Influence of the Earth Structure to the Potential Distribution around a Driven Rod

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ABSTRACT: The estimation of the potential distribution on the surface of the earth is necessary for the design of a grounding system. In this paper the software packages Opera-2d and CDEGS have been used for the simulation of the behavior of a driven rod buried into different types of hemispherical soil volumes. Moreover the potential distribution in the soil around a driven rod is computed by using an analytical equation. The comparison of the results acquired both from the equation and the simulations, demonstrates the influence of the earth's hemispherical structure to the potential distribution on the surface of the earth. In addition the usage of simulation packages can provide valuable assistance to the estimation of the surface potential, regardless of the grounding system' s geometry, considering the fact that closed-form mathematical formulae for multi-layer analysis are subjected to limitations (they can be used only for point current sources).

Keywords: grounding systems, multi-layer earth structure, Opera-2d, CDEGS, potential distribution.

I. INTRODUCTION

The grounding system comprises an essential part of the protection system of any power system, building, etc. Moreover, an efficient grounding system can dissipate the stroke current into the soil and reduce the damages to electrical and electronic equipment and to personnel.

The measurements of the soil resistivity have shown that the soil consists of different layers, each one having different characteristics (resistivity, depth) [1]-[2]. Furthermore, closed-form mathematical formulae for the calculation of the distribution of the surface potential [1]-[4] are limited to vertical or horizontal electrodes and simple soil structures. Therefore arithmetic methods such as Finite Element Method [5]-[11], Method of Moments [12], Boundary Element Method [13], [14] or hybrid methods [15] overcome such limitations and provide a successful implemented method for the calculation of the potential distribution.

II. POTENTIAL DISTRIBUTION ON SOIL SURFACE

A. *Analytical Expressions*

Assuming a homogenous and isotropic soil with resistivity ρ, the potential at any point on the surface of the ground due to a point current source I, situated on the surface, is given by the following formula [1]:

$$V(x) = \frac{\rho \cdot I}{2 \cdot \pi} \int_0^{\infty} J_0(\lambda \cdot x) \cdot \partial\lambda \qquad (1)$$

where J_o is the Bessel function of the first kind of zero order and x is the distance from the current source.

B. *Software Packages*

Opera-2d is a software package for electromagnetic field analysis, which solves a wide range of electromagnetic and electrostatic applications in both XY and axisymmetric coordinate systems. This package uses the Finite Element Method to obtain solutions to partial differential equations (Poisson's, Helmholtz and Diffusion equations) that cannot be solved by analytic methods. Opera-2d can also solve electric field problems in models with conductivity and permittivity. Additionally non-linear materials can be modeled by this program.

Since much information is required before the analysis has been performed, data entry is carried out using a powerful interactive pre-processor. Using the graphical interaction within the pre-processor, the space is divided into a contiguous set of triangular elements.

Once the model has been prepared, the solution is achieved using a suitable analysis module. Several modules exist for analysis of the different types of electromagnetic excitation conditions, e.g. static, transient, steady state. The analysis program iteratively determines the correct solution, including non-linear parameters if these are modelled.

The result may then be examined using a versatile interactive postprocessor. As with the pre-processor, this is predominantly controlled by interaction through a graphical menu system. Many system variables are available for examination, including potentials, currents, fields, forces, temperature. Numerical errors due to non-successful mesh definition are also analysed, so that the mesh can be refined to achieve the required accuracy [16].

In contrary, CDEGS is a software package developed especially for grounding systems' analysis. The program solves grounding problems based on the equations of IEEE Std 80-2000 [17] and is subjected to limitations regarding the geometry of the earth structure.

The advantage of the simulation can be estimated by comparing the results of the field analysis, using the CDEGS and Opera-2d, to the results of other methodologies. From this comparison, it is concluded that these software package can be a useful tool in the simulation of grounding systems and in the accurate calculation of the potential on the ground surface around the location, where the grounding system is installed.

III. DRIVEN ROD IN A MULTI-LAYER EARTH

The grounding systems consisting of a 3m length and 17.2mm diameter single driven rod buried in different soil types and subjected to 100A current are simulated by using Opera-2d and CDEGS. The soil model adopted in this paper is similar to the one suggested by [9] - [10] and is presented in Fig.1. According to the model, the soil consists of 2 concentric hemispheres of radii r_1=5m, r_2=10m. In Table I the values of each zone's soil resistivity for the examined cases are shown. These values are used for the simulations.

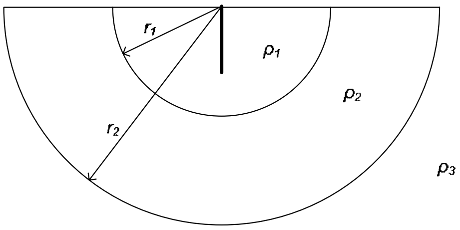

Fig. 1. The geometry of the problem.

TABLE I
THE SOIL PARAMETERS USED FOR THE SIMULATIONS

	Case 1	Case 2	Case 3	Case 4
ρ_1 [Ωm]	50	50	1000	2000
ρ_2 [Ωm]	400	1000	50	400
ρ_3 [Ωm]	1000	200	1000	100
ε_1	41	41	9	3.5
ε_2	16	9	41	16
ε_3	9	20	9	36

In Table II the values of the soil resistivity considering the homogenous soil and point current source are presented. These values are calculated by the formula:

$$\rho = 2\pi r_0 \cdot \left(\int_{r_0}^{r_1} \frac{\rho_1}{2\pi r^2} dr + \int_{r_1}^{r_2} \frac{\rho_2}{2\pi r^2} dr + \int_{r_2}^{\infty} \frac{\rho_3}{2\pi r^2} dr \right) \qquad (2)$$

where $r_0=0.48$m is the radius of a hemisphere electrode having the same resistance with the rod electrode, r_1 and r_2 is the radius of the first and second layer respectively, ρ_1, ρ_2, ρ_3 is the soil resistivity of the first, second and third layer respectively, and ρ is the equivalent soil resistivity for homogenous soil.

TABLE II
THE SOIL PARAMETERS USED FOR THE ANALYTICAL COMPUTATION

	Case 1	Case 2	Case 3	Case 4
ρ [Ωm]	89	83	972	1895

The arrangement is axisymmetric. Mesh generation is of essential importance for simulation by using Opera-2d. Various meshes have been examined in order to define the most appropriate for the problem. A more dense mesh has been used on the common surface of different materials and in the area around the grounding rod. Fig 2 displays the mesh within the examined regions for Case 1.

Moreover, the determination of the boundary conditions is of equal importance. Therefore, the boundary conditions have been carefully selected. In our Opera-2d simulation, the current flow equation was first solved providing the boundary conditions for the electrostatic problem, while the soil resistivity and the relative permittivity (ε_i) were defined as presented in Table I.

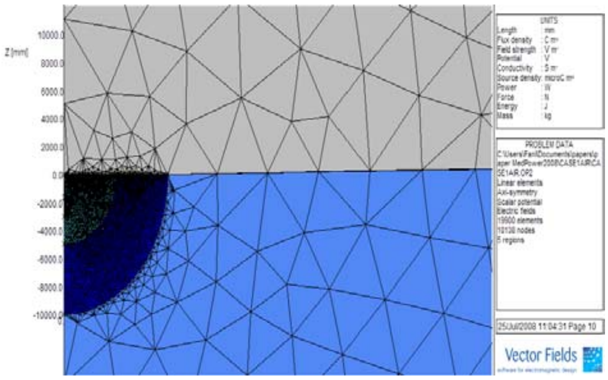

Fig. 2. The Opera-2d model with the mesh for Case 1.

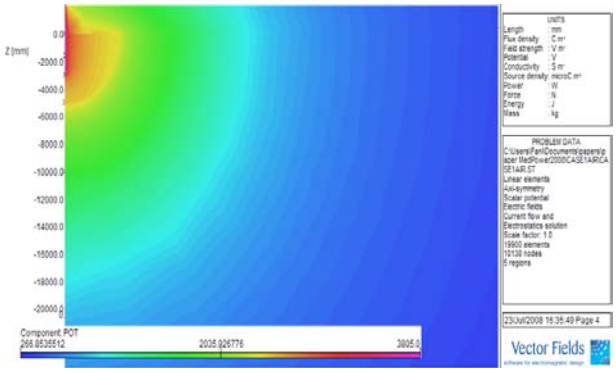

Fig. 3. Filled zone contours of potential for Case 1 up to 20m from the electrode.

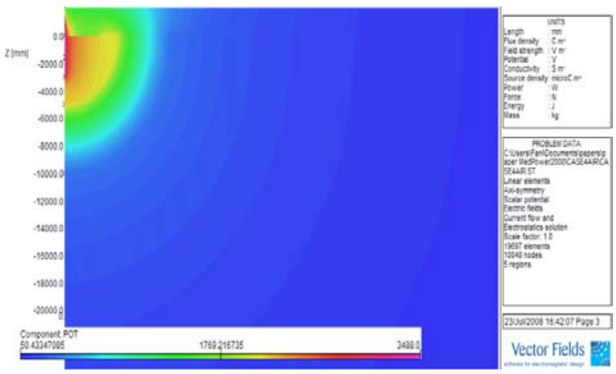

Fig.4. Filled zone contours of potential for Case 2 up to a distance of 20m from the electrode.

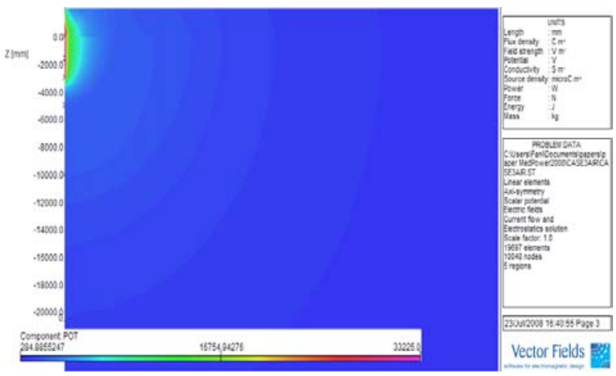

Fig. 5. Filled zone contours of potential for Case 3 up to a distance of 20m from the electrode.

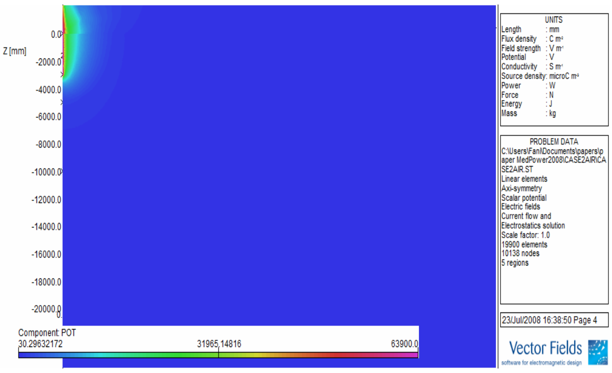

Fig.6. Filled zone contours of potential for Case 4 up to a distance of 20m from the electrode.

Figs. 3 – 6 depict the distribution of the potential on the surface of the soil up to 20m distance from the electrode for the examined cases. In Figs. 3 – 6 it can be observed that the potential's drop is steeper in Cases 3 and 4 in contrast to Cases 1 and 2. This can be attributed to the lower values of soil resistivity of the layers closer to the electrode, leading to higher values of step voltage.

IV. ESTIMATION OF THE SURFACE POTENTIAL

The result of computations and simulations is the variation of surface potential. The results obtained by the simulations are compared with results from the application of equation (1), considering that the soil is homogeneous.

In Figs. 7 - 10 is shown the variation of the surface potential versus the horizontal distance from the rod for the examined grounding systems. As it is depicted in Figs. 7 – 10 the approximation of homogenous soil can lead to under- or overestimation of the developed voltage. In Cases 1 and 2, where the closer to the electrode region is characterized by a lower value of the soil resistivity in comparison to the second region, the results of the homogenous soil's approximation are lower than those derived by using the simulation packages and considering multi-layer soil structure. On the contrary, when the first region's soil resistivity is greater than the second region's resistivity, the values of the potential (Cases 3 and 4) derived by the implementation of (1) are greater when the surface potential is calculated by the simulation programs. However in, Cases 3 and 4 all three curves are in good agreement. In that Cases (1) and (2) can be used for some preliminary estimations of the potential.

Comparing the results of the simulation programs for all the examined cases, it can be observed that the surface potential calculated by CDEGS is lower than the one calculated by Opera-2d, but the curves' form are show grate resemblance.

In Cases 1 and 2 the effect of the soil multi-layer structure on the surface's potential distribution is demonstrated. In Figs. 7 - 8 it can be observed that at a distance of 5m and 10m, where the soil properties change, the rate of the potential's drop also changes. As a result it is evident that the non-uniformity of the soil affects the potential distribution on the surface of the earth. Thus, the multi-layer earth structure must be taken into account when a grounding system is designed.

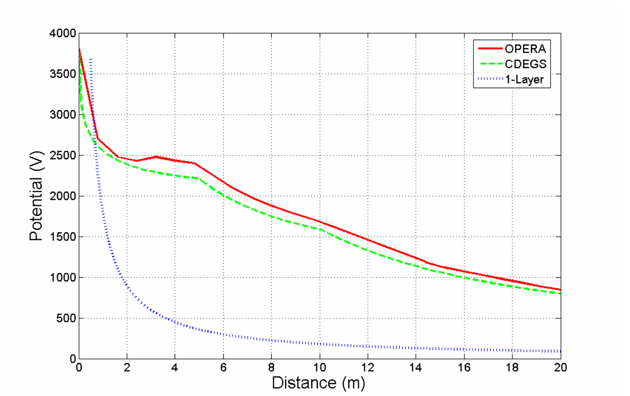

Fig 7. The variation of surface potential versus the horizontal distance from the rod for Case 1.

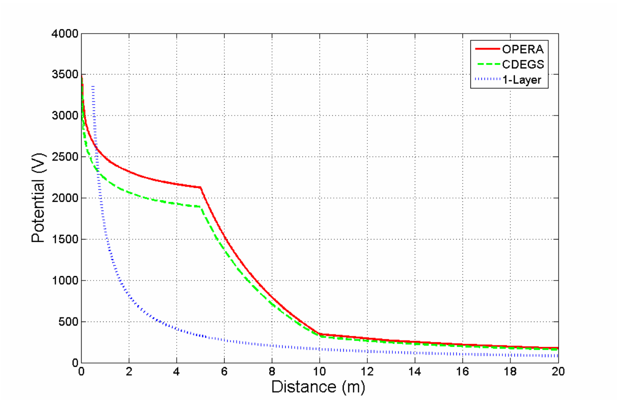

Fig. 8. The variation of surface potential versus the horizontal distance from the rod for Case 2.

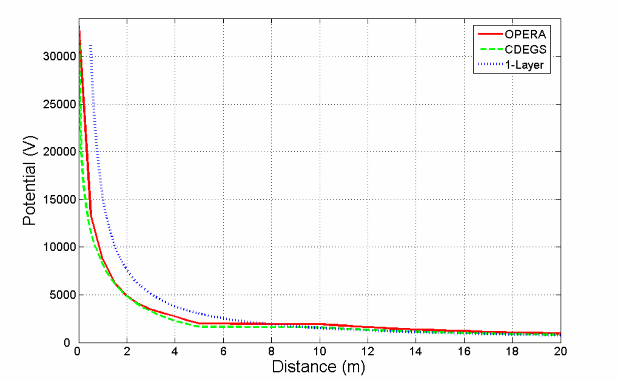

Fig. 9. The variation of surface potential versus the horizontal distance from the rod for Case 3.

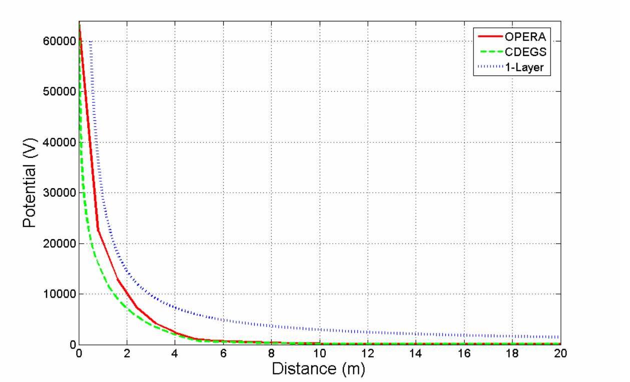

Fig. 10. The variation of surface potential versus the horizontal distance from the rod for Case 4.

Regarding the simulation programs, it can be said that Opera-2d is advantageous in comparison to CDEGS, as long as it can be used to solve more complex geometries, and allows better determination of the soil properties. On the other hand, CDEGS is a program exclusively designed for grounding system's analysis. By using CDEGS, it is easier to parameterize the grounding system's characteristics and study its performance. The program's effectiveness and validness is also acknowledged by [17].

V. CONCLUSION

The results obtained by using (1) can lead either to over or to under-estimation of the voltage developed on the surface of the ground around a grounding system in a form of a driven rod. Thus, the evaluation of surface potential considering multi-layer earth structure is mandatory. However, when the soil resistivity of the inner hemisphere is greater than the resistivity of the other regions, the value acquired by (1) for the case of multi-layer ground structure, whose soil resistivity is given by (2), gives valuable information on the order of magnitude of the developed surface potential.

Considering the fact that the analytical equations for the estimation of the distribution of the potential are subjected to limitations such as grounding system's characteristics (geometry and dimensions) and horizontal stratification of the soil, simulation programs can provide valuable assistance to the estimation of the surface potential developed on the ground and more realistic potential values.

VI. REFERENCES

[1] G. F. Tagg, Earth resistances, George Newnes Limited, London, 1964.

[2] "Estimation of multi-layer soil parameters using genetic algorithms", I.F. Gonos and I.A. Stathopulos, IEEE Trans. on Power Delivery, Vol. 20, No 1, Jan. 2005, pp. 100-106.

[3] "Analysis of apparent resistivity in a multi-layer earth structure", T. Takahashi and T. Kawase, IEEE Trans. on Power Delivery, Vol. 5, No. 2, Apr. 1990, pp. 604-612.

[4] "Calculation of earth resistance for deep-driven rod in multi-layer earth structure", T. Takahashi and T. Kawase, IEEE Transactions on Power Delivery, Vol. 6, No. 2, pp. 608-614, Apr. 1991.

[5] "The influence of an additional substance in the trenches surrounding the grounding grid's conductors on the grounding grid's performance", A. Habjanic, M. Trlep, J. Pihler, IEEE Transactions on Magnetics, Vol. 43, No. 4, Apr. 2007, pp. 1257-1260.

[6] "The analysis of complex grounding systems by FEM", M. Trlep, A. Hamler, B. Hribernik, IEEE Transactions on Magnetics, Vol. 34, No. 5, Sept. 1998, pp. 2521-2524.

[7] "Grounding performance analysis of the substation grounding grids by finite element frequency domain", L. Qi, X. Cui, Z. Zhao, H. Li, IEEE Transactions on Magnetics, Vol. 43, No. 4, Apr. 2007, pp. 1181-1184.

[8] I.F Gonos, M.K Antoniou, I.A Stathopulos, F.V Topalis, "Transient Analysis of the Behaviour of Grounding Systems consisted by driven rod", Proceedings of the 3rd IMACS/IEEE International Multiconference on Circuits, Systems Communications and Computers (IMACS-CSCC '99), Athens, Greece, Jul. 4 - 8, 1999.

[9] "Analysis of Grounding Systems in soils with Hemispherical Layering", J. Ma, F. Dawalibi, and W. Daily, IEEE Trans. PWRD, Vol. 8, pp. 1773-1780, 1993.

[10] "Finite element modelling of grounding systems considering electrode geometry effects" Lorentzou, M.I.; Kladas, A.G.; Hatziargyriou, N.D.; IEEE Transactions on Magnetics, Vol 35, Issue 3, Part 1, May 1999 Page(s):1757 – 1760.

[11] F.E. Asimakopoulou, V.T. Kontargyri, I.F. Gonos, I. A. Stathopulos, "Potentail distribution on the surface of multy-layer earth structure", 13th biennial IEEE Conference on Electromagnetic Field Computation (CEFC2008), Athens, Greece, May 11-15, 2008.

[12] "Numerical analysis of the influence between large grounding grids and two-end grounded cables by the moment method coupled with circuit equations", Bo Zhang, Jinliang He, Jae-Bok Lee, Xiang Cui, Zhibin Zou, Sug-Hun Chang, IEEE Transactions on Magnetics, Vol. 20, No. 2, Apr. 2005, pp. 731-737.

[13] "Analysis of transferred earth potentials in grounding systems, a BEM numerical approach", I. Colominas, F. Navarrina, M. Casteleiro, IEEE Transactions on Power Delivery, vol. 20, no. 1, Jan. 2005, pp. 339-345.

[14] "A numerical formulation for grounding analysis in stratified soils", I. Colominas, F. Navarrina, M. Casteleiro, IEEE Transactions on Power Delivery, Vol. 17, No. 2, Apr. 2002, pp. 587-595.

[15] "The FEM-BEM analysis of complex grounding systems", M. Trlep, A. Hamler, M. Jesenik, B. Stumberger, IEEE Transactions on Magnetics, Vol. 39, Vo. 3, May 2003, pp. 1155-1158.

[16] Vector Fields, Opera-2d User Guide, Vector Fields Limited, England, Aug. 2007.

[17] IEEE Std 80-2000, IEEE Guide for Safety in AC Substation Grounding, Jan. 2000.

VII. BIOGRAPHIES

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