Variation of Soil Resistivity and Ground Resistance during the Year

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***Abstract*-- The scope of this paper is the investigation of the variation of the soil resistivity and the grounding system resistance during the year. Measurements of soil resistivity variation as a function of time, at certain characteristic locations, have been carried out. The annual change of multi-layer earth structure parameters has also been calculated by the analysis of data of measurements. The calculation of the earth layer structure parameters is in fact an optimization problem. On this purpose, data treatment has been based on a methodology which uses a genetic algorithm model. The proposed methodology provides evidence of highly accurate results in the calculation of multi-layer soil parameters. These results are used as input data for the simulation of grounding systems behavior for this particular soil type. In this way, an optimized design of the grounding system under consideration becomes possible, eventually resulting in minimized step-voltage and touch-voltage built-up.**

***Index Terms*--Ground resistance, Multi-layer soil structure, Soil resistivity measurements, Step voltage, Touch voltage.**

I. Introduction

The design and construction of a grounding system requires the knowledge of earth structure, since grounding system location is defined by the home site that it protects.

Measurements of soil resistivity that have been carried out in various regions throughout the country, showed that in the analysis we should consider at least a two-layer earth structure. Further on, the repetition of measurements makes obvious that soil resistivity varies upon time and depends on the season of the year, reaching maximum values in the summer months.

The final setup of the grounding system is determined by multi-layer earth structure parameters, like soil resistivity and depth of each layer. The calculation of such parameters is necessary in order to achieve a safe grounding system with minimized material and construction cost.

The permitted limits for the step and the touch voltage (in V) are given by the following equations [1]:

$$E_{step} = \left(1000 + 6 \cdot C_s \cdot \rho_s\right) \frac{C_w}{\sqrt{t_s}} \quad (1)$$

$$E_{touch} = \left(1000 + 1.5 \cdot C_s \cdot \rho_s\right) \frac{C_w}{\sqrt{t_s}} \quad (2)$$

where t_s is the duration of the shock current (in seconds) and C_w is a constant with values 0.116 / 0.157 for a human body weight 50kg / 70kg respectively. C_s is a derating factor, which is given by the following empirical equation [1]:

$$C_s = 1 - \frac{0.09 \cdot \left(1 - \frac{\rho}{\rho_s}\right)}{2 \cdot h_s + 0.09} \quad (3)$$

where ρ_s and h_s the soil resistivity and the thickness of the surface's material (in Ohms·m and m, respectively). However, a thin layer (8 – 15cm) of a high resistivity material is often spread on the earth's surface above the grounding system to increase the limit of the corresponding touch voltage. In case of absence of such surface material then $C_s = 1$ and $\rho_s = \rho$.

II. Calculation of the Soil Structure

The soil type affects the behavior of a grounding system significantly. The impact of soil type can be

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studied by means of measuring soil resistivity. The analysis of results coming from soil resistivity measurements is important for the accurate analysis of grounding systems [1], [2]. The contribution of soil resistivity in the ground resistance value is very important. Many techniques have been developed for the computation of soil resistivity [2]-[7]. The most important of them are: a) the Wenner method, b) the Schlumberger method, c) the dipole method and d) the alternate configuration method.

The design of a grounding system requires determination of earth's structure parameters like (soil resistivity and thickness of each soil's layer). These parameters are calculated according to measurements of soil resistivity. After that, the most suitable earth structure is chosen (according to the number of the layers) in order to start grounding system design [6].

The Four-Point (Wenner) method [2], [5], [6] is the most accurate for the measurement of average soil resistivity. Four electrodes (rods) are driven in line, in a depth b at equal distances α from each other. A test current I is injected at the two terminal electrodes and the potential between the two middle electrodes is measured. The ratio V/I gives the apparent resistance R (in Ohms). The apparent soil resistivity ρ is given by the following equation [2]:

$$\rho = \frac{4 \cdot \pi \cdot a \cdot R}{1 + 2 \cdot a \Big/ \sqrt{a^2 + 4 \cdot b^2} - a \Big/ \sqrt{a^2 + b^2}} \tag{4}$$

The parameter calculation of the two layer earth structure is an optimization problem which involves the calculation of three parameters (the soil resistivity ρ_1 of the upper layer, the soil resistivity ρ_2 of the lower layer and the depth h of the upper layer) and the minimization of the function F_g is necessary [2], [6]:

$$F_g = \sum_{i=1}^{N} \left| \frac{\rho_{\alpha i}^{m} - \rho_{\alpha i}^{c}}{\rho_{\alpha i}^{m}} \right| \tag{5}$$

where $\rho_{\alpha i}^{m}$ is the η i^{th} measurement of the soil resistivity of the soil, using the Wenner method [2] for a distance between two sequentially auxiliary electrodes equal to α, and $\rho_{\alpha i}^{c}$ is the calculated value of the soil resistivity at distance α between the auxiliary electrodes corresponding to the i^{th} pair of measurements. The calculation of the soil resistivity is made using equations (6-8) [2], [6]:

$$\rho_{\alpha}^{c} = \rho_1 \cdot \left(1 + 4 \sum_{n=1}^{\infty} \left(\frac{K^n}{\sqrt{1+A}} - \frac{K^n}{\sqrt{4+A}} \right) \right) \tag{6}$$

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{7}$$

$$A = \left(2 \cdot n \cdot \frac{h}{\alpha} \right)^2 \tag{8}$$

III. Genetic Algorithm

In this paper a Genetic Algorithm (GA) is used for the optimization of the soil structure parameters. This GA has been developed using Matlab. The same GA produces excellent results in several optimization problems [6], [8]-[10]. It has been applied for the computation of earth structure parameters [6], [8], factorization of multidimensional polynomials [9], and calculation of arc parameters at polluted insulators [10].

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 points P_s, which are called "population" analogically to biological system terms. 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 reproduction, the population of "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 to be solved. F_g represents the error between given and optimized data. 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 P_s-members population is no longer improved or the number of iterations is greater than the maximum number of iterations N_{max}.

IV. Soil Resistivity Measurements

The main result of this work is the measurement of the apparent soil resistivity and the recording of its variation during the year. Applying the Wenner method four electrodes of 50cm in length have been used, which were driven in a straight line. The conductors that connect the auxiliary electrodes with the ground meter had a cross section of $4mm^2$. The distance between two successive electrodes was α and it was varying with discrete steps.

The soil resistivity was recorded at various distances between the electrodes for the determination of the earth's structure parameters. The measurements were repeated in scheduled time intervals in order to evaluate the effect of environmental conditions depending upon climate changes, season of the year etc. (Fig. 1). According to these measurements, conclusions on the structure of the soil may be conducted.

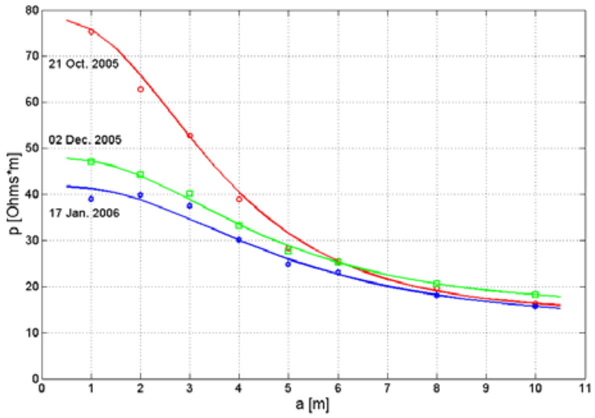

Fig. 1. Variation of the apparent soil resistivity in relation to the distance of the auxiliary electrodes in three different days.

Fig. 1 shows that the measured values of soil resistivity decrease with the distance between the electrodes. This provides strong evidence of two layer soil structure with the upper layer having higher soil resistivity than the lower layer [2].

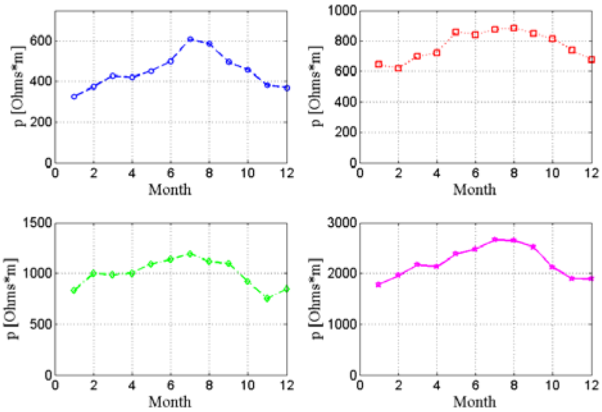

Fig. 2. Variation of the apparent soil resistivity during the year at various areas (a=10m).

According to Fig. 2, the ratio of maximum to minimum apparent soil resistivity that have been recorded at various areas during a time interval of five years, receives values ranging from 1.5 to 3. It is obvious that soil resistivity gets its peak values during the summer months, (Fig. 2). If it is not possible to carry out any measurements during the summer, then it is advised that available data coming from other seasons of the year to be increased proportionally, by a suitable multiplier according to soil resistivity variation data through the year.

For the measurements results on 21 October 2005, the convergence of the parameters and the error of solution using the GA method are presented in Fig. 3.

The GA has been applied with a randomly generated population of P_s chromosomes (P_s=20). It generates 20 random values for the first layer resistivity ($0<\rho_1<200$), 20 random values for the second layer resistivity ($0<\rho_2<50$) and 20 random values for the thickness of first layer ($0<h_1<10$). Each parameter is converted to a 16-bit binary number. Each chromosome has m variables (m=3); so 48 bit 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 a probability P_m = 20% for mutation. The procedure is terminated after N_{max} = 100 generations.

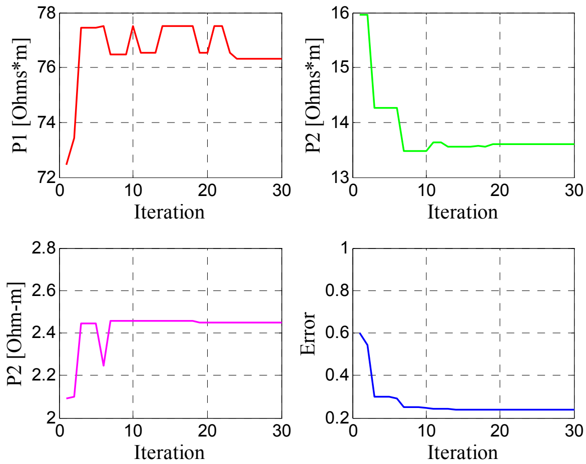

Fig. 3. Convergence of two-layer earth parameters.

The application of the GA with the above parameters (for the measurements presented in the table I) results in the solutions, which are shown in Table II. In Table II are also presented results using the Levenberg - Marquardt method (L-M). It is obvious that the solutions, which have been obtained using the GA, produce more accurate results than the Levenberg - Marquardt method.

TABLE I

SOIL RESISTIVITY MEASUREMENTS

	α_i [m]	1	2	3	4	5	6	8	10
1	ρ_i[Ωm]	75.4	62.8	52.8	38.9	28.3	25.6	19.6	16.3
2	ρ_i [Ωm]	76.6	65.3	53.9	39.4	28.9	26.4	19.6	16.3
3	ρ_i [Ωm]	84.8	69.1	58.4	41.4	28.6	26.4	19.1	15.7
4	ρ_i [Ωm]	40.2	40.3	37.7	31.4	25.1	23.4	17.6	15.7
5	ρ_i [Ωm]	38.9	39.8	37.5	30.1	24.8	23.0	18.1	15.7
6	ρ_i [Ωm]	53.4	44.6	41.1	33.9	28.3	24.5	19.6	16.3
7	ρ_i [Ωm]	47.1	44.2	40.1	33.2	27.6	25.2	20.6	18.2
8	ρ_i [Ωm]	47.1	45.2	39.9	33.2	26.7	24.5	19.1	17.0
9	ρ_i [Ωm]	45.2	42.3	37.7	31.7	26.4	23.7	19.6	15.7
10	ρ_i[Ωm]	45.2	42.2	37.7	31.1	25.1	22.6	16.6	12.6

The values for the soil resistivity and the thickness of the layer are not constant during the year as they are presented in Table II and Fig. 4. For this reason the values of the permitted limits for step and touch voltage vary proportionally through the year. The permitted limits for step and touch voltage have been calculated for a human body weight of 50kgr and fault clearing time of 0.5s using CDEGS software package [11]. It is obvious that the small divergence of the calculated values (between GA and L-M results) earth parameters has no considerable effect on the permitted limits for step and touch voltage. It must be pointed out that the calculation of these permitted limits for the step and the touch voltage is necessary to be done with high accuracy as they are input data for the study of grounding system safety.

TABLE II
COMPARISON OF THE GA SOLUTION WITH THE LEVENBERG - MARQUARDT SOLUTION

Case	ρ_1 [Ωm]	ρ_2 [Ωm]	h_1 [m]	Error F_g	E_{step} [V]	E_{touch} [V]	Method
1	77.8	14.8	2.31	0.229	229.6	173.3	GA
	77.6	14.4	2.32	0.237	229.5	173.2	L-M
2	78.11	13.60	2.45	0.226	229.9	173.4	GA
	79.4	14.3	2.34	0.267	231.2	173.7	L-M
3	86.06	13.17	2.37	0.297	237.6	175.3	GA
	87.5	13.7	2.30	0.311	239.0	175.6	L-M
4	43.8	12.4	3.02	0.258	196.8	165.1	GA
	42.5	11.5	3.27	0.261	195.5	164.8	L-M
5	41.8	12.2	3.14	0.229	194.9	164.6	GA
	41.4	11.8	3.24	0.236	194.5	164.5	L-M
6	53.6	13.2	2.77	0.155	206.3	167.4	GA
	51.9	13.3	2.84	0.166	204.6	167.0	L-M
7	47.9	14.8	2.91	0.094	200.8	166.1	GA
	48.4	15.1	2.82	0.097	201.3	166.2	L-M
8	47.9	15.15	2.76	0.164	200.8	166.1	GA
	49.0	13.6	2.86	0.159	201.8	166.3	L-M
9	45.8	12.03	3.13	0.128	198.7	156.6	GA
	45.8	12.6	3.04	0.134	198.7	165.6	L-M
10	45.6	8.6	3.32	0.154	198.5	165.5	GA
	45.5	8.67	3.34	0.162	198.5	165.5	L-M

The variation of the apparent soil resistivity upon the distance between the auxiliary electrodes (*a*=1m, *a*=4m and *a*=10m) is presented in Fig. 4. The shorter the test electrode span of Wenner configuration method is, the higher the variation of the apparent soil resistivity versus time gets.

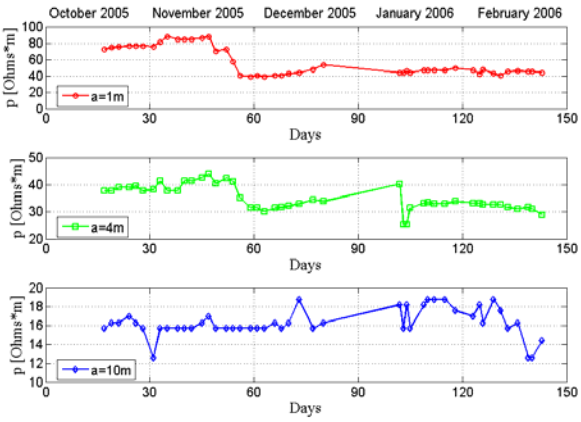

Fig. 4. Variation of the apparent soil resistivity upon the distance of the auxiliary electrodes (*a*=1m, *a*=4m and *a*=10m).

The variation of the two-layer earth parameters during the year is presented in Fig. 5. It is obvious that the variation of the soil resistivity of the first layer is similar to the variation of the apparent soil resistivity at distances of the auxiliary electrodes equal to 1m.

Also, similar variation versus time has the resistance of a vertical electrode, which is driven in this area, as it is shown in Fig. 6. The grounding system resistance has been carried out using the fall of potential method [1].

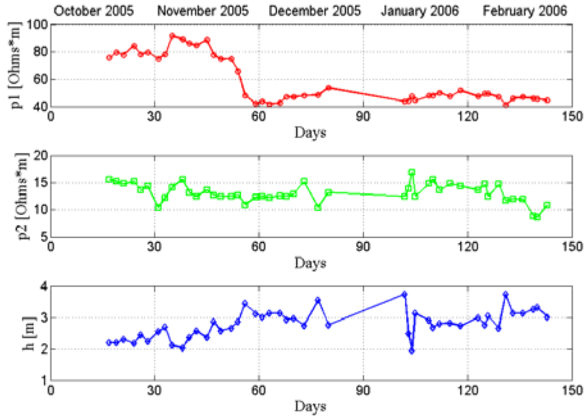

Fig. 5. Variation of two-layer earth parameters during the year.

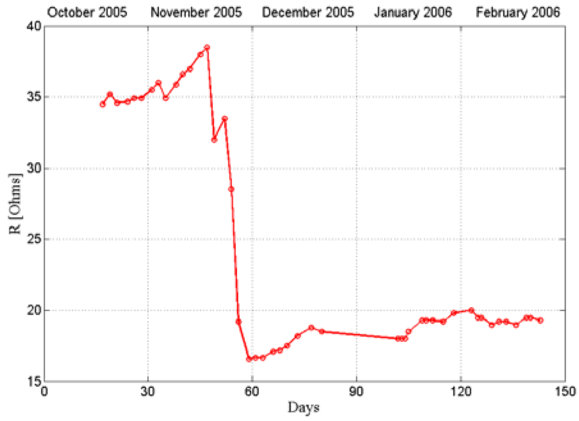

Fig. 6. Variation of grounding system resistance during the year.

V. CONCLUSION

Measurements of the variation of soil resistivity during the year have been carried out. A methodology using GA has been proposed, according to which, using a set of soil resistivity measurements, someone is able to calculate the parameters of the multi-layer earth structure with high accuracy. The variation of the two-layer earth parameters during the year has been also presented. Calculation of the two-layer earth parameters variation provides the necessary input data for the estimation of the step and of the touch voltage.

Also, the variation of the grounding resistance for a grounding system made of a driven rod, has been presented in this paper.

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