COMPUTATION OF POTENTIAL PROFILE AT A SURFACE ABOVE ENERGIZED UNEQUALLY SPACED GROUNDING GRID

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Abstract: A detailed analysis of potential profile at a surface above energized unequally spaced grounding grid has been carried out, for soils with multiple layers. Exact and approximated algorithms are used to obtain the voltage profile and then to calculate the step and touch voltages. The analysis shows that the voltage distribution is highly dependent on soil structure type and characteristics and also the spacing between conductors.

Keywords: Grounding Design, Layered Soils, Multilayered, Ground Potential Rise, Touch Voltages.

1. Introduction

Studying the effect of voltage distribution is an important parameter to design the grounding systems of substations to ensure the safety of people above the substation ground .This can be achieved by equalizing the potential distribution of the ground surface and reducing step and touch potentials [1].

The earth surface potential distribution above the equally spaced grid is extremely non-uniform. In this paper the voltage distribution is calculated for unequally spaced by using the suggested image method and also by using approximated method in case of multi-layer soil. The obtained results are compared with the IEEE method [2]. IEEE guide has proved to be a very popular guide for substation grounding applications. IEEE gradient analysis method allows a recursive point by point integration of surface gradients through all parallel grid conductors .The analytically most significant equations of the IEEE gradient analysis method are given in reference [3].

In the suggested algorithm the expressions of potential at any point due to a point current source in multi-layer soils can be obtained by image technique or by solution of Laplace's equations [3]. These are in the form of infinite summation series. The rate of convergence of these series is mainly dependent on the reflection factor between layers of the soil. For a reasonable accuracy, up to a few thousand terms of series may have to be computed. Determination of potential from such expressions, therefore, forms significant part of computational effort in analysis and design of a grounding system in three-layer soil.

A new simplified method for calculating the grounding voltage distribution of grounding grid in three-layer earth structure (multi-layers) has been presented.

2. Analytical Analysis

Figure (1) shows the grounding system model under study, which consists of horizontal three layers. The grid is placed in the first layer of grounding system which its resistivity (ρ_1), over a second layer of resistivity (ρ_2), which is over the third layer of resistivity (ρ_3). Thickness of the first layer and second layer are (d_1), and (d_2) respectively. The depth of the buried grid in the first layer is (b), while the distance between the grid and surface of the second layer is (h). The ground voltage profile of the grid can be determined with the use of image technique.

The three boundary planes between air, first layer, second layer, and third layer produce an infinite sequence of images. All these images discharge current into the first layer of its resistivity (ρ_1). Whenever an image is taken on the boundary between air and first layer, the current of the image remains the same. However, when an image is taken on the boundary between the first and second, the current of the image reduces by a ratio.

$$k_{12} = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (1)$$

Whenever, an image is taken on the boundary between the second and third, the current of the image reduces by a ratio

$$k_{23} = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2} \quad (2)$$

Where K_{12}: Reflection factor between first and second layer, K_{23}: Reflection factor between second and third layer

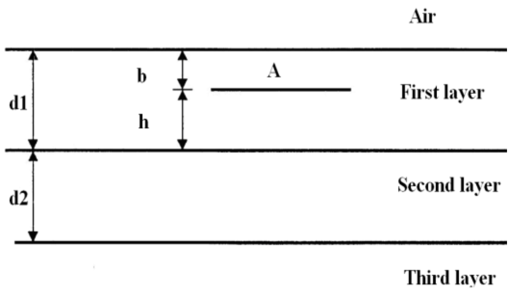

Figure (1) Grounding system model under study

2.1 Infinite series potential (I.S.M.) expressions in three dimension

If a conductor of length (l) is buried in non- uniform earth structure at the top layer of resistivity (ρ_1), where the x-axis is coaxial with the conductor, and y-axis is normal to the conductor at the mid point of the conductor. Figure (1) shows the three-layer model under study in case calculating the voltage distribution on the grid surface where:

A: Area of grid, m^2, b: Burial depth of grid, m,

For any grounding system in three-layer earth structure, the current in each conductor element produces a potential at a point (x, y, z) in the surrounding medium in three dimension with taking the reflection factors between first, second and third layer in account will be as follows [4-7]:

$$v(x,y,z) = \frac{I\rho_1}{4\pi l}[$$

$$\ln f(x,y,z) + \ln f(x,y,2b) +$$

$$+\sum_{n=1}^{\infty}(k_{12}^{n}.\ln f(x,y,z+n2h+(n-1)2b) +$$

$$2k_{12}^{n}\ln f(x,y,z+n2h+n2b) +$$

$$k_{12}^{n}\ln f(x,y,z+n2h+(n+1)2b) +$$

$$\sum_{n=1}^{\infty}(k_{23}^{n}.\ln f(x,y,z+n2(d_2-h)+(n-1)2(d_1+h)) +$$

$$2k_{23}^{n}\ln f(x,y,z+n2(d_2-h)+n2(d_1+h))$$

$$+k_{12}^{n}\ln f(x,y,z+n2(d_2-h)+$$

$$(n+1)2(d_1+h)))] \quad (3)$$

Where,

$$f(x,y,z) = \frac{\sqrt{(x+l/2)^2+y^2+z^2}+x+l/2}{\sqrt{(x-l/2)^2+y^2+z^2}+x-l/2} \quad (4)$$

l: Length of a grid side, m, r: Radius of grid conductor, m, , n: Number of images

2.2 Optimum Compression Ratio (OCR)

In unequally spaced grid when the conductors are arranged according to an exponent regularity, the span from the center could be calculated by the equations

$$d_n = d_{max}.C^n \quad (5)$$

$$d_{max} = \frac{L(1-c)}{1+c-2c^{(N/2+1)}} \quad \text{N even} \quad (6)$$

$$d_{max} = \frac{L(1-c)}{2(1-2c^{(N-1)/2})} \quad \text{N odd} \quad (7)$$

Where C is the compression ratio, L is the side length of grounding system, N is the conductors number arranged on it and d_{max} is the central; span .Empirical expression is obtained to calculate (OCR) [8,9].

2.3 Test and verify

The analytical analysis in three-dimension is applied for a grid grounding system that consists of 96 meshes with dimensions given in table 1 and soil structure given in table 2 to obtain the voltage profile on the earth surface in the different position along the grid length . The short circuit current of 220kV substation grounding system is 10kA. The (I.S.M.) method suggested in this paper is applied on example of IEEE [2] and proves that it is very accurate. The maximum percentage difference is approximately 5 %. Figure 3 to Figure 6 show the voltage profile for the ground grid with different compression factor

Table (1) Grid dimension parameters

Grid dimension parameters	
grid area, m^2	120X80
burial depth, m	0.6
Radius of grid conductors, m	0.0175
number of meshes	96

Table (2) Soil structure parameters

soil structure parameters	
thickness of the first layer , m	2
thickness of the second layer. m	2
resistivity of the first layer Ωm $\rho_1=30$	30
resistivity of the second layer Ωm $\rho_2=40$	40
resistivity of the third layer Ωm $\rho_3=250$	250
Number of images that vary to infinity.	30

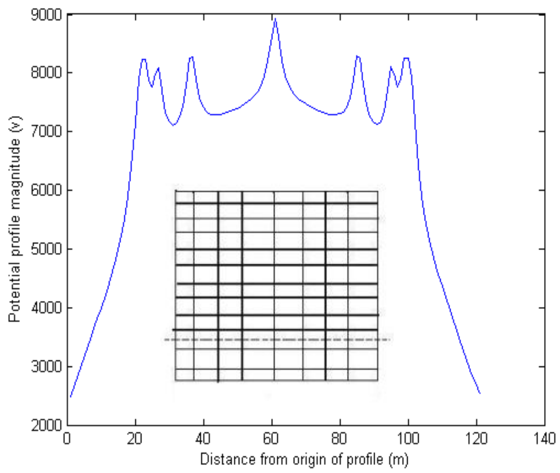

Figure 2 Voltage profile along the unequally spaced grid in case of C=0.4

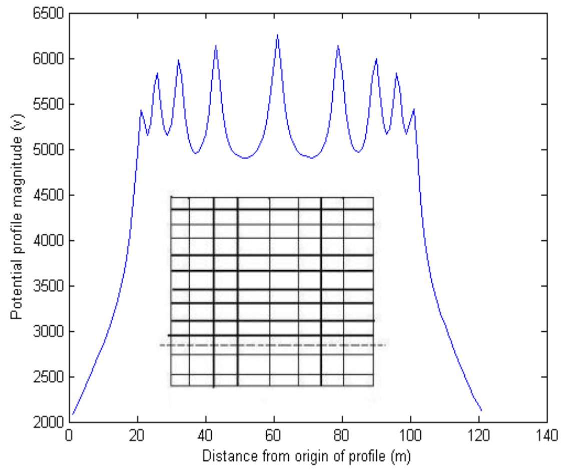

Figure 3 Voltage profile along the unequally spaced grid in case of C=0.6

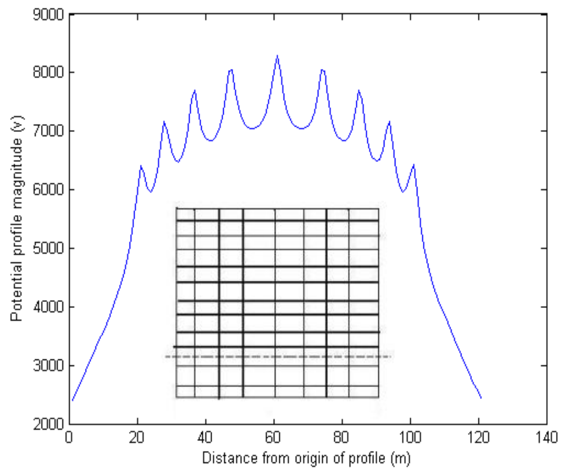

Figure 4 Voltage profile along the unequally spaced grid in case of C=0.8

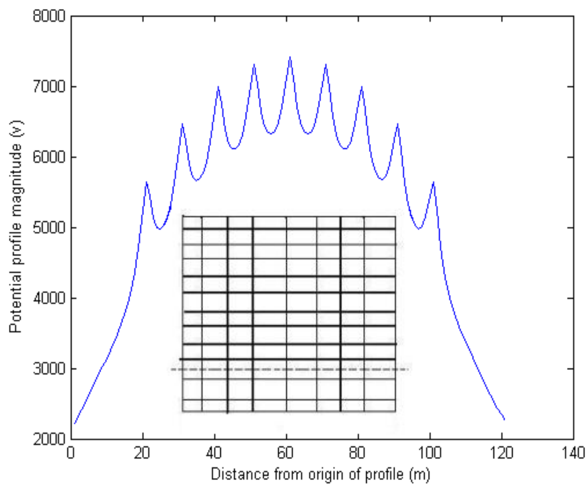

Figure 5 Voltage profile along the unequally spaced grid in case of C=1.0

From the obtained results given in figures it is noticed that when C$\approx$0.6 the potential difference between any two conductors is minimum and this may lead to minimum difference between the maximum and minimum touch potential, this is in agreement with the obtained results given by ref [1] in calculating OCR.

Calculating the voltage profile by the used method consumes long calculation time to give accurate result for this reason the following method may be used.

2.4 Approximated analysis to calculate voltage profile using apparent soil resistivity

The apparent soil resistivity of the three layers is calculated by using IEEE formula [2,10]

In this case the potential at a point (x,y,z) in surrounding medium in three-dimension for any grounding system in three-layer earth structure will be as follows:

$$v(x,y,z) = \delta \frac{I\rho_a}{4\pi l}\left[\ln f(x,y,z) + \ln f(x,y,z+2b)\right] \quad (8)$$

Where,

$$f(x,y) = \frac{\sqrt{(x+l/2)^2 + y^2 + z^2} + x + l/2}{\sqrt{(x-l/2)^2 + y^2 + z^2} + x - l/2} \quad (9)$$

δ Scaling factor

2.5 Scaling factor

Scaling factor δ depends on geometry of the grid, distance from the point of origin and compression ratio C

Table 3 shows the values of scaling factor that gives voltage profile closer to that calculated by (I.S.M.) method using different Compression ratio

Table (3) The influence of scaling factor with compression ratio

Compression ratio C	**Scaling factor** δ
1	4.1
0.8	4.72
0.6	4
0.4	5.571

In order to ascertain the scaling factor when the compression ratio is known, a general law should be found. The paper obtains this relation by using the method of least squares to fitting curves.

The fitting equation is as follows:

$$\delta = -76.088C^3 + 165.67C^2 - 115.71C + 30.215$$

2.6 Test and verify the approximated method

The designed computer program requires various parameters of the grounding system, which are divided as follows:

The same grid and soil parameters given in table 1 and 2 are used to calculate the voltage profile by using the approximated method using ρa=220.

The obtained results are given in figures 6, 7, 8 and 9

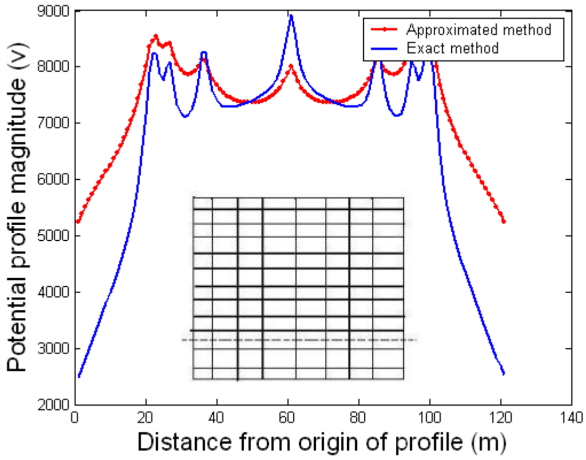

Figure 6 Voltage profile along the unequally spaced grid in case of C=0.4

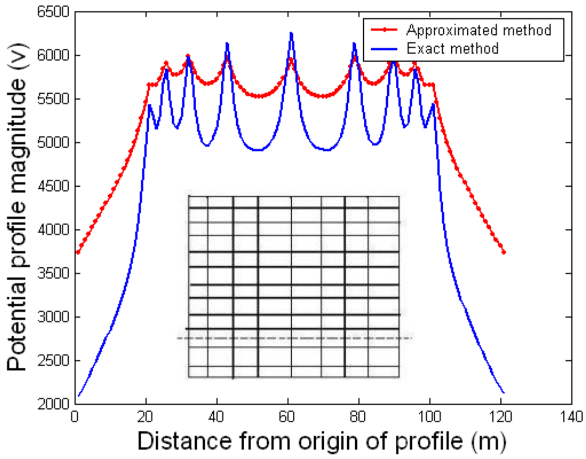

Figure 7 Voltage profile along the unequally spaced grid in case of C=0.6

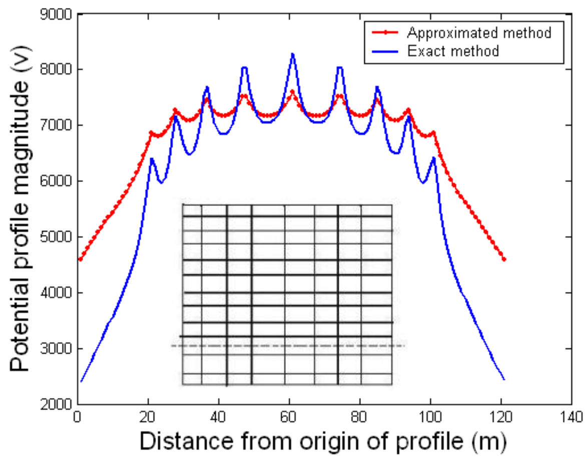

Figure 8 Voltage profile along the unequally spaced grid in case of C=0.8

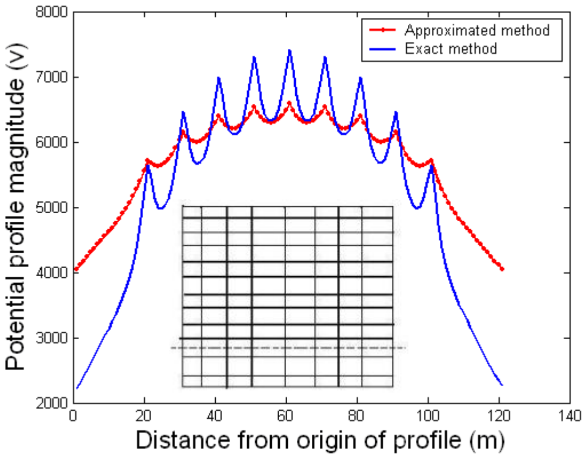

Figure 9 Voltage profile along the unequally spaced grid in case of C=1

From the obtained results given in figures 6 the maximum difference between the peaks values of the two methods is about 12% in case of compression ratio=0.4 and minimum difference is 0 %.

When C=0.6,0.8 and 1 Figures 7,8 and 9 the maximum difference between the peak values of the two methods is about 4%, 8% and 13% respectively and the minimum difference in all cases is 0%.

The minimum value of the maximum percentage difference between the I.S.M. and the approximated method occurs at C=0.6.

CONCLUSION

1- In this paper, a new methodology is presented that allows obtaining the voltage profile by solving a linear programming problem. This method is applied to different grids and its accuracy has been verified.

2- An approximated method is suggested to calculate voltage Profile. It is fast and gives satisfactory results accuracy instead of calculating the voltage profile using the (I.S.M.) method consumes long calculation time to give accurate result.

3- From the obtained results, using the compression ratio $C \approx 0.6$ is the optimal value from the point of view of personal safety. This ratio gives 4% difference between the peak values of voltage profile calculated by the (I.S.M.) method and the approximated method.

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