World Applied Sciences Journal 10 (7): 741-747, 2010
ISSN 1818-4952

Grounding Systems Analysis in Hemispherical and Cylindrical Soils

A. Sadeghi, Hadi Ezoji and M. Esmaeili

MAPNA Electrical and Control, Engineering and Manufacturing Company
(MECO), Mapna Blvd. 6th km, Malard Road, Karaj, Iran

Abstract: In this paper, a theoretical model has been presented In order to analyze the grounding systems inside or near hemispherical and cylindrical soils heterogeneities. Exact closed-form Analytical expressions have been obtained to calculate the earth surface potential due to current sources in different regions of this soil structure. There are many practical structures for these types of soils such as hydro power plants, Foundation grounding systems (FGSs), swimming pools, power transformers sumps and depression in soil, dumping sites for material refuse, lakes and open mines, rivers beside the high voltage substations, etc. To implement the represented method, software had been designed, implemented and developed. Numerical results of the software have been compared with existing references for various grounding systems and hemispherical and vertical cylindrical type and horizontal cylindrical type of soils. The results show that the limited hemispherical and cylindrical volumes of soil highly affect the performance of grounding systems.

Key words: Power system grounding · Hemispherical soil · Cylindrical soil · Voltage profile · Grounding system resistance · Step and touch voltages · GPR (Ground System Rise)

INTRODUCTION

Recent years the performances of grounding systems are widely investigated and analyzed for homogeneous and horizontal two-layer soils [1-6]. Studying of buried grounding systems for horizontal multi-layer soils was being noteworthy for many of researchers [7-11]. But no much research has been carried out to analyze the calculations of buried grounding systems in or near the heterogeneous soils with limited volumes [12, 13]. It is very significant to study these types of soils because in many real situations, grounding systems are placed in or near the hemispherical volumes of soil that have different structure than the adjacent soil. It was seen that whatever the foresaid heterogeneous volumes are smaller, they will have more efficacy on surface potentials of ground on the point in or near these limited volumes. There are many practical examples for these types of soils that were mentioned above. On studying of grounding systems, water is considered as a type of soil with a small resistivity. Also, foundation grounding systems with a little connivance are in this class, because their grounding system can be buried in a cubic form concrete volume that is surrounded by soil and cubic form concrete volume is approximately modelled as hemispherical volume.

Numerical methods can be used in order to analyze the calculation of buried grounding systems in limited volumes heterogeneous soils, but whenever it is possible to model the soil in hemispheric or, vertical or horizontal half cylindrical, we can use accurate analytical equations in order to perform the calculations of grounding system parameters and then it will more reduce the calculating time than the other numerical methods.

Problem Description: Fig. 1 shows the construction of the soil that has been investigated in this paper. As it can be seen in Fig. 1, soil may have three hemispherical layers or two vertical or horizontal half cylindrical layers that are produced by two concentric hemispheres with radiuses of a_1 and a_2 or by a cylinder with radius of "a" and with resistivity of ρ_1, ρ_2 and ρ_3.

In this paper, grounding system may be consist of grounding grid, rods or a combination of grounding grid and rods and exist in each layer of soil that is shown in Fig. 1 and even in various layers of it. There is no limitation in grounding grid dimension and meshes that

Corresponding Author: Hadi Ezoji, MAPNA Electrical and Control, Engineering and Manufacturing Company (MECO), Mapna Blvd. 6th km, Malard Road, Karaj, Iran.
Tel: +989363688436, E-mail: hadi.ezoji@gmail.com.

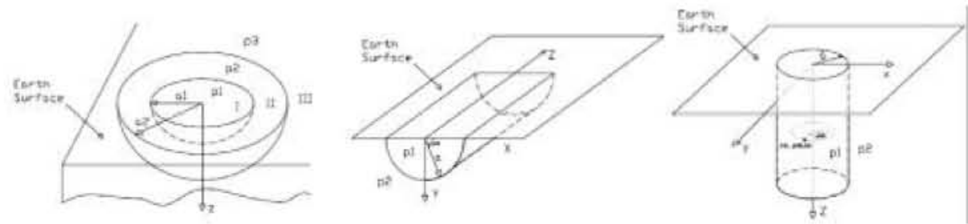


Fig. 1: Soil with hemispherical, horizontal and vertical cylindrical layering

are existed in its surface and number of rods and their length as well.

Analytical Equations Description

Electrical Potential Due to the Point Current Source: First, consider a point current source in an environment that has been divided by two concentric spheres into three spherical zones or by a cylinder into two cylindrical zones. Assume that electrical potential value at the center of the sphere, on cylinder axis and also at infinite point has limited value. Also, for electrical potential function we write the boundary conditions and continuity at the boundary points between the zones. The purpose is to calculate the potential of each point of the space due to the point current source, which could be placed in each layer of soil. For example, in case of spherical layering, three separated zones are imagined for source location: $r_0<a_1$, $a_1<r_0<a_2$ and $r_0>a_2$ (r_0 is the radius of the point current source in spherical coordinate system). With respect to each source location, three different zones could be considered for observation point location (a point that the potential should be calculated there); therefore, nine phrases of voltage distribution functions with regard to source location and observation point location have to be obtained. Considering the point current source in each space locations and using the basic electromagnetism rules results in obtaining the equations of voltage distribution function in various space locations. Then, by applying boundary conditions and continuity, we obtain the answers of above equations. Similar method is performed in cylindrical layering soil.

Electrical Potential Due to the Linear Current Element: After the voltage distribution functions due to the point current sources were achieved then it will be possible to calculate the voltage distribution functions due to the linear current element. Here, it is assumed that the injected current by linear current element to the environment is homogeneous along the length of the element. The length of linear element is considered to be much longer than its diameter as it could be negligible. Integrating of voltage distribution functions due to the point current source along the linear current element length gives the voltage distribution functions of linear current element.

The Effect of Air Half Space on Analytical Equations: The equations that are achieved by above descriptions are for the state that the space is divided into three spherical zones via two concentric spheres, or it is divided into two cylindrical zones via a cylinder (vertical or horizontal), but the analytical equations of soil model illustrated in Figure.1 will be easily obtained by applying the method of images and by using of the achieved equations for spherical or cylindrical zones. When the main current source is on point $(r_0, \theta_0, \varphi_0)$ or (r_0, φ_0, z_0) then the image of mentioned current source will be respectively at $(r_0, \pi-\theta_0, \varphi_0)$ in spherical state and at $(r_0, \varphi_0, -z_0)$ or $(r_0, -\varphi_0, z_0)$ in cylindrical state and it has the same current strength as the main source has. Therefore, electrical potential of each point of space is equal with sum of potentials due to the main source and its image. Voltage distribution function due to the image of each element is easily obtained by replacing θ_0 with $\pi-\theta_0$, φ_0 with $-\varphi_0$ and z_0 with $-z_0$ in voltage distribution function of mentioned element

Determining the Current Distribution: If the purpose is to calculate the grounding system resistance, then there would be no need to know how the current distribution in conductors of grounding system is, but in order to calculate the variation curve values of electrical potential in the surface of the ground and the values of Step voltage and touch voltage it will be necessary to obtain current distribution method in conductors of grounding system. First, the conductors of grounding system at the points on bounder between soil layers are divided into shorter conductors for the above purpose. Then, if it is necessary, each existed part of conductors in each layer is divided again to provide the homogeneous distribution for each part of conductor along its length. After that, by considering the observation point on parts of conductors and writing all voltage distribution functions related to this observation points and parts of conductors (as linear current elements), we will have a set of linear equations. Solving this set of equations results in achieving the current of each part of conductors or the method of current distribution in conductors of grounding system.

Calculating the Electrical Parameters of Grounding System: After characterizing the way of current distribution in conductors of grounding system, it could be possible to obtain all electrical parameters of the grounding system such as voltage variation curve of ground surface, Step and touch voltages, value of GPR (Ground Potential Rise), resistance of grounding system and etc. taking into account the current effects of all current elements make it feasible to calculate the electrical potential value of each point of space. In order to calculate the maximum touch voltage it is sufficient to obtain the electrical potential of ground surface in the middle of four meshes in the corner of the grounding grid and calculate their difference with GPR value and consider the biggest voltage difference as touch voltage. To calculate the maximum value of Step voltage, the electrical potential value of ground surface is calculated in four corners of the grounding grid and also in four points that are placed diagonally in 1 meter far from its corners, out of grounding grid. Then, the voltage difference of each two congruous points is determined that the biggest voltage difference will be the maximum Step voltage. Also, by calculating the electrical potential of each point on the surface of ground, it could be possible to achieve Step voltage for each two adjacent point with distance of 1 meter and touch voltage for each desired point. It is sufficient to calculate the electrical potential on conductors of grounding system in order to calculate the GPR value. Electrical resistance of grounding system is obtained by dividing GPR on total ground fault current.

Comparing of Software Result: Software is provided to implement the above represented theory [3]. Some numerical results of mentioned software (GrndSoft) are compared with CDEGS software [14].

The Resistance of Grounding System, Soil with Hemispherical, Half Cylindrical and Homogeneous Layering: A. Table 1 shows the current software and CDEGS software results in order to calculate the resistance of a rod. Grounding system in this example is a 10 cm rod that is at 4 m depth of the three-layer soil. The radiuses of the input and output hemispheres are 5 and 10 cm, respectively (Fig. 2).

B. Results show that the maximum fault of the GrndSoft software is less than 1%.

Table 2 shows the results of the current software and CDEGS software in order to calculate the resistance of a horizontal bar: Grounding system in recent example is a 15 cm horizontal bar at depth of 0.5 m of two-layer soil. Results show that the maximum fault of GrndSoft software is less than 3%.

C. Resistance of the Grounding Grid:

Fig. 3 shows a grounding grid that is placed near the hemispheric layering of soil.

As it can be seen in Fig. 3, the first layer radius of soil is 4 m and the second layer radius of soil is 6 m. Dimension of grounding grid is 8×8 m and is placed at 0.5 m depth of third layer of the soil. Table 3 shows the resistances of grounding system.

D. Resistance of buried 12×12 m grounding grid at depth of 0.5 m from vertical two-layer cylindrical soil is shown in Table 4:

E. Resistance of the 18×12 m buried grounding grid in Fig. 4 at 0.5 m depth of cylindrical soil with two vertical layers is shown in Table 5.

Voltage Profile, Hemispherical and Half Cylindrical Layering: Since rod reveals the effect of soil construction

Table 1: The resistance of grounding system (rod)-(ohms)

Error (%)	GrndSoft [3]	CDEGS [14]	Resistivity (Ω/m)
0.15	49.29	49.23	ρ_1=50, ρ_2=400, ρ_3=1000
0.7	23.83	24.00	ρ_1=2000, ρ_2=400, ρ_3=100
0.14	27.70	27.74	ρ_1=1000, ρ_2=50, ρ_3=1000
0.66	31.73	31.52	ρ_1=50, ρ_2=1000, ρ_3=200

Table 2: The resistance of grounding system (horizontal

Error (%)	GrndSoft [3]	CDEGS [14]	Resistivity (Ω/m)
-1.2	2.42	2.45	ρ_1=10, ρ_2=100
2.5	9.0	8.78	ρ_1=100, ρ_2=10
1.8	10.9	10.7	ρ_1=100, ρ_2=100
1.8	1.09	1.07	ρ_1=10, ρ_2=10

Table 3: Resistance of grounding system (grounding grid)-(ohms)

Error (%)	GrndSoft [3]	CDEGS [14]	Resistivity (Ω/m)
0.2	12.67	12.6	ρ_1=100, ρ_2=1000
0.2	4.119	4.11	ρ_1=100, ρ_2=100
0.2	41.19	41.1	ρ_1=1000, ρ_2=1000

Table 4: Resistance of grounding system (grounding grid)-(ohms)

Error (%)	GrndSoft [3]	CDEGS [14]	Resistivity (Ω/m)
1.8	5.6	5.5	ρ_1=50, ρ_2=300
3.9	10.6	10.2	ρ_1=300, ρ_2=300

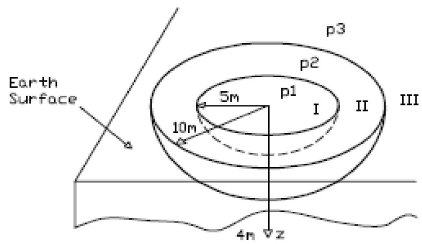


Fig. 2: 10 cm bar at depth of 4 m of the three-layer soil

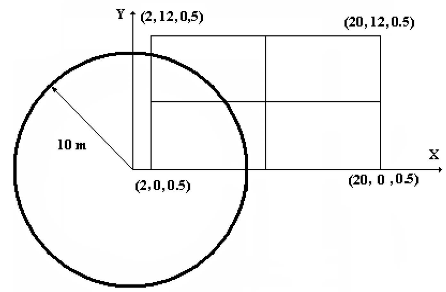


Fig. 4: Grid buried in 2 layers of vertical cylindrical soil.

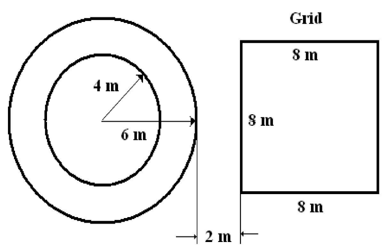
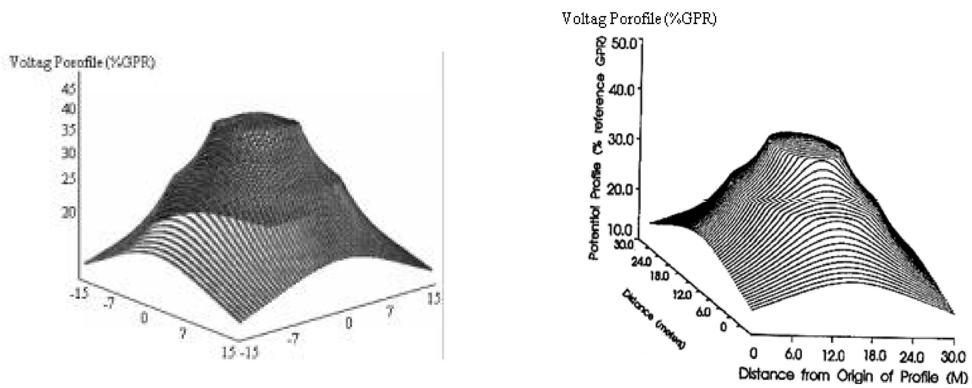


Fig. 3: Grounding grid buried in hemispherical soil with 3 layers

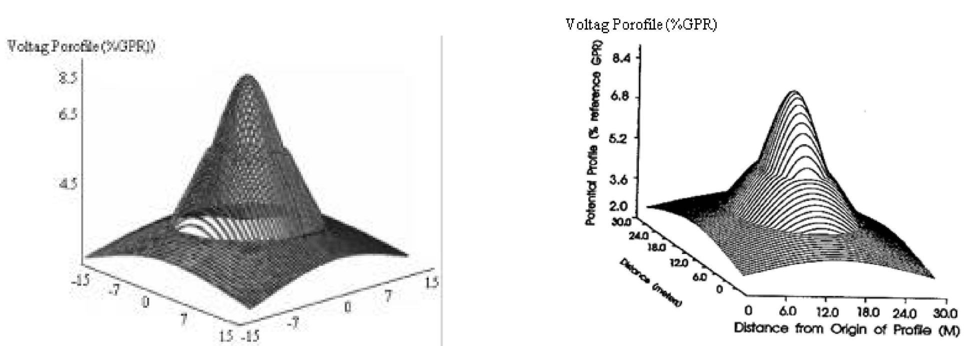
on voltage profile very well, the results of GrndSoft and CDEGS softwares are given for a rod (Fig. 5 to Fig. 8). Also, the variations of ground surface voltage calculated by GrndSoft software and variations of ground surface voltage resulted from CDEGS software are given to be compared for a grounding system consist of a 12×12 m grounding grid (Fig. 9). Grounding grid has 4 meshes and is symmetrically in the first layer of soil with respect to the center of spherical axis. Resistivity of first layer is 100 and its radius is 9 m and



A: Grnd Soft

B: CDEGS

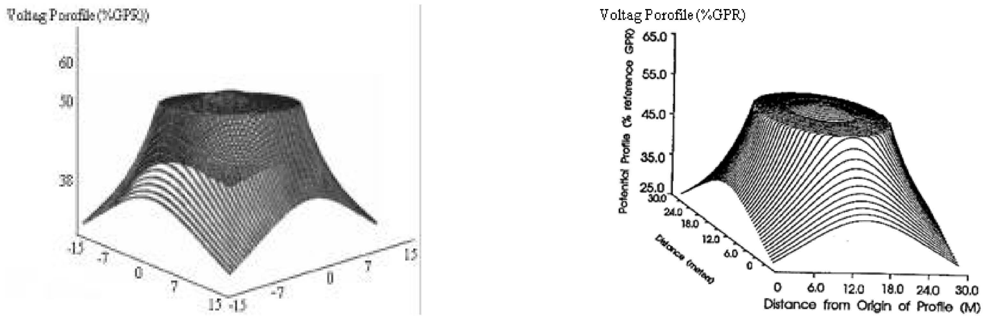
Fig. 5: Ground surface voltage as a percent of GPR. ρ1=50, ρ2=400, ρ3=1000 (ohm-m)



A: Grnd Soft

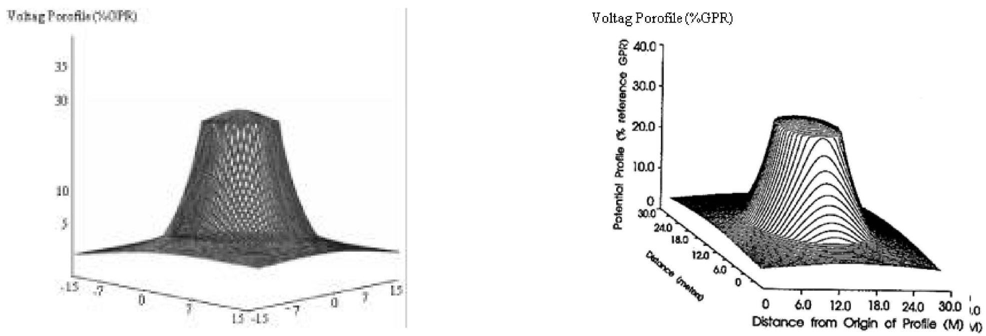
B: CDEGS

Fig. 6: Ground surface voltage as a percent of GPR. ρ_1=2000, ρ_2=400, ρ_3=100 (ohm-m)



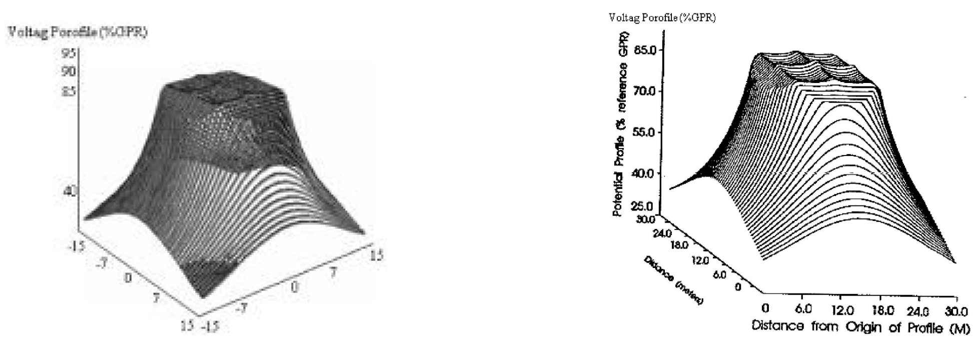
A: Grnd Soft B: CDEGS

Fig. 7: Ground surface voltage as a percent of GPR. ρ_1=1000, ρ_2=50, ρ_3=1000 (ohm-m)



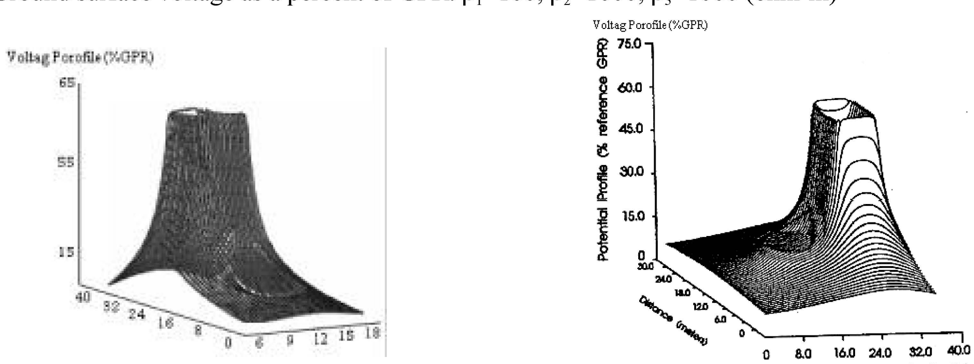
A: Grnd Soft B: CDEGS

Fig. 8: Ground surface voltage as a percent of GPR. ρ_1=50, ρ_2=1000, ρ_3=200 (ohm-m)



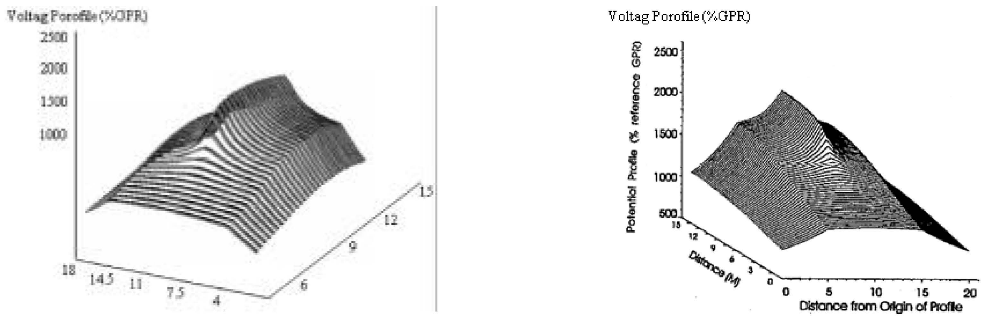
A: Grnd Soft B: CDEGS

Fig. 9: Ground surface voltage as a percent of GPR. ρ_1=100, ρ_2=1000, ρ_3=1000 (ohm-m)



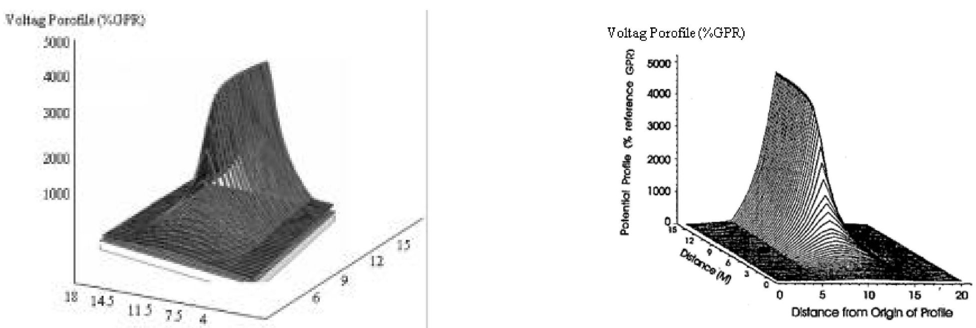
A: Grnd Soft B: CDEGS

Fig. 10: Ground surface voltage as a percent of GPR. ρ_1=50, ρ_2=200, ρ_3=50 (ohm-m)



A: Grnd Soft B: CDEGS

Fig. 11: Ground surface voltages profile for a buried rod in soil with two half vertical cylindrical layers. ρ_1=10, ρ_2=100 (ohm-m)



A: Grnd Soft B: CDEGS

Fig. 12: Ground surface voltages profile for a buried rod in soil with two half vertical cylindrical layers. ρ_1=100, ρ_2=10 (ohm-m)

Table 5: Step and touch voltages, homogeneous soil

No.	Grid Dimension (m)	Number of Meshes	E (%) Step Voltage	E (%) Touch Voltage	Step Voltage (V) RESIS[15]	Step Voltage (V) GrndSoft	Touch Voltage (V) RESIS[15]	Touch Voltage (V) GrndSoft
1	20x20	4	0.4	10	420	422	943	1046
2	20x20	16	3.2	8.5	342	353	576	625
3	24x24	9	6	14	292	310	591	674
4	40x40	4	0	9	206	206	564	617
5	40x40	16	-0.6	7.4	166	165	349	375
6	40x40	64	2	5.8	137	140	224	237
7	60x60	16	0	7.4	107	107	255	274
8	100x100	100	-1.4	4	48	47.3	98	102
9	80x5	16	0.6	13.4	257	258.5	476	540
10	80x20	4	0.3	10	189	189.6	543	600
11	80x20	16	-0.3	8.4	154	153.5	332	360
12	160x10	16	0.8	11	125	126	290	322
13	120x30	16	1	7.3	100	101	245	263
14	240x15	16	-0.6	9.8	82	82.5	214	235

resistivity of second layer is 1000 ohm-m. Fig. 10 shows the variations of ground surface voltage for grounding grid illustrated in Fig. 3.

Since the horizontal bar shows the effect of soil construction with cylindrical vertical layering on voltage profile very well, the results of GrndSoft and CDEGS softwares are given here for a rod (Fig. 11 and Fig. 12).

Step and Touch Voltages, Homogeneous Soil: In continuation of above, In order to verify the results of GrndSoft software in homogeneous soil conditions, the results of RESIS software [15] is used which was prepared to analyze the buried grounding systems in homogeneous soils. All grounding grids are quadrangular and rectangular with various dimensions, different mesh numbers and resistivity of 100 ohms-m at depth of 0.5 m under the homogeneous soil. Resistance of grounding system was calculated as follows below. Note that the meshes are quadrangular in all situations.

CONCLUSIONS

Hemispherical, vertical and horizontal half cylindrical soil theoretical model and the software to implement this model were prepared. In order to fulfill the grounding system calculations, exact closed-form analytical equations that were achieved in spherical coordinate system for bar shaped current source were used, which bring reduction about mentioned calculating time in spite of other numerical methods. Software numerical results for different soils and various types of grounding systems were compared with results of CDEGS software and also with results of RESIS software. Comparing the results shows that the GrndSoft software has very good accuracy and could be used to analyze the grounding systems in hemispherical soils, homogeneous soils and also grounding systems in form of cubic concrete volume. The results of GrndSoft can be used as a validity criterion of results of numerical methods.

REFERENCES

1. Nejati. Majid, 1997. “Grounding System Designing in high Voltage Substations”, thesis of Master of Science in Electrical Engineering, Electrical Engineering Faculty, IUST University,
2. Shahrtash, S.M., 2000. "New Approaches for Solving Special and Novel Problems in Substation Grounding Systems", Researching Project, Relays and Protection Laboratory, IUST University,
3. Heppe, R.J., 1975. “Computation of potential at surface above an energized grid or other electrode, allowing for Non-Uniform current distribution”, IEEE Trans. on PAS., 98(6), November-December 1975. pp: 1978-1989.
4. Meliopoulos, A.P., R.P. Webb and E.B. Joy, “Analysis of grounding systems”, IEEE Trans. on PAS., Vol. 100, No. 3, March 1981. pp: 1039-1048.
5. Jinxi Ma and F.P Dawlibi," Analysis of grounding systems in soils with cylindrical soil volumes"Power Delivery, IEEE Transactions on, Vol. 15, Issue 3, 2000 pp: 913-918.
6. Lagace, P.J., J.L. Houle, Y. Gervais and D. Mukhedkar, “Evaloation of voltage distribution around torroidal HVDC ground electrodes in N-Layer soils”, IEEE Trans. on PWRD, Vol. 3, No. 4, October 1988, pp: 1573-1577.
7. Dawalibi, F.P. and N. Barbeito, 1991. “Mesurements and compution of the performance of grounding systems buried in Multilayer soils”, IEEE Tran, 6(4): 1483-1490.
8. Markowska, R., A. Sowa and J. Wiater, 2008. “Step and Touch Voltage Distributions at GSM Base Station during Direct Lightning Stroke, International Conference IEEE, 2008 , pp: 199-202.
9. Chow, Y.L., J.J. Yang and K.D. Srivastava, “Grounding resistance of buried electrodes in Multi-Layer earth predicted by simple voltage mesurements along earth surface-A theoriticaldiscussion”, IEEE/PES 1992 summer meeting, paper #92 SM 608-0 PWRD.
10. http://www.SESTech.com/Softwares
11. Baldev Thapar, Victor Gerez, Arun Balakrishnam and Donald A. Blank, 1991. “Simplified equations for mesh and step voltages in an AC substation”, IEEE Trans. on PWRD, 6(2) : 601-606.
12. Sadeghi. Ali, 2003. "Surveying of Grounding System Calculations in Hemispherical and Cylindrical Soils", thesis of Master of Science in Electrical Engineering, Electrical Engineering Faculty, IUST University.
13. Ghoneim, S., H. Hirsch, A. Elmorshedy and R. Amer," Improved Design of Square Grounding Grids"PowerCo2006 pp: 1-4.

Used Parameters in this Paper Are as Follows:

∇^2: Laplacian operator in spherical coordinate system

V_I, V_{II}, V_{III}: observation point voltage in threefold zones of soil (volts)

ρ_1, ρ_2, ρ_3: resistivity of soil various zones (ohm-m)

I: current of bar shaped source (A)

$\delta\left(\vec{r}-\vec{r_0}\right)$: Direct delta function (centralized in point $r=r_0$)

r: radius of observation point (m)

r_0: radius of point source

a_1 and a_2: radiuses of input and output spheres (concentric), respectively, that divided soil into 3 separated ρ_1, ρ_2, ρ_3 zones (m)

r, θ and φ: observation point axis (m, radian, radian)

r_0, θ_0 and φ_0: point current source axis (m, radian, radian)