International Journal of Fuzzy Logic and Intelligent Systems, vol. 7, no. 3, September 2007 pp. 171-175

Determination of Multilayer Earth Model Using Genetic Algorithm

Min-Jae Kang, Chang-Jin Boo, Ho-Chan Kim,

School of Electrical & Electronic Engineering, Research Institute of Advanced Technology, Cheju National University
minjk@cheju.ac.kr, boo1004@cheju.ac.kr, hckim@cheju.ac.kr

Abstract

In this paper a methodology has been proposed to compute the parameters of the multilayer earth model 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. This methodology allows to proceed toward a very efficient simulation of the grounding system and an accurate calculation of potential on the ground's surface. The sets of soil resistivity used for GA are measured in Jeju area.

Key words : Genetic algorithms, grounding system, multilayer earth model, compute simulation, soil resistivity measurements

1. Introduction

When a grounding system is to be installed, knowledge of the earth model in the given location is compulsory. The parameters of the earth model 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 two layer structure at least.

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 determination of the parameters of the multilayer earth model is transformed to a problem of minimization; a methodology proposed in this paper, based on a genetic algorithm(GA), which calculates the parameters of the multilayer earth model, 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 model 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.

In this paper the computer simulation has been carried out for testing, if the proposed method can be used for analyzing the two and three layer earth model. The soil resistivities measured in Jeju area have been used for this computer simulation.

Manuscript received May 10, 2007; revised Jul. 10, 2007.
This work was supported by the research grant of the Cheju National University in 2005.

2. The Soil Resistivity of the Multilayer Earth Model

The potential at any point in the earth due to a current, flowing through a point electrode situated on the surface is given by the following equation [1].

$$V_0 = \frac{\rho_0 I}{2\pi}\int_0^\infty e^{-\lambda |z|} J_0(\lambda x)\partial\lambda \quad (1)$$

where $J_0(\lambda r)$ is the Bessel function of the first kind of order zero and ρ_0 is assumed a homogeneous and isotropic soil resistivity and $|z|$ .is depth. Using the Tagg model [1] of a horizontally stratified two-layer earth model (with soil resistivity ρ_1 and ρ_2), the potential V_2 due to a current I, flowing through a point electrode situated on the surface is given by the following equation [1]:

$$V_2(x) = \frac{\rho_1 I}{2\pi x}\left[1 + F_2(x)\right] \quad (2)$$

where

$$F_2(x) = 2x\int_0^\infty \frac{k_1 e^{-2\lambda h_1}}{1 - k_1 e^{-2\lambda h_1}} J_0(\lambda x)\partial\lambda \quad (3)$$

and h_1 is the thickness of the first layer and k_1 is the coefficient of reflection from the upper to the lower layer, which is given by (4)

$$k_1 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (4)$$

A method for the calculation of the surface potential in case of a multilayer earth model of the has been developed by Takahashi and Kawase [3,4]. 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 (N th) layer is infinity, and its soil resistivity is ρ_N. The potential at any point on the earth surface for a current I entering to the earth through a point electrode is described by the following equations (5)–(9) [3,4].

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

where

$$F_N(x) = 2x\int_0^\infty \frac{k_{N1}e^{-2\lambda h_1}}{1-k_{N1}e^{-2\lambda h_1}} J_0(\lambda x)\partial\lambda \tag{6}$$

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

$$K_{NS} = \frac{k_S + K_{N(S+1)}e^{-2\lambda h_{s+1}}}{1 + k_s K_{N(S+1)}e^{-2\lambda h_{s+1}}} \tag{8}$$

$$K_{N(N-1)} = k_{N-1} \tag{9}$$

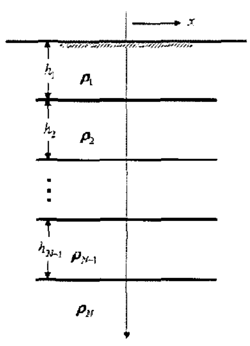

Fig. 1. Multilayer earth model

Through processing many groups of measurements [5-8], we are directed to the conclusion that the earth usually has a multilayer structure. Consequently, a methodology for the calculation of earth model 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-layer [5,6] and three-layer earth models [7,8] 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). Therefore the calculation of parameters of a three-layer earth is an optimization problem 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 an optimization problem of $2N-1$ parameters.

3. Parameters of Multilayer Earth model

The four-point method has been known the most accurate one among the methods for measuring the average resistivity of the earth model [2]. Four small point electrodes are buried in a straight line with same distance(a) and the voltage (ΔV) is measured between the inside two electrodes after injecting through the outer two electrodes. Then the resistance(R) can be obtained by using $\Delta V / I$. The average soil resistivity in depth(a) can be calculated approximately as follows.

$$\rho = 2\pi a R \tag{10}$$

The calculation of parameters of a two-layer earth is a three-parameter optimization problem. The objective function F_g of three parameters (soil resistivity of both layers and depth of the upper layer) can be expressed as follows

$$F_g = \frac{1}{M}\sum_{i=1}^{M}\frac{\left|\rho_{ai}^m - \rho_{ai}^c\right|}{\rho_{ai}^m} \tag{11}$$

where ρ_{ai}^m is the ith measurement of the soil resistivity when the distance between two sequential probes is a, while ρ_{ai}^c is the computed value of the soil resistivity for the same distance. The soil resistivity is calculated using [5,6].

$$\begin{aligned}\rho_a^c &= 2\pi a\frac{\Delta V}{I} = 2\pi a\frac{2(V_2(a) - V_2(2a))}{I} \\ &= \rho_1(1 + 2F_2(a) - F_2(2a))\end{aligned} \tag{12}$$

$$F_2(a) = 2a\sum_{n=1}^{\infty}\frac{k_1^n}{\sqrt{a^2 + (2nh_1)^2}} \tag{13}$$

As shown in equation (13), the infinite term is required for the accurate calculation, however k_1 is smaller than 1, so the approximate soil resistivity can be calculated by selecting n_k as the last term for n as follows

$$\begin{aligned}\rho_a^c &= \rho_1\left(1 + 4\sum_{n=1}^{n_k}k_1^n\left(\frac{1}{\sqrt{A}} - \frac{1}{\sqrt{A+3}}\right)\right), \\ A &= 1 + \left(\frac{2nh_1}{a}\right)\end{aligned} \tag{14}$$

The calculation of the parameters for a N-layer earth model is an optimization problem with $2N-1$ variables. N-layer soil resistivity can be calculated by using equation (6) as follows

$$\rho_a^c = \rho_1(1 + 2F_N(2a)) \tag{15}$$

Generally, the calculation of soil resistivity becomes complicated as the earth model becomes complex. As same in the two-layer earth model, the approximated soil resistivity for three-layer model can be calculated using the following equation.

$$\rho_a^c = \rho_1(1 + 2F_3(a) - F_3(2a)) \tag{16}$$

$$F_3(a) = 4a\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}\sum_{l=0}^{\infty} C_n^m C_m^l (-1)^{m-l}\Big[k_1^{m+1}k_1^{n-l} \times \frac{1}{\sqrt{a^2 + 4\left[(n-m+l+1)h_1 + (n-l)h_2\right]^2}} + \frac{k_1^m k_2^{n-l+1}}{\sqrt{a^2 + 4\left[(n-m+l+1)h_1 + (n-l+1)h_2\right]^2}}\Big] \tag{17}$$

4. Determination of Multilayer Earth Model Using Genetic Algorithm

GA is a computerized model to solve the complicated real problem by using a nature evolution phenomenon. In the early 1970's, J. Holland introduced GA which can find a global solution by using the law of survival of the fittest [9]. For solving a problem by using GA, each individual has information in a chromosome, where information can be presented by bits, constant number or real number string. Each individual is decided to exist or not depending on the individual fitness to a problem.

GA relies on the processes of reproduction, crossover and mutation for searching an optimal solution. GA is a population search method which is different from other methods which use points. Therefore GA does not require a continuity or differentiate problem space.

Each individual is duplicated through the process of reproduction, where the more fit string has more next generations. In the process of crossover, two individuals use a one-point crossover for exchanging parts of their string, where crossover point is selected randomly. Also crossover is restricted by crossover rate. The mutation process selects an individual randomly and changes one bit in the string resulting in making a totally different character. The mutation process can help the system escaping from a local minimum, however this process has to be carried out with limitation. Because too many mutation processes cause GA to perform a random search resulting in long calculation time [10].

This paper proposes a methodology, which uses the developed GA for the calculation of the parameters of a multilayer earth model. This GA has been developed using the software package Matlab. This GA produces excellent results in several optimization problems [11]. It has been applied for minimization in multidimensional systems, calculation of arc parameters for polluted insulators, and the computation of the parameters of the earth model.

The relation between earth apparent resistivity and earth parameters can be expressed as follows.

$$\rho_a^c = \rho(a, \rho_1, h_1, \rho_2, h_2, \cdots, \rho_N) \tag{18}$$

Number of earth layers is to be determined for calculating earth apparent resistivity. With Gauss-Newton like methods, the soil resistivity, which is archived by Wenner method, is used for determining number of earth layers and $\rho - a$ curve [12].

Fitness function is specifically determined depending on problem being solved. Generally the reciprocal of objective function or exponential function is used for defining a fitness function. For calculating $2N-1$ parameters (the earth resistivities of N layers and the depths of $N-1$ layers), the fitness function in this paper is the reciprocal of relative restoration error as follows [11].

$$f_c = M\left(\sum_{i=1}^{M}\frac{\left|\rho_{a_i}^m - \rho_{a_i}^c\right|}{\rho_{a_i}^m}\right)^{-1} \tag{19}$$

where M is the total number of the soil resistivities measured by Wenner method. The operation of GA, which has been developed, is described in the flowchart of Fig. 2

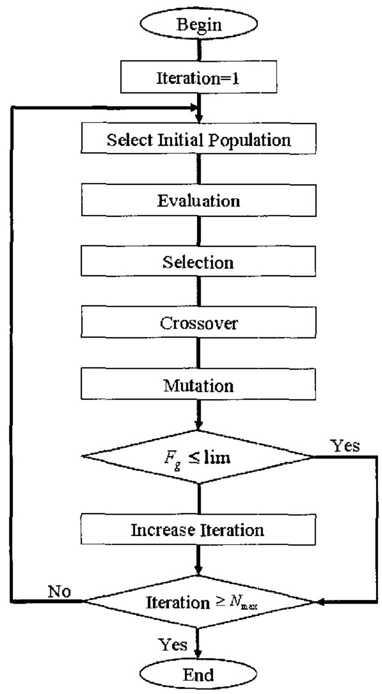

Fig. 2. Flowchart of GA

5. Computer Simulation

Computer simulation has been carried out for testing the proposed method and the measured data in Jeju area are used for analyzing two - layer and three - layer earth models.

The fitness function used for GA is equation (19) and a chromosome is presented by binary system and a gene is composed of 12 bits. Each chromosome has variables m=3 for two-layer and m=5 for three-layer model so 36 bits and 60 bits are required for the chromosome. The performance of GA depends on the crossover, mutation rate of parameter and size of group. In this paper, the group size is 40, the crossover happens with 0.95 probability and the mutation does with 0.01 probability. The roulette wheel is used as selecting method and the procedure is terminated after 10,000 generations.

5.1 The DATA for soil resistivity

The data used for computer simulation are collected from two different places in Jeju and YOKOGAWA 3244 measurement instrument and Wenner four-point method are used for collecting data.

For measuring soil resistivity, the four electrodes (C1,P1,P2,C2) are buried with same distance in the straight line [13]. C1 and C2 are current electrodes and P1 and P2 are voltage electrodes. The distances between electrodes are 0.5, 1, 2, 3, 4, 5, 7, 10, 15, 20, 25, 30[m] and the soil resistances [Ω] are measured by using YOKOGAWA 3244 as shown in Table 1.

Table 1. Experimental Results

$a_i[m]$	$\rho_{ai}^{m}[\Omega \cdot m]$	
	Case 1	Case 2
0.5	483.9	1256.0
1	653.7	1695.6
2	867.9	2650.1
3	1281.1	3918.7
5	1413.0	5024.0
7	1771.6	5275.2
10	1789.8	5149.6
15	1893.4	4710.0
20	2196.7	4019.2
25	2231.0	3218.5
30	2242.0	2486.8

5.2 Determination of the soil resistivity using GA

The analysis results of the earth resistivity by using GA are shown in Table 2. The earth resistivity, the depth and the error are presented when the two-layer and three-layer models are applied for analysis.

As shown in Table 2, the error of three -layer analysis is smaller than that of two-layer analysis in both cases. Therefore, both cases could be assumed as three-layer model. However, the depth (h_2) is too small for regarding one layer's depth, so two-layer model is a resonable conclusion for case 1.

Table 2. Results of the application of the GA

$a_i[m]$	Case 1		Case 2	
	2-layer	3-layer	2-layer	3-layer
$\rho_1[\Omega m]$	679.5	669.1	1179.2	1552.6
$\rho_2[\Omega m]$	2454.8	1641.6	5255.6	5436.9
$\rho_3[\Omega m]$	-	2491.5	-	776.3
$h_1[m]$	1.58	1.55	0.67	1.03
$h_2[m]$	-	0.32	-	20.08
Error F_g	0.127	0.096	0.207	0.166

Fig. 3 and Fig. 4 show the measured soil resistivities (small circles) and $\rho - a$ curves (continuous line) by using parameters in Table 1. and Table 2 respectively. As shown in these figures, it is proved that the soil resistivities are well presented over all. Case 1 can be analyzed as a two-layer model because the $\rho - a$ curve in Fig. 3 is calculated using two-layer model and follows the measured data closely. Case 2, however, should be more than three-layer model because the calculated resistivities by two -layer model are too much different from the measured data. Fig. 4 shows that the $\rho - a$ curve, calculated by three-layer structure, follows approximately the measured data..

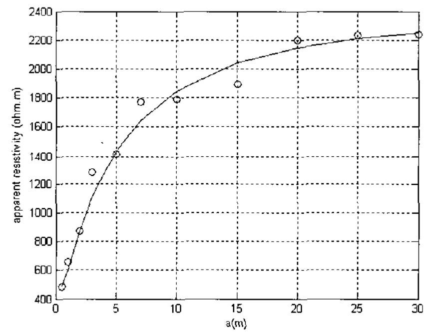

Fig. 3. Variation of soil resistivity versus the distance between the electrodes (Case 1)

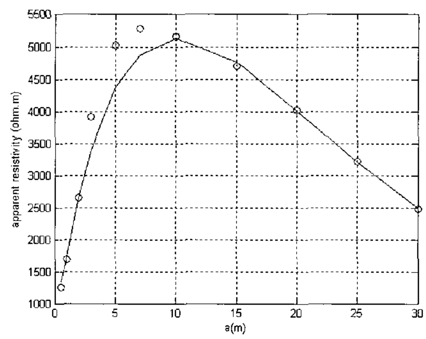

Fig. 4. Variation of soil resistivity versus the distance between the electrodes (Case 2)

6. Conclusions

In this paper the analysis algorithm of multilayer soil parameters by using GA is proposed. GA algorithm is able to find a global minimum by using only objective function. Therefore, GA is expected to be applied efficiently to the problem that finds the optimum soil resistivities in multilayer earth model.

The data used for computer simulation is measured in two different Jeju area. The approximated value to the real soil resistivity can be found by using GA. A multilayer(more than four) analysis algorithm and a weighted objective function are left for the future research.

References

[1] R. Tagg, G.F., *Earth Resistance*, London, U.K.: George Newnes Ltd., 1964.

[2] *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System*, IEEE Std. 81-1983, Mar. 11, 1983.

[3] T. Takahashi and T. Kawase, "Analysis of apparent resistivity in a multi-layer earth structure," *IEEE Trans. Power Del.*, vol. 5, no. 1, pp. 604-612, 1990.

[4] T. Takahashi and T. Kawase, "Calculation of earth resistance for deep-driven rod in multi-layer earth structure," *IEEE Trans. Power Del.*, vol. 6, no. 1, pp. 608-614, 1991.

[5] F.P. Dawalibi and C.J. Blattner, "Earth resistivity measurement interpretation techniques," *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 1, pp. 374-382, 1984.

[6] J.L.D. Alamo, "A comparison among eight different techniques to achieve an optimum estimation of electrical grounding parameters in two-layered earth," *IEEE Trans. Power Del.*, vol. 8, no. 4, pp. 1890-1899, 1993.

[7] I.F. Gonos, *Transient behavior of grounding system*, Ph.D. dissertation, Nat. Tech. Univ. Athens, Greece, 2002.

[8] P.J. Lagace, J. Fortin, and E.D. Crainic, "Interpretation of resistivity sounding measurements in N-layer soil using electrostatics images," *IEEE Trans. Power Del.*, vol. 11, no. 3, pp. 1349-1354, 1996.

[9] H. Holland, *Adaptation in Nature and Artificial Systems*, Ann Arbor, MI: Univ. Michigan Press, 1992.

[10] I.F. Gonos, N.E. Mastorakis, and M.N.S. Swamy, "A genetic algorithm approach to the problem of factorization of general multidimensional polynomials," *IEEE Trans. Circuits and Syst.*, pt. 1, vol. 50, no. 1, pp. 16-22, 2003.

[11] I.F. Gonos and I.A. Stathopulos, "Estimation of multilayer soil parameters using genetic algorithm," *IEEE Trans. Power Del.*, vol. 20, no. 1, pp. 100-106, 2005.

[12] B. Chen, *Theory and Arithmetic of Optimization*, Beijing, Tsinghus University Press, 1989.

[13] J. Zou, J.L. He, R. Zeng, W.M. Sun, G. Yu, and S.M. Chen, "Two-stage algorithm for inverting structure parameters of the horizontal multilayer soil," *IEEE Trans. Magnetics*, vol. 40, no. 2, pp. 1136-1139, 2004.

Min-Jae Kang
He received the B.S. degree in Electrical Engineering from Seoul National University in 1982 and Ph.D. degree in Electrical & Computer Engineering from University of Louisville in 1991. Since 1992, he has been with school of Electrical and Electronic Engineering at Cheju National University, where he is currently a professor.

Phone : +82-64-754-3666
Fax : +82-64-756-1745
E-mail : minjk@cheju.ac.kr.

Chang-Jin Boo
He received his B.S. and M.S. and Ph.D. degrees in Electrical Engineering from Cheju National University in 2001, 2003, and 2007 respectively. He has researched grounding theory and genetic algorithms.

Phone : +82-64-754-3797
Fax : +82-64-756-5281
E-mail : boo1004@cheju.ac.kr

Ho-Chan Kim
He received the B.S., M.S., and Ph.D. degrees in Control & Instrumentation Engineering from Seoul National University in 1987, 1989, and 1994, respectively. He was a research staff from 1994 and 1995 at the Korea Institute of Science and Technology (KIST). Since 1995, he has been with the Department of Electrical Engineering at Cheju National University, where he is currently a professor.

Phone : +82-64-754-3676
Fax : +82-64-756-5281
E-mail : hckim@cheju.ac.kr