Regular paper

SINGLE WIRE GROUNDING ELECTRODE IN THE PRESENCE OF SEMI-SPHERICAL INHOMOGENITY

Nenad N. CVETKOVIĆ[1], Predrag D. RANČIĆ[2]

Abstract: The influence of semi-spherical semi-conducting ground inhomogenity on electrical characteristics of ground wire electrode is analyzed in the paper. Using the Moment method, the leakage current distribution from conductor surface is determined. This is carried out solving integral equation formed using quasi-stationary image theories in flat and spherical semi-conducting mirror. The influence of different parameters on the grounding system characteristics is investigated.

Keywords: Grounding systems, inhomogenity, image theory, quasi-stationary regime

1. INTRODUCTION

Spherical and semi-spherical ground inhomogenity can be present in different type of problems. This kind of problems are for example, grounding system in the vicinity of vertical container (silage, reservoir) having semi-spherical bases with a lower one buried in the ground, or pillar ground electrode, when concrete found is approximated with semi-spherical ground inhomogenity. The model described and applied in this paper can be used for analyzing influence of large holes in the ground (pond, small lake) filled with water on grounding systems. Those holes are treated as semi-spherical ground inhomogenity.

In order to solve problems mentioned above, general model for semi-spherical semi-conducting inhomogenity and point current source, or point ground electrode (PGE) placed inside or outside semi-sphere is formed. This is carried out combining quasi-stationary image theory for multi-layer ground and spherical inhomogenity. For the boundary case, when specific conductivity of semi-spherical inhomogenity tend to infinitely large value, the general model becomes model for determining conductive semi-sphere on grounding system characteristics.

The analysis of non-homogeneous ground by its approximating it with few homogeneous layers has been researched by many authors ([1]-[5]). A part of those results is presented at last year Summer School in paper [6].

Concerning spherical inhomogenity, authors could use models for determining influence of conductive and dielectric spherical bodies ([7]-[17]), on point source electric field distribution.

The model used in this paper is based on the combination of quasi-stationary model for EM field of Hertz's dipole buried in homogeneous ground ([1]-[5]) and expression for the Green's function of point current source in the vicinity of semi-conducting sphere proposed in [13] and applied in [14]-[17]. Using described models, the general method is developed and expressions for electric scalar potential at arbitrary ground point are derived. In order to calculate value of the potential, it is necessary to determine leakage current distribution from conductor surface in the surrounding ground. This is done solving of integral equation of Rabenn type having leakage current distribution as unknown function. This integral equation is formed using condition that electrode surface is approximately equipotential and it can be numerically solved applying the Moment method ([18]).

The described model has been already applied on the analysis of the point ground electrode ([19]), as well as on the solving of contour circle wire ground electrode ([20]) in the vicinity of the semi-spherical semi-conducting inhomogenity. Also, the model was used for determining of mutual-impedance of the grounding systems formed by wire conductor placed inside semi-spherical inhomogenity and thin plate electrode placed outside inhomogenity ([21]).

In this paper, model is applied on the analysis of the grounding systems consisting of one ground wire electrode. The program packages for numerical calculations based on the described procedure are realized and large number of numerical experiments was performed. Small part of the results is presented in the fourth chapter of the paper.

2. THEORETICAL BASIS OF THE MODEL

2.1. Model description and electrical scalar potential

Non-homogeneous semi-conducting ground approximated by two isotropic homogeneous semi-conducting domains is analyzed in the paper. The first one is semi-sphere of the radius r_{s} and known electrical parameters σ_{s}, $\varepsilon_{\mathrm{s}} = \varepsilon_0 \varepsilon_{\mathrm{rs}}$ and $\mu_{\mathrm{s}} = \mu_0$ (σ_{s} - specific conductivity, $\varepsilon_{\mathrm{s}} = \varepsilon_0 \varepsilon_{\mathrm{rs}}$ - permittivity, $\mu_{\mathrm{s}} = \mu_0$ - permeability). The second domain is homogeneous isotropic semi-conducting semi-space of known electrical parameters σ_1, $\varepsilon_1 = \varepsilon_0 \varepsilon_{\mathrm{r1}}$ and $\mu_1 = \mu_0$. Following labels are also used in the paper: $\underline{\sigma}_i = \sigma_i + \mathrm{j}\omega\varepsilon_i$, $i = 0, 1, \mathrm{s}$ - complex conductivity; $\underline{\gamma}_i = (\mathrm{j}\omega\mu_0 \underline{\sigma}_i)^{1/2}$, $i = 0, 1, \mathrm{s}$ - complex propagation constant; and $\underline{n}_{1\mathrm{s}} = \underline{\gamma}_1 / \underline{\gamma}_{\mathrm{s}}$, $\underline{n}_{i0} = \underline{\gamma}_i / \underline{\gamma}_0$, $i = 1, \mathrm{s}$ - refraction coefficients between ground/semi-sphere, ground/air and semi-sphere/air, respectively. The Descartes' coordinate system is associated to the described geometry, hav-

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[1] Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: csone@elfak.ni.ac.yu

[2] Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: prancic@elfak.ni.ac.yu

ing origin at the semi-sphere center. Illustrations for two of four possible PGE problem geometries and part of the images are presented in Fig. 1. and Fig. 2.

Combining image theory models, final approximate expression for electrical scalar potential at ground arbitrary point are derived, when the point source is placed outside ($\vec{r}\,'=\vec{d}\geq\vec{r}_{\mathrm{s}}$, Fig. 1), and inside semi-spherical inhomogenity ($\vec{r}\,'=\vec{d}\leq\vec{r}_{\mathrm{s}}$, Fig. 2). It is carried out with successive application of the image theory in the flat semi-conducting mirror and Green's function for point source placed outside/inside semi-conducting sphere.

2.2.1. Point source outside semi-conducting semi-spherical inhomogenity

The electrical scalar potential in the point P placed in the surrounding of the point source (P') located outside semi-spherical inhomogenity, Fig. 1, is expressed as

$$\varphi_{11}(\vec{r},\vec{r}\,')=\frac{\mathrm{d}I}{4\pi\underline{\sigma}_1}\left\{\left[\frac{1}{r_1}+r_{\mathrm{s}}R_{1\mathrm{s}}\left(\frac{1}{r'r_2}-\frac{1}{r'r}\right)+\right.\right.$$

$$\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r'}\ln\left(\frac{r-D\cos\alpha+r_2}{2r}\right)\right]+$$

$$+\left[\frac{1}{r_{1i}}+r_{\mathrm{s}}R_{1\mathrm{s}}\left(\frac{1}{r'r_{2i}}-\frac{1}{r'r}\right)+\right.$$

$$\left.\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r'}\ln\left(\frac{r-D\cos\alpha'+r_{2i}}{2r}\right)\right]\right\},\quad r\geq r_{\mathrm{s}}\,,\qquad(1)$$

$$\varphi_{\mathrm{s}1}(\vec{r},\vec{r}\,')=\frac{\mathrm{d}I}{4\pi\underline{\sigma}_1}\left\{\left[T_{1\mathrm{s}}\frac{1}{r_1}-R_{1\mathrm{s}}\frac{1}{r'}+\right.\right.$$

$$\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r'}\ln\left(\frac{r'-r\cos\alpha+r_1}{2r'}\right)\right]+$$

$$+\left[T_{1\mathrm{s}}\frac{1}{r_{1i}}-R_{1\mathrm{s}}\frac{1}{r'}+\right.$$

$$\left.\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r'}\ln\left(\frac{r'-r\cos\alpha'+r_{1i}}{2r'}\right)\right]\right\},\quad r\leq r_{\mathrm{s}}\,,\qquad(2)$$

where: $\mathrm{d}I$ - leakage current from the point source; $R_{1\mathrm{s}}$ and $T_{1\mathrm{s}}$, $R_{1\mathrm{s}}=T_{1\mathrm{s}}-1=(\underline{n}_{1\mathrm{s}}^2-1)/(\underline{n}_{1\mathrm{s}}^2+1)$ - quasi-stationary reflection and transmission coefficients; and $D=r_{\mathrm{s}}^2/d=r_{\mathrm{s}}^2/r'$ - image constant for the spherical mirror. Reflection and transmission coefficients in the application of semi-conducting flat mirror image theory $R_{i0}=T_{i0}-1=(\underline{n}_{i0}^2-1)/(\underline{n}_{i0}^2+1)\approx 1$, $i=1,\mathrm{s}$, are approximately equal to one, because $\underline{n}_{10},\underline{n}_{\mathrm{s}0}>>1$. This allows us to express electrical scalar potential with finite number of images. The rest of the parameters in the expressions (1) and (2) can be noticed from Fig. 1.

Two indexes are used to label the potential. The first one denotes medium in which potential is determined, and the second one, medium where point source is placed.

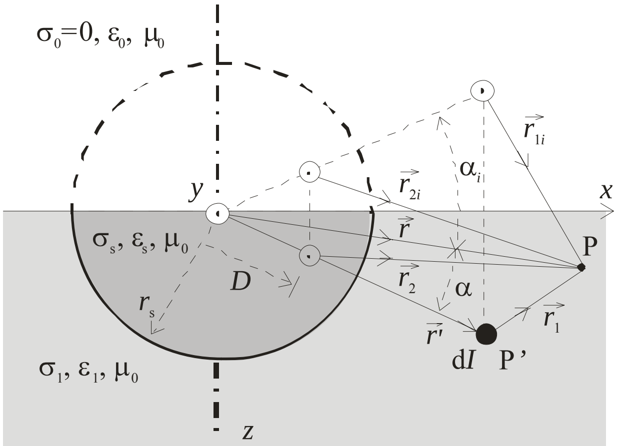

Fig. 1 - *Point source outside semi-conducting semi-spherical inhomogenity and part of discreet images for determining potential outside inhomogenity.*

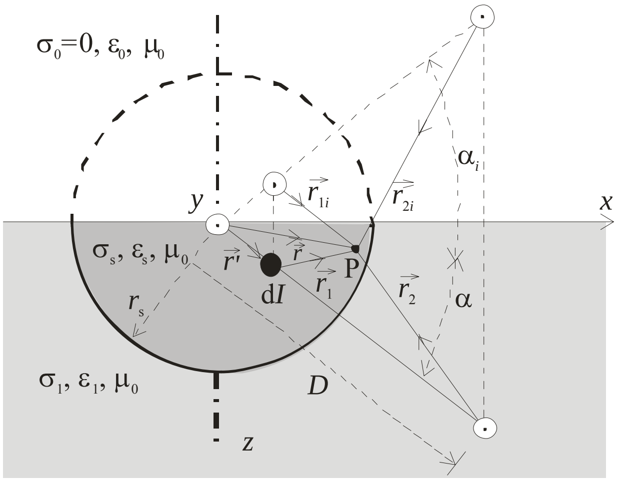

Fig. 2 - *Point source inside semi-conducting semi-spherical inhomogenity and part of discreet images for determining potential inside inhomogenity.*

2.2.2 Point source inside semi-conducting semi-spherical inhomogenity

In the way similar to the those ones described in the previous chapter, the expressions for the potential in the point P placed in the surroundings of the point source (P') located inside semi-spherical inhomogenity are derived, Fig. 2. Those expressions have the following form

$$\varphi_{1\mathrm{s}}(\vec{r},\vec{r}\,')=\frac{\mathrm{d}I}{4\pi\underline{\sigma}_1}\left\{\left[T_{1\mathrm{s}}\frac{1}{r_1}-R_{1\mathrm{s}}\frac{1}{r}+\right.\right.$$

$$\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r_{\mathrm{s}}}\ln\left(\frac{r-r'\cos\alpha+r_1}{2r}\right)\right]+$$

$$+\left[T_{1\mathrm{s}}\frac{1}{r_{1i}}-R_{1\mathrm{s}}\frac{1}{r}+\right.$$

$$\left.\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r_{\mathrm{s}}}\ln\left(\frac{r-r'\cos\alpha'+r_{1i}}{2r}\right)\right]\right\},\quad r\geq r_{\mathrm{s}}\,,\qquad(3)$$

$$\varphi_{\mathrm{ss}}(\vec{r},\vec{r}\,')=\frac{\mathrm{d}I}{4\pi\underline{\sigma}_1}\left\{\left[\frac{\underline{n}_{1\mathrm{s}}^2}{r_1}-R_{1\mathrm{s}}\left(r_s\frac{\underline{n}_{1\mathrm{s}}^2}{r'r_2}+\frac{1}{r_\mathrm{s}}\right)+\right.\right.$$

$$\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r_\mathrm{s}}\ln\left(\frac{D-r\cos\alpha+r_2}{2D}\right)\right]+$$

$$+\left[\underline{n}_{1\mathrm{s}}^2\frac{1}{r_{1i}}-R_{1\mathrm{s}}\left(r_s\underline{n}_{1\mathrm{s}}^2\frac{1}{r'r_{2i}}+\frac{1}{r_\mathrm{s}}\right)+\right.$$

$$\left.\left.+\frac{T_{1\mathrm{s}}R_{1\mathrm{s}}}{2}\frac{1}{r_\mathrm{s}}\ln\left(\frac{D-r\cos\alpha'+r_{2i}}{2D}\right)\right]\right\},\quad r\le r_\mathrm{s}\,. \tag{4}$$

The labels used in expressions (3)-(4) correspond to those used in expressions (1)-(2) and can be noticed from Fig. 2.

In the text that follows, corresponding Green's functions defined based on expressions (1)-(4) will be used,

$$G_{ij}(\vec{r},\vec{r}\,')=\varphi_{ij}(\vec{r},\vec{r}\,')/\mathrm{d}I\,,\; i,j=1,\mathrm{s}\,. \tag{5}$$

3. MODEL APPLICATION ON GROUNDING SYSTEMS

3.1. Single wire grouond electrode (WGE)

3.1.1. Electrical scalar potential

The single wire electrode placed outside semi-conducting semi-spherical inhomogenity, Fig. 3, is observed. Potential at points placed outside and inside inhomogenity can be determined using expressions

$$\varphi_{11}(\vec{r})=\int_l \mathrm{d}I(\vec{r}\,')G_{11}(\vec{r},\vec{r}\,')\,, \tag{6a}$$

$$\varphi_{\mathrm{s}1}(\vec{r})=\int_l \mathrm{d}I(\vec{r}\,')G_{\mathrm{s}1}(\vec{r},\vec{r}\,')\,, \tag{6b}$$

respectively. In a similar way, the potential expressions when single wire electrode is placed inside inhomogenity (Fig. 4) for the points placed outside and inside inhomogenity are respectively

$$\varphi_{1\mathrm{s}}(\vec{r})=\int_l \mathrm{d}I(\vec{r}\,')G_{1\mathrm{s}}(\vec{r},\vec{r}\,')\,, \tag{7a}$$

$$\varphi_{\mathrm{ss}}(\vec{r})=\int_l \mathrm{d}I(\vec{r}\,')G_{\mathrm{ss}}(\vec{r},\vec{r}\,')\,. \tag{7b}$$

If single wire electrode which penetrates inhomogenity (Fig. 5) is observed, the expressions for the potential in the points outside (φ_1), or inside inhomogenity (φ_s) are respectively

$$\varphi_1(\vec{r})=\int_{l_1} \mathrm{d}I(\vec{r}\,')G_{11}(\vec{r},\vec{r}\,')+\int_{l_2} \mathrm{d}I(\vec{r}\,')G_{1\mathrm{s}}(\vec{r},\vec{r}\,')\,, \tag{8a}$$

$$\varphi_\mathrm{s}(\vec{r})=\int_{l_1} \mathrm{d}I(\vec{r}\,')G_{\mathrm{s}1}(\vec{r},\vec{r}\,')+\int_{l_2} \mathrm{d}I(\vec{r}\,')G_{\mathrm{ss}}(\vec{r},\vec{r}\,')\,. \tag{8b}$$

In expressions (6-8), $\mathrm{d}I(\vec{r}\,')=I'(\vec{r}\,')\mathrm{d}l$ is total leakage current from the part of the wire electrode, where $I'(\vec{r}\,')$ leakage current density per unit length, and $G_{ij}(\vec{r},\vec{r}\,')$, $i,j=1,\mathrm{s}$, are Green's functions given by (5).

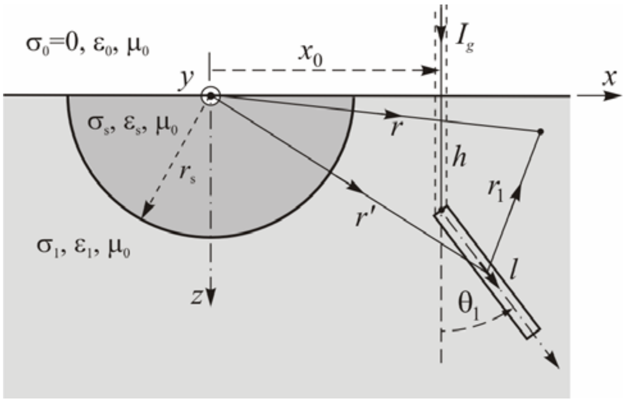

Fig. 3 - *Single wire ground electrode outside inhomogenity.*

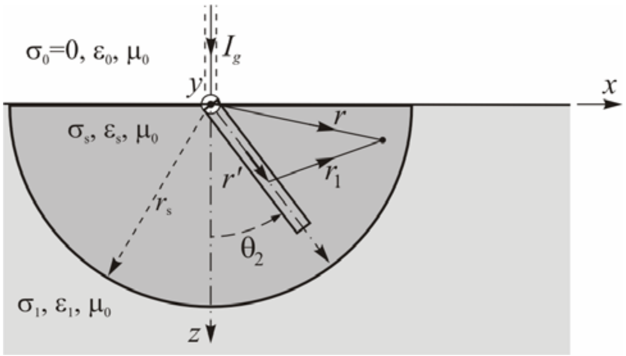

Fig. 4 - *Single wire ground electrode inside inhomogenity.*

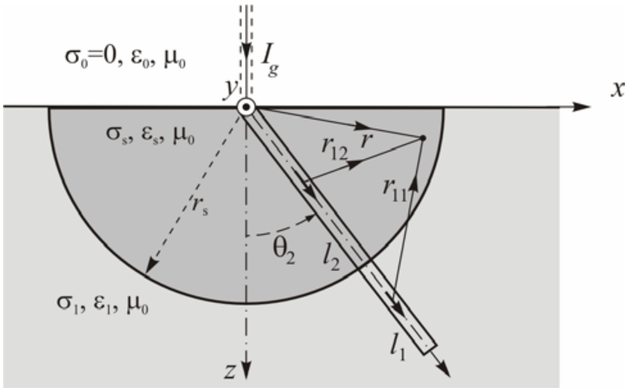

Fig. 5 - *Single wire ground electrode that penetrates inhomogenity.*

3.1.2. Determining of grounding impedance

Applying the Moment method, wire conductor is divided in finite number of segments *N*. Matching potential value at *N* points on the segment surface, the equation system is formed

$$\varphi=U=\sum_{n=1}^{N}\frac{I_n}{\Delta_n}\int_{\Delta_n}G(\vec{r}\,')\,\mathrm{d}l\,. \tag{9}$$

In previous expression, Δ_n and I_n are length and leakage current of the *n*-th segment, $n=1,\ldots N$. $G(\vec{r}\,')$ is one of the Green's function given by expression (5), whose choice depends on the ground electrode position. The solution of the equation system (9) are leakage currents of the segments, I_n, $n=1,2,\ldots N$. The impedance of the ground system is determined using the expression

$$Z_g=R_g+\mathrm{j}X_g=U/I_g=U\Big/\sum_{n=1}^{N}I_n\,. \tag{10}$$

The density per unit length of the leakage current from the conductor surface is $I'(r') = I'_{\text{leak}} = -\partial I_{\text{long}} / \partial s$, where I_{long} is longitudinal current that flows along electrode axis ([4]). With s is labeled coordinate coinciding with electrode axis and whose origin is placed at the conductor ending point. Longitudinal current can be determined directly from the segments leakage current, also in polynomial form, matching values of current derivative on the conductor surface.

4. NUMERICAL RESULTS

4.1. Single wire electrode outside inhomogenity

The procedure described in chapter 3.1 is applied for analyzing single electrode placed inside semi-conducting semi-spherical inhomogenity, Fig. 3. In order to verify validity of the used model, the obtained results are compared with the impedance values of single electrode buried in homogeneous ground, e.g. impedance of wire electrode in the presence of sectoral type inhomogenity, ([5]).

The resistance of single ground electrode from Fig. 3 versus distance x_0 is shown in Fig. 6 and compared to the resistance of the electrode buried in homogenous earth, determined using procedure given in [5]. Corresponding parameter values are given in the Fig 6, and procedure described in 3.1.2 is applied on $N = 10$ segments. Increasing the distance from inhomogenity, grounding impedance tends to the value of the impedance of electrode buried in homogeneous earth.

In Fig. 7, the resistance of the single ground electrode is shown versus radius r_s, while difference $x_0 - r_s$ is constant taking value $x_0 - r_s = 1\,\text{m}$. Values determined in this way are compared to resistance of single WGE buried in the sectoral ground determined using procedure given in [5]. Corresponding parameter values are given in the Figure. With increasing r_s, the grounding resistance tends to the impedance of the electrode buried in sectoral ground, at distance $1\,\text{m}$ from the sector boundary and at the position defined with given parameters.

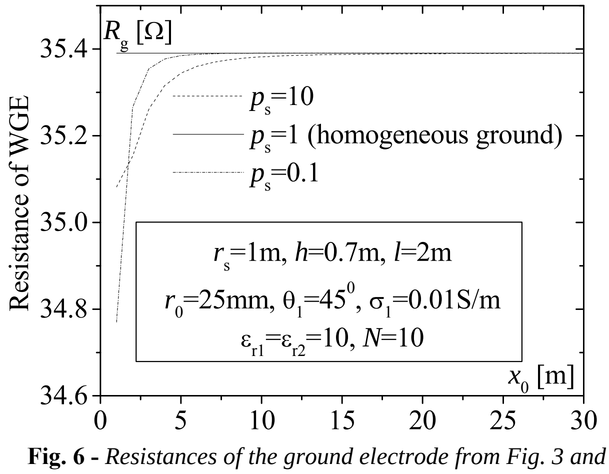

Fig. 6 - *Resistances of the ground electrode from Fig. 3 and electrode buried in homogeneous ground versus x_0 and $p_s = \sigma_1/\sigma_s$ as parameter.*

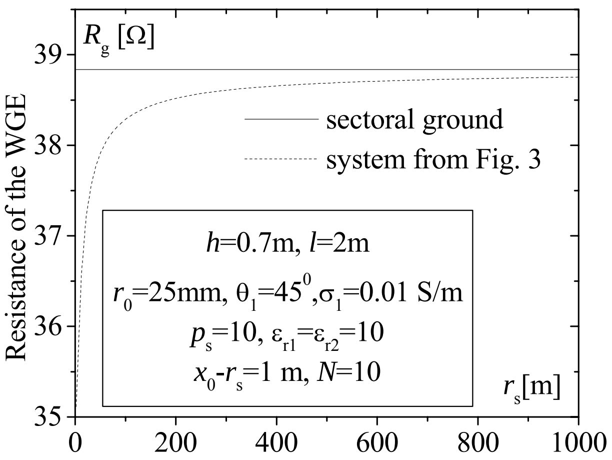

Fig. 7 - *Resistance of the ground electrode from Fig. 3, versus radius r_s and ratio $p_s = \sigma_1/\sigma_s$ as parameter, and resistance of the electrode buried in sectoral ground.*

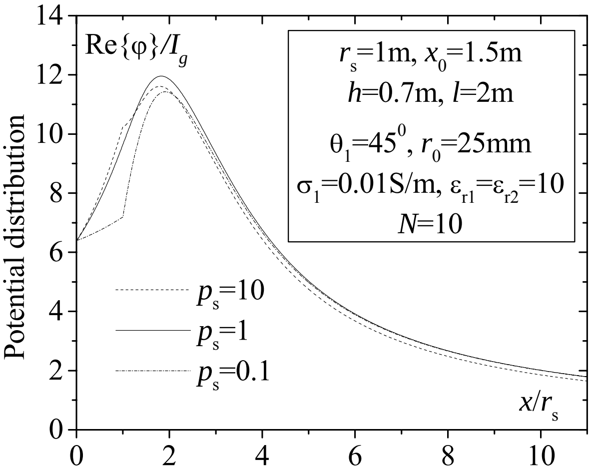

Fig. 8 - *Potential distribution in the surroundings of the ground electrode from Fig. 3, with $p_s = \sigma_1/\sigma_s$ as parameter.*

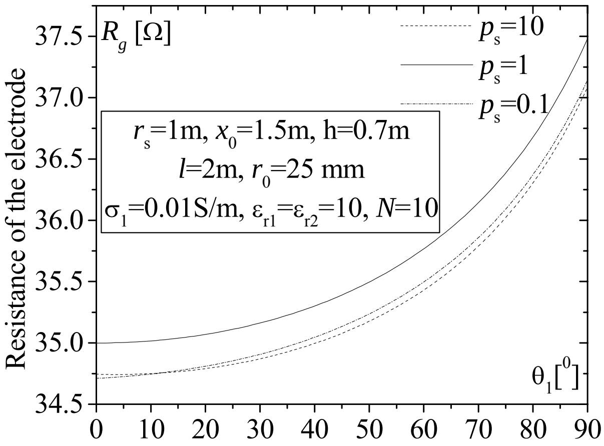

Fig. 9 - *Resistance of the ground electrode from Fig. 3, versus angle θ_1 with ratio $p_s = \sigma_1/\sigma_s$ as parameter.*

The electrical scalar potential distribution on ground surface in the surroundings of the electrode from Fig. 3, is shown in Fig. 8. Ratio $p_s = \sigma_1/\sigma_s$ takes different values and the parameter values are given in Fig. 8.

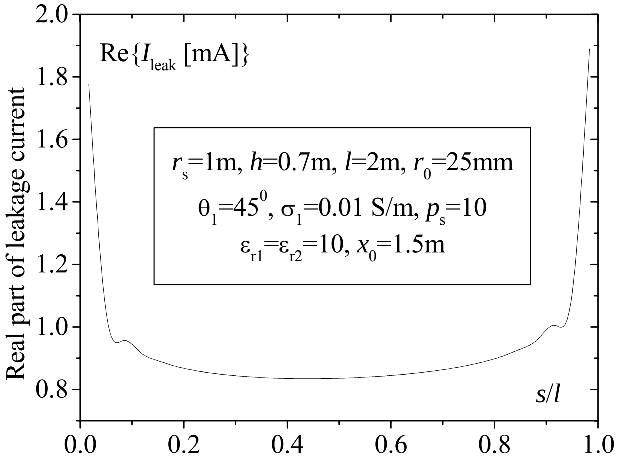

Fig. 10 - *The leakage current distribution for the ground electrode from Fig. 3.*

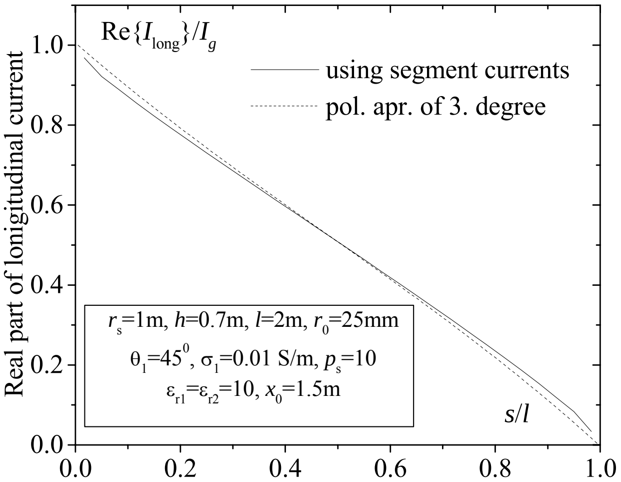

Fig. 11 -*The longitudinal current distribution for the ground electrode from Fig.3, based on the leakage current from Fig. 10.*

Resistance of the electrode from Fig. 3 versus angle θ_1 and ratio $p_s = \sigma_1 / \sigma_s$ taken as parameter, is shown in Fig. 9. The rest of parameter values are given in Fig. 9.

The leakage current distribution I_{leak} for the WGE shown in Fig. 3 for $p_s = 10$, is presented in Fig. 10. The parameter values are given in the Fig. 10. Based on this function, for the same parameter values, longitudinal current I_{long} is determined directly from the leakage current, polynomial form also and is shown in Fig. 11.

4.2. Wire electrode inside inhomogenity

The resistance of the ground electrode shown in Fig. 4 versus angle θ_2 and ratio $p_s = \sigma_1 / \sigma_s$ taken as parameter, is presented in Fig. 12. The parameter values are given in Fig. 12, and the procedure from 3.1.2 is applied on $N = 10$ segments.

4.3. Wire electrode penetrating inhomogenity

The leakage current I_{leak} distribution of the ground electrode from Fig. 5 is shown in Fig. 13. Parameter values are given in Fig. 13 .

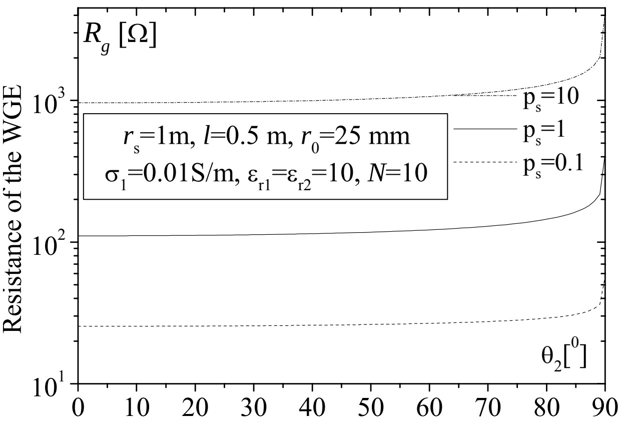

Fig. 12 - *Resistance of the ground electrode from Fig.4 versus angle θ_2 and ratio $p_s = \sigma_1 / \sigma_s$ as parameter.*

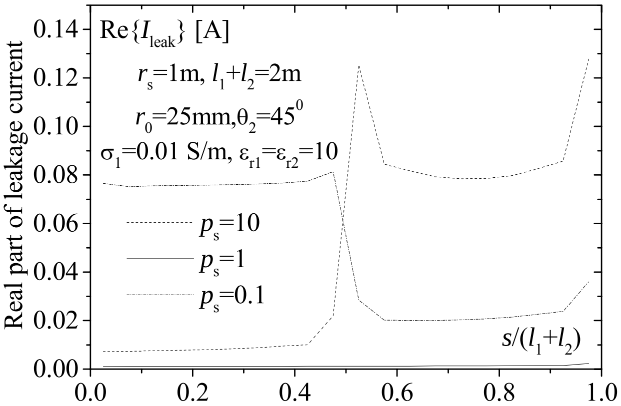

Fig. 13 - *The leakage current for the ground electrode from Fig.5.*

CONCLUSION

The general method for determining influence of the semi-conducting semi-spherical inhomogenity on grounding systems is described and applied for analyzing and solving different types of grounding systems. The method is based on the quasi-stationary image theories for plate and spherical semi-conducting mirror. Solution of integral equation formed in that way is leakage current distribution from the electrodes surface. After that, all other parameters can be determined using usual procedures.

The influence of the semi-sphere electrical parameters as well as system geometry on grounding characteristics is analyzed. The obtained results are compared to the results for boundary cases, such as homogeneous and sectoral ground. Presented results indicate good validity of the model.

Described methodology can be applied on problems of semi-spherical geometries on the flat ground surface, with supplying conductors being in the ground, semi-sphere or in the air.

It should be remarked that used expressions for Green's function, including image theory for flat and spherical mirror, represent approximate solution for electrical potential with very small error related to exact solution given in [7]. The analysis of this error will be object of particular future researches.

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Nenad N. Cvetković was born in Niš, Serbia in 1970. He received the Dipl. Ing and M.Sc. degrees from the Faculty of Electronic Engineering of Niš in 1995 and 2002, respectively. From 1995 he has been engaged as associate on the Department of Theoretical Electrical Engineering, Faculty of Electronic Engineering of Niš. His research interests are numerical methods for electromagnetic field calculation, especially in transmission line and grounding systems analysis. He is author or co-author of more than 25 papers presented on home and international scientific assemblies and co-author of two textbooks.

Predrag D. Rančić was born in Leskovac, Serbia in 1947. He received the Dipl. ing. degree, M.Sc. and Ph.D. degree at the Department of Electromagnetics of the Faculty of Electronic Engineering from Niš University, Niš, Serbia, in 1972, 1977 and 1983, respectively. He is a full professor of the Department of Power Eng. at the Faculty of Electronic Engineering from Niš. His main interests are the EM field structures in an inhomogeneous media (antennas, transmission lines, groundings and others) and their analytical and numerical modeling. Analytical and numerical modeling of the light field characteristics are also an area of his researches. An area of his practical research includes: illumination technique, LV electrical installations, cable distribution systems

(RA, TV, CATV and SATV). He is the author of numerous realized systems in the mentioned area. Dr. Rančić is IEEE member, IESNA Subscriber member, Individual CIE member and a member of National Illumination Society - DOS.