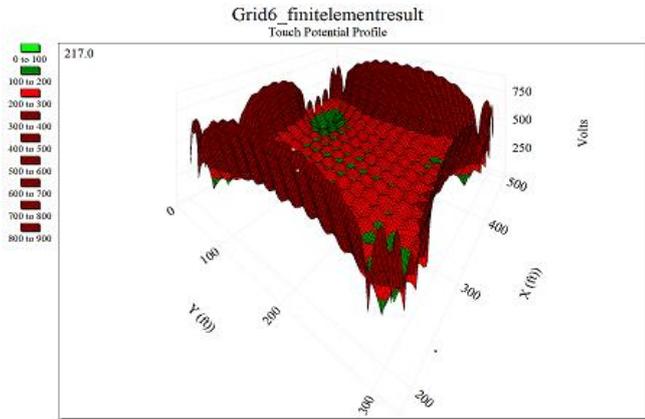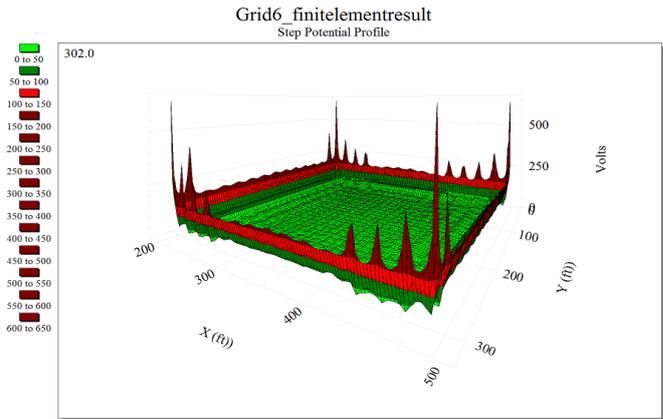
Fig.9. Touch Potential
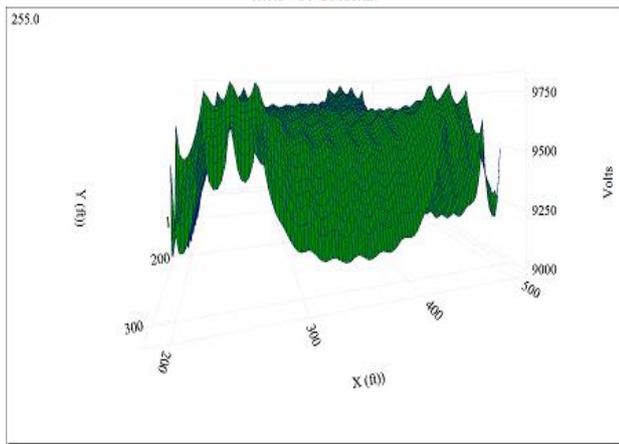

Fig. 10 Step potential voltage profile.
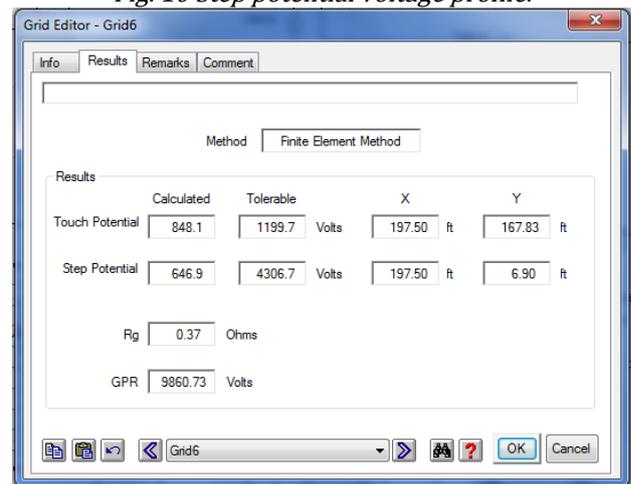

Fig 11 Absolute potential profile

Fig. 12: Final result of FEM analysis

Because of the lower cost of design, the grid configuration for optimized number of rods and conductors for Case 1 are used

Required conductors: The analysis of the results shows that ground grid mesh structure is more when using FEM method (9000ft) than IEEE method (3600ft).

Rod required: The number of rod is more for IEEE method than FEM. But the per length of each rod for FEM (100ft) is more than IEEE (32.80ft) thereby making the rods for FEM more effective than IEEE, since FEM reaches to the lower earth layers which are less affected by environmental factors such as temperature and moisture content.

Design cost: The results shows that the cost of ground grid mesh design is more using FEM method ($ 1868) than IEEE method ($966). The reason is that the horizontally and vertically laid conductors are more in mesh designed by FEM than IEEE methods.

Effectiveness: The final result shows that the ground resistance (R_g) of ground grid mesh structure design using FEM is lower (0.374Ω) than IEEE method (0.480Ω). This means that the rate of dissipation of short circuit current will be higher for grid mesh designed by FEM than one done with IEEE method.

It was discovered that the best grid configuration is for the Case 1 which optimized the number of rods and conductors used . Finally this work has shown that design done with FEM is better that of IEEE methods in terms of effectiveness but is cost more than IEEE method.

7. CONCLUSIONS

The result in this paper shows the ground grid mesh design of a 132/33kV substation with expected maximum grid current of 26kA. Two different methods FEM and IEEE, based on Etap 12 software were used for the design analysis to determine tolerable limit of different design parameters (GPR, mesh voltage, step and touch voltages and R_g). The design by FEM method after satisfying the safety criteria limits showcased a highly effective mesh grid structure that can withstand more excessive fault current when compared to IEEE method ie (R_g FEM $<R_g$ IEEE) and an expensive mesh structure when compared to IEEE method as shown in case 1.

Grid mesh structure degenerate with time, this leads to various design parameters GPR, Estep Etouch and R_g exceeding their safety criteria limits overtime therefore it is importance that a method that accommodate the smallest property be used. FEM method is suggested since it gives more realistic results when implemented than the conventional method.

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APPENDIX A

Project:		ETAP		Page:	1
Location:		12.6.0H		Date:	11-21-2015
Contract:				SN:	
Engineer:		Study Case: GRD15		Filename:umuahia network	
				Revision:Base	

Ground Grid Input Data

System Data:

			Short-Circuit Current				Fault Duration (Seconds)		
Freq. Hz	Weigh kg	Ambient Temp. °C	Total Fault Current kA	X/R	Sf Division Factor %	Cp Projection Factor %	Tf for Total Fault Duration	Tc for Sizing Ground Conductors	Ts for Available Body
50.0	50	40.00	25.810	8.26	100.0	100.0	0.50	0.50	0.50

Soil Data:

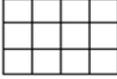| Surface Material			Upper Layer Soil			Lower Layer Soil	
Material Type	Resistivity Ohm.m	Depth ft	Material Type	Resistivity Ohm.m	Depth ft	MaterialType	Resistivity Ohm.m
Crushed rock	4267.2	9.999	Dry soil	250.0	5.00	Moist soil	100.0

Material Constants:

Conductor/Rod	Type	Conductivity %	α r Factor @ 20 °C 1/°C	K0 @ 0 °C	Fusing Temperatu °C	Resistivity of Ground @ 20°C micro ohm.cm	Thermal Capacity Per Unit J/(cm³.°C)
Conductor & Rod	Copper-clad steel rod	20.0	0.00378	245.0	1084.0	8.62	3.85

Rod Data:

Diameter inch	Length ft	No. of Rods	Arrangement	Cost $/Rod
0.750	32.80	75	Rods Throughout Grid	2.00

Grid Configuration:

Conducto Size AWG/kcm	Depth ft	Grid Length ft Lx	Grid Length ft Ly	Number of in X Direction	Number of in Y Direction	Separation ft in X Direction	Separation ft in Y Direction	Cost $/ft
500	6.00	300.00	300.00	18	18	17.6	17.6	0.20

Shape:

Cost:

Conductor Total No.	Conductor Total Length ft	Conductor Cost $	Rod Total No.	Rod Total Length ft	Rod Cost $	Total Cost $
36	10800.00	2160.00	75	2460.00	150.00	2310.00

Project:
Location:
Contract:
Engineer:

ETAP
12.6.0H

Study Case: GRD15

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Revision: Base

Ground Grid Summary Report

Rg Ground Resistance ohm	GPR Ground Potential Rise Volts	Maximum Touch Potential Tolerable Volts	Maximum Touch Potential Calculate Volts	Maximum Touch Potential Calculated %	Coordinates (ft) X	Coordinates (ft) Y	Maximum Step Potential Tolerable Volts	Maximum Step Potential Calculate Volts	Maximum Step Potential Calculated %	Coordinates (ft) X	Coordinates (ft) Y
0.374	9860.7	1199.7	848.1	70.7	197.5	167.8	4306.7	646.9	15.0	197.50	6.90

Total Fault Current	25.810 kA	Reflection Factor (K):	-0.889
Maximum Grid Current:	26.369 kA	Surface Layer Derating Factor (Cs):	0.986
		Decrement Factor (Df):	1.022