Estimation of Multilayer Soil Parameters Using Genetic Algorithms

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***Abstract*—In this paper, a methodology has been proposed according to which, after carrying out a set of soil's resistivity measurements, one can compute the parameters of the multilayer earth structure using a genetic algorithm (GA). The results provided by the GA constitute the indispensable data that can be used in circuital or field simulations of grounding systems. The methodology, developed on the base of the PC Opera software package, allows to proceed toward a very efficient simulation of the grounding system and an accurate calculation of potential on the ground's surface.**

***Index Terms*—Genetic algorithms (GAs), grounding system, multilayer soil, simulation, soil resistivity measurements.**

I. INTRODUCTION

WHEN a grounding system has to be installed, knowledge of the earth structure in the given location is compulsory. The parameters of the earth structure are the necessary data for the circuital or field simulations of grounding systems. The measurements of the soil resistivity, which have been carried out, have shown that the soil has to be simulated as a (at least) two-layer structure. It is also clear that the value of soil resistivity is changing during the year reaching its maximum value in summer months [1], [2]. The calculation of the parameters of the earth's multilayer structure is transformed to a problem of minimization; a methodology is proposed in this paper, based on a genetic algorithm (GA), which calculates the parameters of the earth's multilayer structure, using the measurements of soil resistivity. The effectiveness of this GA is proved by comparing the results of the GA to the results of other researchers. The conclusion of this comparison is that the application of the GA on the computation of the parameters of the earth structure gives more accurate results than other published methods. Hence, using the suggested methodology, it is possible to calculate accurately the multilayer earth parameters, which will be the essential input data for the simulation of the behavior of the grounding system that will be installed in this ground. A further advantage of the proposed methodology is that it is very suitable to calculate the parameters of practically any soil structure, independent of the number of layers, with a relatively fast convergence.

The field simulation has been carried out using the PC Opera package. The developed methodology allows, in case of a known earth structure, the efficient simulation of the system and the accurate calculation of the potential on the surface of the ground. The advantage of this program is that it can be used in every grounding system, while the use of closed-form mathematical formulae for multilayer analysis are limited only to point, vertical, or horizontal electrodes. There are also other methodologies for the calculation of surface potential such the boundary element method [3], [4], the method of moments [5], or the hybrid finite-boundary element method [6], which could use as input data the results of GA. The advantage of the proposed simulation can be estimated by comparing the results of the field analysis, using the PC Opera package to the results of other methodologies. From this comparison, it is concluded that the PC Opera 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.

II. VARIATION OF SURFACE POTENTIAL OF MULTILAYER SOIL

The potential V_o at any point (defined by the cylindrical coordinates x, ϑ, z) in the earth (assuming a homogeneous and isotropic soil resistivity ρ_o) due to a current I, flowing through a point electrode situated on the surface is given by the following equation [1]:

$$V_o(x) = \frac{\rho_o \cdot I}{2 \cdot \pi} \int_0^{\infty} e^{-\lambda \cdot |z|} \cdot J_o(\lambda \cdot x) \cdot \partial\lambda \tag{1}$$

where J_o is the Bessel function of the first kind of order zero.

Using the Tagg model [1] of a horizontally stratified two-layer earth structure (with soil resistivity ρ_1 and ρ_2), the potential V due to a current I, flowing through a point electrode situated on the surface is given by the following equation [1]:

$$V(x) = \frac{\rho_1 \cdot I}{2 \cdot \pi \cdot x} \cdot [1 + F_2(x)] \tag{2}$$

where

$$F_2(x) = 2 \cdot x \cdot \int_0^{\infty} \frac{k_1 \cdot e^{-2 \cdot \lambda \cdot h}}{1 - k_1 \cdot e^{-2 \cdot \lambda \cdot h}} J_o(\lambda \cdot x) \cdot \partial\lambda \tag{3}$$

and k_1 is the coefficient of reflection from the upper to the lower layer, which is given by (4)

$$k_1 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}. \tag{4}$$

A method for the calculation of the surface potential in case of a multilayer structure of the earth has been developed by Takahashi and Kawase [7], [8]. The structure of N-layer earth model is shown in Fig. 1. The first layer has thickness h_1 and soil resistivity ρ_1, the second layer has thickness h_2 and soil resistivity ρ_2, the thickness of the last (Nth) layer is infinity, and its soil resistivity is ρ_N.

Manuscript received February 27, 2003; revised July 25, 2003. Paper no. TPWRD-00083-2003.

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Digital Object Identifier 10.1109/TPWRD.2004.836833

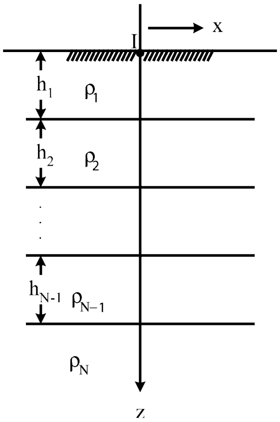

Fig. 1. Multilayer earth model.

The potential at any point x on the earth surface for a current I entering to the earth through a point electrode is described by the following (5)–(9) [7], [8]:

$$V_N(x) = \frac{\rho_1 \cdot I}{2 \cdot \pi \cdot x} \cdot [1 + F_N(x)] \tag{5}$$

where

$$F_N(x) = 2 \cdot x \cdot \int_0^{\infty} \frac{K_{N1} \cdot e^{-2\cdot\lambda\cdot h_1}}{1 - K_{N1} \cdot e^{-2\cdot\lambda\cdot h_1}} J_o(\lambda \cdot x) \cdot \partial\lambda \tag{6}$$

for $1 < i < N - 1$, the coefficient of reflection k_i for two sequential layers is given by the formula

$$k_i = \frac{\rho_{i+1} - \rho_i}{\rho_{i+1} + \rho_i}. \tag{7}$$

In addition, for $N > 2$ and $1 < S < N - 2$, the factor K_{NS} is given by the formula

$$K_{NS} = \frac{k_S + K_{NS+1} \cdot e^{-2\cdot\lambda\cdot h_{S+1}}}{1 + k_S \cdot K_{NS+1} \cdot e^{-2\cdot\lambda\cdot h_{S+1}}} \tag{8}$$

and

$$K_{NN-1} = k_{N-1}. \tag{9}$$

Through processing many groups of measurements [9]–[18], we are directed to the conclusion that the earth usually has a multilayer structure. Consequently, a methodology for the calculation of earth structure parameters (resistivity and depth of each earth layer) is essential. In the bibliography, there are available methodologies for the calculation of these parameters for two- [9]–[16] and three-layer earth structures [16]–[18] using soil resistivity measurements. The calculation of parameters of a two-layer earth is a three-parameter optimization problem (soil resistivity of both layers and depth of the upper layer, while the depth of the lower layer is considered to be infinite). Respectively, the calculation of parameters of a three-layer earth is a problem of optimization of five parameters (soil resistivity of all three layers and depth of the upper two, while the last layer's depth is considered to be infinite). Hence, with the same logic, the calculation of parameters of N-layer earth is a problem of optimization of $(2 \cdot N - 1)$ parameters.

III. GA

GAs were first introduced by John Holland for the formal examination of the mechanisms of natural adaptation [19], but since then, the algorithms have been modified to solve computational problems in research. Modern GAs deviate greatly from the original form proposed by Holland, but their lineage is clear. GAs are now widely applied in science and engineering as adaptive algorithms for solving practical problems. Certain kinds of problems are particularly suited to being tackled using a GA approach. The general assumption is that GAs are particularly suited to multidimensional global problems where the search space potentially contains multiple local minima. Unlike other methods, correlation between the search variables is not generally a problem. The basic GA does not require extensive knowledge of the search space, such as solution bounds or functional derivatives. A task to which simple GAs are not suited is rapid local optimization; however, coupling the GA with other techniques to overcome this problem is trivial. Whenever multidimensional systematic searching is the technique of choice despite the fact that the large number of comparisons makes that approach intractable, a GA should be considered the best choice for the reasons outlined in the sections below [19], [20].

A simple GA relies on the processes of reproduction, crossover, and mutation to reach the global or "near-global" optimum. To start the search, GAs require the initial set of the points P_s, which is called population, analogous to the biological system. A random number generator creates the initial population. This initial set is converted to a binary system and is considered as chromosomes, actually sequences of "0" and "1." The next step is to form pairs of these points that will be considered as parents for a reproduction. Parents come to reproduction and interchange N_p parts of their genetic material. This is achieved by crossover. After the crossover, there is a very small probability P_m for mutation. Mutation is the phenomenon where a random "0" becomes "1" or a "1" becomes "0." Assume that each pair of "parents" gives rise to N_c children. Thus, the GA generates the initial layouts and obtains the objective function values. The above operations are carried out and the next generation with a new population of strings is formed. By the reproduction, the population of the "parents" is enhanced with the "children," increasing the original population since new members are added. The parents always belong to the considered population. The new population has now $P_s + N_c \cdot P_s/2$ members. Then, the process of natural selection is applied. According to this process, only P_s members survive out of the $P_s + N_c \cdot P_s/2$ members. These P_s members are selected as the members with the lower values of F_g since a minimization problem is solved. Repeating the iterations of reproduction under crossover and mutation and natural selection, GAs can find the minimum of F_g. The best values of the population converge at this point. The termination criterion is fulfilled if either the mean value of F_g in the

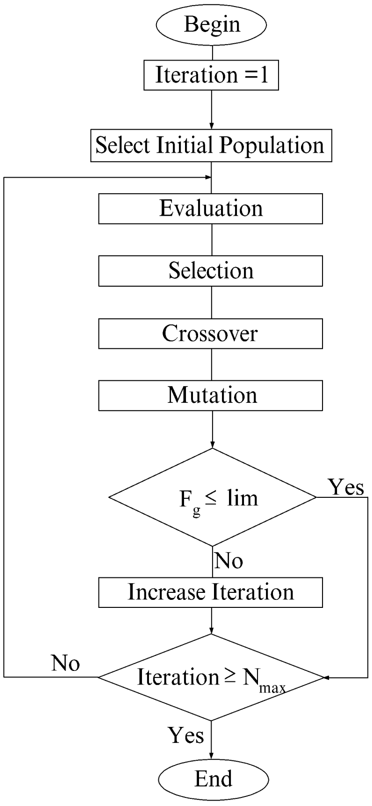

Fig. 2. Flowchart of our GA.

P_s-members population is no longer improved or the number of iterations is greater than the maximum number of iterations $N_{\max}$.

This paper proposes a methodology, which uses the developed GA for the calculation of the parameters of a multilayer structure of the earth. This GA has been developed using the software package Matlab. This GA produces excellent results in several optimization problems [21]–[23]. It has been applied for minimization in multidimensional systems [21], [22], calculation of arc parameters for polluted insulators [23], and the computation of the parameters of the earth structure [16]. The operation of GA, which has been developed, is described in the flowchart of Fig. 2.

IV. CALCULATION OF TWO-LAYER EARTH STRUCTURE PARAMETERS

The most accurate method in measuring the average resistivity of large volumes of undisturbed earth is the four-point method [2]. Small electrodes are buried in four small holes in the earth and spaced (in a straight line) at intervals α. A test current I is passed between the two outer electrodes and the potential V between the two inner electrodes is measured with a high-impedance voltmeter. Then, the ratio V/I gives the resistance R in ohms. The formula

$$\rho = 2 \cdot \pi \cdot \alpha \cdot R \tag{10}$$

gives approximately the average soil resistivity in depth α.

TABLE I
COMPARISON WITH THE METHOD OF SEEDHER AND ARORA

Case	ρ_1 [Ωm]	ρ_2 [Ωm]	h_1 [m]	Error F_g	Method of solution
1	1003.35	21.14	0.99	1.2913	[11]
	1000.003	20.526	1.00	1.2750	GA
2	98.38	1018.80	2.44	0.0354	[11]
	98.194	973.609	2.424	0.0139	GA
3	99.99	302.64	5.04	0.0054	[11]
	100.762	327.962	5.323	0.0150	GA
4	383.498	147.657	2.563	0.2084	[9, 11]
	389.493	152.996	2.403	0.2417	[11]
	367.739	143.569	2.708	0.1651	GA

The calculation of the parameters of a two-layer structure of the earth is an optimization problem. For the computation of the three parameters (soil resistivity of both layers and thickness of the upper layer), the minimization of the function F_g is necessary

$$F_g = \sum_{i=1}^{N} \frac{|\rho_{\alpha i}^m - \rho_{\alpha i}^c|}{\rho_{\alpha i}^m} \tag{11}$$

where $\rho_{\alpha i}^m$ is the ith measurement of the soil resistivity when the distance between two sequential probes is α_i, while $\rho_{\alpha i}^c$ is the computed value of the soil resistivity for the same distance. The soil resistivity is calculated using (12)–(14) [9]–[12]

$$\rho_\alpha^c = \rho_1 \cdot \left(1 + 4 \cdot \sum_n k^n \cdot \left(\frac{1}{\sqrt{A}} - \frac{1}{\sqrt{B}}\right)\right) \tag{12}$$

where $n = 1 \ldots \infty$, k is the reflection coefficient, and

$$A = 1 + \left(\frac{2 \cdot n \cdot h_1}{\alpha}\right)^2 \tag{13}$$

$$B = A + 3. \tag{14}$$

The procedure of the GA starts with a randomly generated population of $P_s = 20$ chromosomes. It generates 20 random values for the first layer resistivity $(0 < \rho_1 < 1200)$, 20 random values for the second layer resistivity $(0 < \rho_2 < 1200)$, and 20 random values for the thickness of first layer $(0 < h_1 < 6)$. Each parameter is converted to a 16-b binary number. Each chromosome has variables $m = 3$ so 48 b are required for the chromosome. Each pair of parents with crossover generates $N_c = 4$ children. The crossover begins as each chromosome of any parent is divided into $N_p = 6$ parts, the pair of parents interchange their genetic material. After crossover, there is $P_m = 5\%$ probability for mutation. The procedure is terminated after $N_{\max} = 50$ generations.

The application of the GA with the above parameters (for the measurements of Table V of the Appendix) results in the solutions shown in Table I. It is obvious that the solutions, which have been obtained using the GA, produce more accurate results than other published methods [9]–[13]. The same GA for the measurements of Table VI of the appendix results in the solutions of Table II. These solutions are more accurate than the best of the eight methods, which are published in [10].

TABLE II
COMPARISON OF THE GA SOLUTION WITH THE BEST METHOD OF DEL ALAMO

Case	ρ_1 [Ωm]	ρ_2 [Ωm]	h_1 [m]	Error F_g	Method of solution
1	372.729	145.259	2.690	0.1884	8th [10]
	374.921	144.518	2.559	0.1600	GA
2	246.836	1058.62	2.139	0.2126	7th [10]
	243.419	986.960	2.000	0.1829	GA
3	57.343	96.712	1.651	0.4043	5th [10]
	58.229	91.039	1.310	0.3635	GA
4	494.883	93.663	4.370	0.2338	7th [10]
	499.827	89.847	4.409	0.2029	GA
5	160.776	34.074	1.848	0.1852	8th [10]
	168.694	39.463	1.625	0.1512	GA
6	125.526	1093.08	2.713	0.8538	8th [10]
	128.645	1060.965	2.896	0.2771	GA

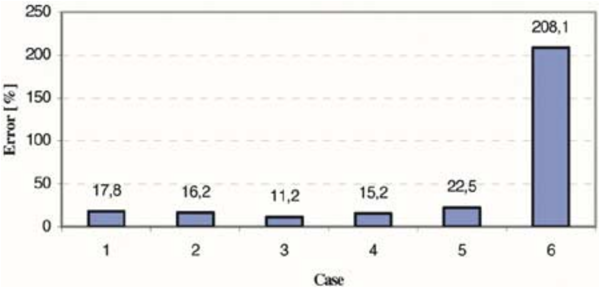

Fig. 3. Comparison of the GA solution with the best method of Del Alamo.

The comparison between the error produced by the application of the best method, as it has been published by Del Alamo [10] and the error of the GA solution is presented in Fig. 3. It is observed that even if Del Alamo [10] has collected the best of the existing methodologies for the calculation of parameters of two-layer earth, the error in this case is comparing with the GA methodology, considerably higher (from 11–23%, once indeed it reaches 208%). Consequently, it is clear that the use of GA increases the accuracy in the calculation of parameters of two-layer earth. Furthermore, it must be pointed out that the method presented here is very suitable to calculate the parameters of practically any soil structure, independent of the number of layers as will be demonstrated in Section V (Calculation of multilayer earth structure parameters). In this paragraph, examples of the calculation of the parameters of a three-layer earth are presented.

V. CALCULATION OF MULTILAYER EARTH STRUCTURE PARAMETERS

The calculation of the parameters of a N-layer soil structure is an optimization problem with $(2N-1)$ variables. It is necessary to minimize the function F_g using M pairs of measurements (soil resistivity and distance between electrodes)

$$F_g = \sum_{i=1}^{M} \frac{|\rho_{\alpha i}^{m} - \rho_{\alpha i}^{c}|}{\rho_{\alpha i}^{m}} \tag{15}$$

TABLE III
EXPERIMENTAL RESULTS

Case A		Case B	
α_i [m]	ρ_i [Ωm]	α_i [m]	ρ_i [Ωm]
1	214	1	138
3	256	3	79
5	273	6	71
10	307	8	67
15	284	10	80
20	250	15	88
30	225	20	99
50	210	40	151
80	186	60	170

TABLE IV
RESULTS OF THE APPLICATION OF THE GA

	Case A	Case B
ρ_1 [Ωm]	196.9	164.5
ρ_2 [Ωm]	351.7	71.6
ρ_3 [Ωm]	185.2	203.7
h_1 [m]	1.7	1.2
h_2 [m]	8.4	10.6
Error F_g	0.2662	0.3652

where $\rho_{\alpha i}^{m}$ is the ith measurement of the soil resistivity when the distance between two sequential probes is α while $\rho_{\alpha i}^{c}$ is the computed value of the soil resistivity for the same distance. The soil resistivity is calculated using the equations [7]

$$\rho_{\alpha}^{c} = \rho_1 \cdot [1 + 2 \cdot F_N(\alpha) - F_N(2 \cdot \alpha)] \tag{16}$$

where the function F_N is given in (6).

The measurements [16] are presented in Table III, whereas the results of the GA application to the mentioned measurements are shown in Table IV.

The variation of soil resistivity versus the distance between the electrodes for case A and B is presented in Figs. 4 and 5, respectively; both figures demonstrate in a very clear way the high quality and accuracy of the GA. For case A of Table III, the convergence of the parameters and the error of solution are presented in Fig. 6. The results presented here demonstrate the high accuracy and the fast convergence of the proposed methodology.

VI. CALCULATION OF SURFACE POTENTIAL

PC Opera is a software package for electromagnetic (EM) field analysis. This package uses the finite-element method to solve the partial differential equations (Poisson's, Helmholtz, and diffusion equations) that describe the behavior of fields. A lot of different ground arrangements can be simulated using PC Opera. The result of computations is the calculation of the variation of surface potential. The results obtained and presented here are compared with other researchers' results [7], [8].

A. Driven Rod in Five-Layer Earth

The grounding system, which is simulated in this example, is shown in Fig. 7. It consists of a rod, which is driven in a five-layer earth. The arrangement is axis-symmetric, that's why in Fig. 7, only half of it is shown. The parameters of the structure

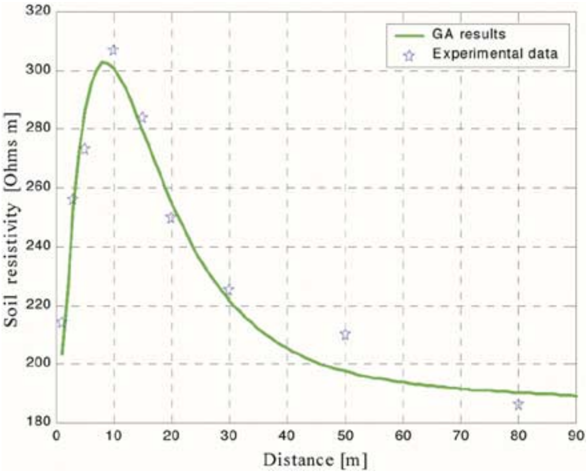

Fig. 4. Variation of soil resistivity of a three-layer earth versus the distance between the electrodes (case A).

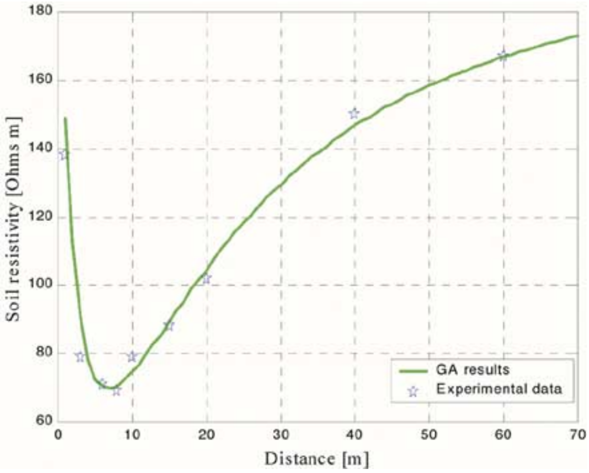

Fig. 5. Variation of soil resistivity of a three-layer earth versus the distance between the electrodes (case B).

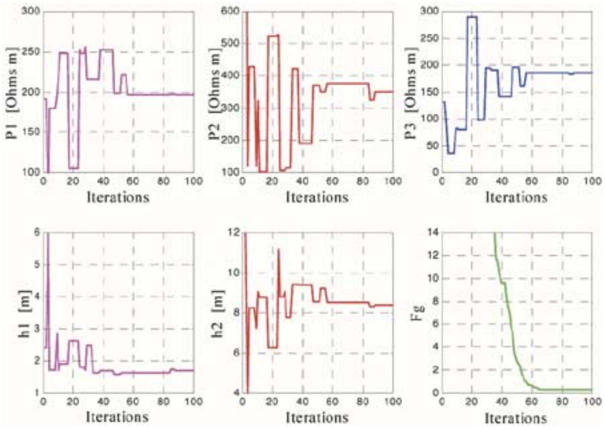

Fig. 6. Convergence of three-layer earth parameters.

are the soil resistivity and the thickness of each layer; the values are, respectively, $\rho_1 = 10\ \Omega\text{m}$, $\rho_2 = 50\ \Omega\text{m}$, $\rho_3 = 100\ \Omega\text{m}$, $\rho_4 = 500\ \Omega\text{m}$, $\rho_5 = 1000\ \Omega\text{m}$, $h_1 = 5$ m, $h_2 = 10$ m, $h_3 = 20$ m, $h_4 = 40$ m, and h_5 is infinite.

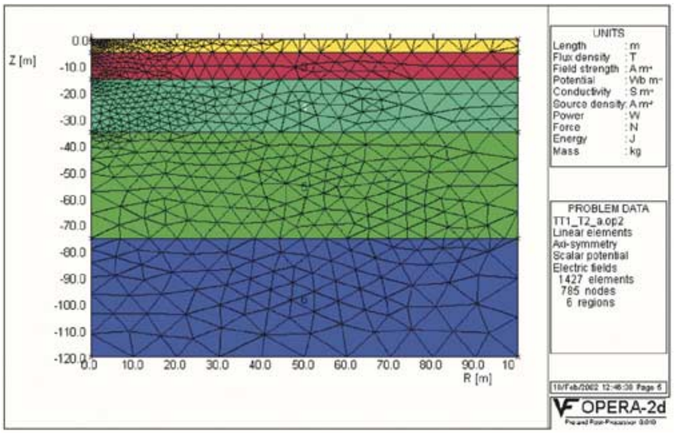

Fig. 7. Geometry of the five-layer earth problem.

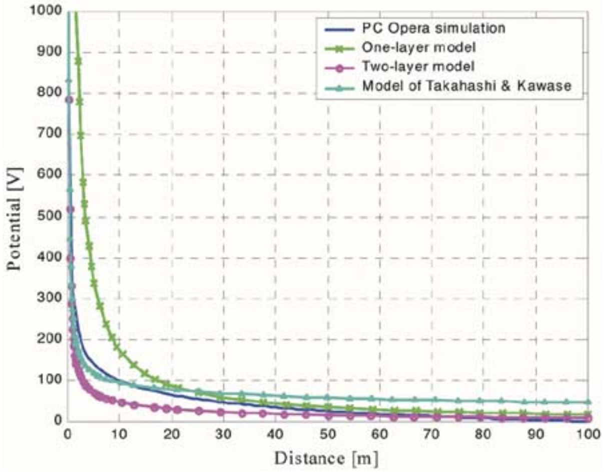

Fig. 8. Variation of surface potential versus the horizontal distance from the rod.

The variation of the surface potential versus the horizontal distance from the rod is shown in Fig. 8; the results obtained using the PC Opera simulation are compared with: a) results from the application of (1), considering that the soil is homogeneous and its resistivity is equal to the resistivity ρ_1 of the first layer; b) results from the application of (2), considering that the soil has two layers with parameters ρ_1 and h_1 for the first layer and ρ_2 and infinity h_2 for the second layer; c) results from the application of the (5), considering that the soil has four layers.

B. Grid in Two-Layer Earth

In this example, the examined grounding system is a 16-mesh grounding grid buried in two-layer earth. The soil resistivity of the first layer is $\rho_1 = 20\ \Omega\text{m}$ and its depth is $h_1 = 5$ m. The soil resistivity of the second layer is $\rho_2 = 100\ \Omega\text{m}$ and its depth h_2 is infinite. The dimensions of the 16-mesh grid are 20×20 m. The burial depth of the grid is 0.5 m and the ground conductor radius is 1 cm. The results referring to the variation of the surface potential are presented in Fig. 9.

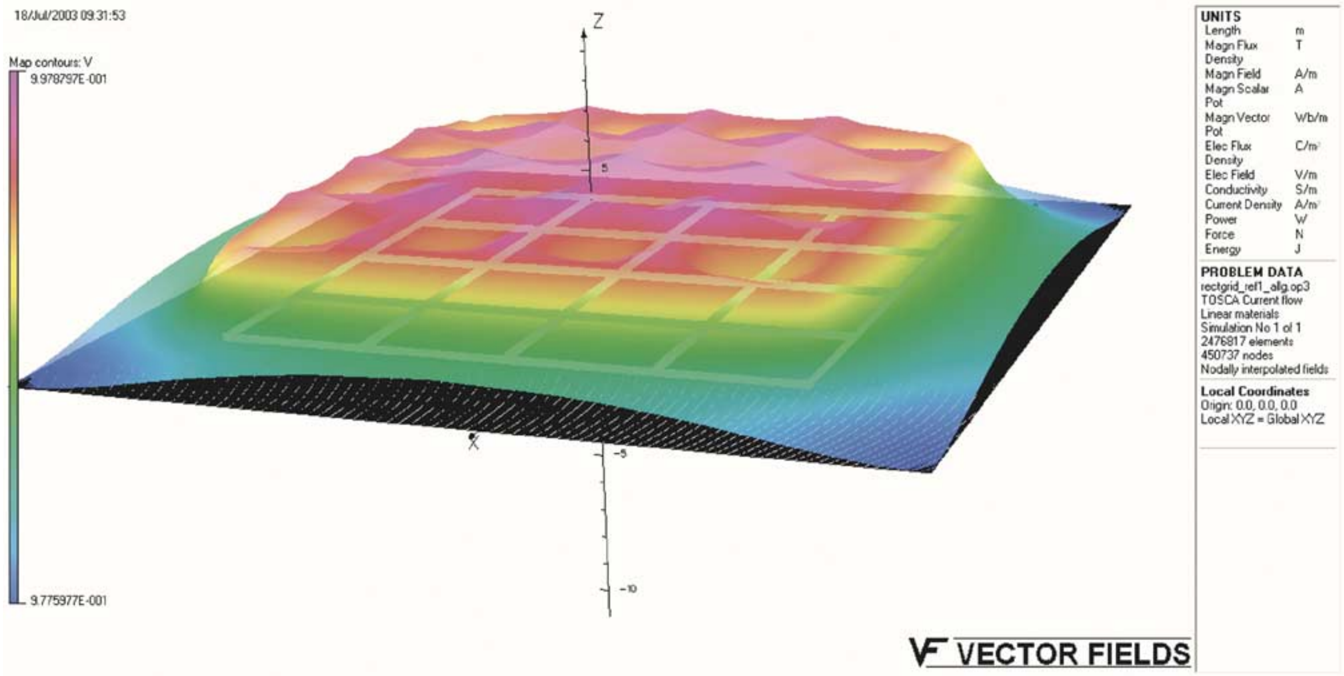

Fig. 9. Earth surface potential of the grid.

VII. CONCLUSION

In this paper, a methodology has been proposed according to which using a set of ground's resistivity measurements, one can compute the parameters of the multilayer earth structure with high accuracy. The calculation of the parameters of the multilayer soil structure can be reduced to a minimization problem. The efficiency of the GA has been demonstrated by comparing the GA's results to those obtained by other researchers. The results provided by the GA constitute the indispensable data that can be used in circuital or field simulations of grounding systems.

The methodology, which has been developed through PC Opera, allows to proceed toward a very efficient simulation of the grounding system and an accurate calculation of potential on the ground's surface.

Analysis of the graphs referring to the considered cases leads to the conclusion that the potential distribution computed through the PC Opera approach is very close to that obtained by multilayer analysis [7], [8], by making use of (5). The advantage of using this software package is that it can be applied to any grounding system case, whereas the utilization of (5) is limited only to point or vertical electrodes [7], [8].

The use of (1), which corresponds to the calculation of the potential on the surface of one-layer structure earth, generates, as expected, a significant divergence from the results in every studied case since the earth structures, which are studied, are multilayer.

In the examined cases, a remarkable convergence has been stated between the results of the PC Opera simulation and those of the complex, less exploitable, and subjected to many restrictions (5). Therefore, PC Opera can provide precious assistance in computing the potential distribution on the ground surface around the earthing system installation place.

TABLE V
EXPERIMENTAL RESULTS BY SEEDHER AND ARORA

Case								
	1	α_i [m]	1.0	2.0	3.0	4.0	5.0	
		ρ_i [Ωm]	693.74	251.62	84.56	37.64	25.32	
	2	α_i [m]	2.0	4.0	6.0	8.0	10.0	
		ρ_i [Ωm]	123.33	189.99	258.93	320.27	374.13	
	3	α_i [m]	2.0	4.0	6.0	8.0	10.0	
		ρ_i [Ωm]	102.26	113.07	129.77	147.52	163.95	
	4	α_i [m]	2.5	5.0	7.5	10.0	12.5	15.0
		ρ_i [Ωm]	320	245	182	162	168	152

TABLE VI
EXPERIMENTAL RESULTS BY DEL ALAMO

1	α_i [m]	2.5	5.0	7.5	10.0	12.5	15.0		
	ρ_i [Ωm]	320	245	182	162	168	152		
2	α_i [m]	1.0	1.5	2.5	3.0	5.0	10.0		
	ρ_i [Ωm]	255	290	315	376	528	690		
3	α_i [m]	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
	ρ_i [Ωm]	58.71	61.79	58.10	61.00	73.79	78.00	79.13	78.19
4	α_i [m]	2.5	5,0	7.5	10.0	12.5	15.0	20.0	25.0
	ρ_i [Ωm]	451.6	366.7	250.2	180.0	144.2	120.2	115.5	96.5
5	α_i [m]	1.0	2.0	3.0	4.0				
	ρ_i [Ωm]	156.4	113.1	95.2	65.3				
6	α_i [m]	1.0	2.0	4.0	10.0	20.0	40.0		
	ρ_i [Ωm]	136	140	214	446	685	800		

APPENDIX

Experimental results, which have been published by Seedher and Arora [11], are presented in Table V.

Experimental results, which have been published by Del Alamo [10], [13], are presented in Table VI.

ACKNOWLEDGMENT

The authors want to express their sincere gratitude to the Vector Field Company and especially to Dr. A. M. Michaelides for their kind support in simulating the multilayer soil structure using PC Opera.

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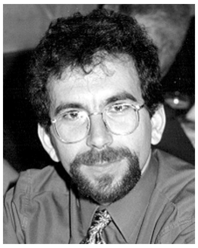

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