Perfmance Assessment And Modeling Of Grounding Grid
Case Study of Alkhom 400Kv-Substation

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Abstract:

The "grounding" or "earthing" system of an electrical substation comprises all interconnected grounding facilities of a specific area, being the "grounding grid" its main element. The accurate design of a grounding system is essential to assure the safety of the persons, to protect the equipment. Thus, the electrical resistance of the grounding system must be low enough, while the values of electrical potentials between close points on the earth surface that can be connected by a person must be kept under certain maximum safe limits. Field measurements of soil resistivity are *required to determine a suitable soil model for design purpose. Field measurements of soil resistivity using Wenner method are conducted at different sites for Al kHOMS-Libya 220/400KV substation. Computer program based on* ***Finite Wenner resistivity expressions*** *method is developed for soil resistivity measurements interpretation.*

For computing the grid resistance, a method based on two kinds of two-layer models (i.e., grid buried in the upper-layer of two-layer soil, two-layer soil simplified with one-layer structure of the Sverak's and empirical equations) is used and compared with the method proposed by the one-layer model of the Schwarz's or Sverak's equation in IEEE Standard 80-2000 edition.

1.1 Introduction:

The grounding system consists of different conductive equipment. It can be divided into two major parts: the first part is generally called the grounding electrode which is the conductor buried in the ground; the second part is generally called grounding conductor which a copper wire is connecting the equipment housing with the grounding electrode. The grounding conductor leads fault current into grounding electrode, and then drain fault into the earth. High voltage installations require an earthing system to protect human life against excessive touch voltages and to keep transferred potential to a minimum. The increase of fault currents to earth affects the importance of earthing systems and the need for low resistance of the earth grid. Planning, calculations and measurements of earthing systems can be performed according to regulations, i.e. IEEE standard 80-1986 or IEEE 80-2000.The basic values for these procedures are the maximum earth fault currents and the fault duration of the different voltage levels. As parts of the fault current return within the earthing system (i.e.

transformer neutrals, earth wire, cable sheath) only the remaining part has to be considered for the design of the earthing system of the high voltage station. Determination of the resulting current flowing into the earth electrodes is therefore an important task. Another factor of importance is knowledge of the decisive soil resistivity for an extended earthing system

1.2 Soil Resistivity Measurement And Modeling For The Case Study Substation:

Soil is an important parameter for the grounding system performance. Efficiency of grounding system depends of the type of soil and its characteristics. Grounding grid performance can be measured in terms of grounding resistance, but it is preferable to include step and touch voltages as good parameters for grounding quality. Primarily, several measurements had been done for the soil resistivity at different locations, labeled site #1 to site#4 as shown in Figure (1).

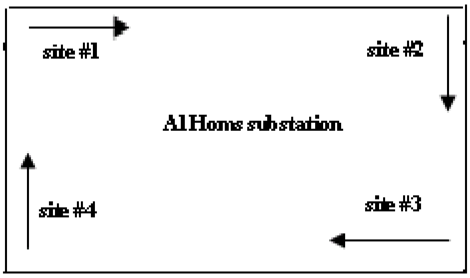

Fig.1. Experimental site

By applying Wenner's method, the following results were obtained:

Table 1: Apparent soil resistivity values for different sites of case substation

Spacing	Apparent resistivity ($\Omega.m$)			
	Site #1	Site #2	Site #3	Site #4
1	87.3363	125.0354	133.9628	150.2938
1.5	83.2208	108.6677	___	___
2	72.7593	85.3257	72.5080	146.0212
2.5	___	69.4292	___	___
3	65.9734	55.4177	34.0504	___
4	60.3186	37.4478	36.9451	130.1876
5	48.3801	30.7876	___	___
6	38.8301	26.0124	28.6513	111.9664
7	35.1858	22.8708	___	99.8398
8	28.1487	16.0850	29.6566	___
9	23.1850	17.5301	___	78.0372
10	16.9646	16.3364	___	64.7168
11	___	___	___	59.4389

1.3 Interpretation of Soil Measurements

The interpretation of the results obtained in the field is perhaps the most difficult part, because the earth resistivity variation is great and complex [1]. Rarely a soil composition is found where the resistivity varies little with respect to depth. Such a soil can be interpreted as a uniform soil[2]. A two layer soil model is generally an adequate representation of non homogeneous soil for grounding system design. Parameters of two layer soil are obtained from soil resistivity measurements at the proposed site of the grounding system. The measurements are more commonly done by Wenner four probe method. Evaluation of two layer soil model from the measured data is done either by graphical methods or by computer based methods. Graphical methods require interpolation and judgment, especially when the actual soil is more complex than a real two layer pattern. Computer based methods, however, give an optimal two layer soil fit when the actual soil structure is complex [3].

1.4 Estimation of Two Layer Soil Parameters Using Finite Wenner Resistivity Expressions:

When the measured apparent resistivity at a site is not uniform, the data can be interpreted to obtain the best fit two layer equivalent. The process basically involves an iterative search for such values of two layer parameters ρ_1 , ρ_2 and h as make the appropriate theoretical apparent resistivity expression for the two layer soil fit the measured data by the least squares criterion. The infinite series expression of apparent resistivity is given by the following equation

$$\rho_a = \rho_1\left[1 + 4\sum_{n=1}^{\infty} K^n\left(\frac{1}{\sqrt{1+(2nh/a)^2}} - \frac{1}{\sqrt{4+(2nh/a)^2}}\right)\right] \tag{1}$$

Finite Expression for ρ_a When $\rho_2 < \rho_1$

The finite expression for ρ_a can be obtained as the following equation:

$$\rho_a = \rho_2 + (\rho_1 - \rho_2)[2e^{-b(a)a} - e^{-b(2a)2a}] \tag{2}$$

Where:

$$b = \frac{[bm - (bm - x_1)e^{-X_2 a/h}]}{h} \tag{3}$$

$$b_m = X_3 - X_4\left(\frac{\rho_2}{\rho_1}\right)^{X_5} \tag{4}$$

The respective values of X_1, X_2, X_3, X_4 and X_5 are 0.673191, 0.479513 , 1.33335 , 0.882645 and 0.697106.

The objective function to be minimized in the search process is formulated as the following equation:

$$F = \sum_{J=1}^{n} \left(\frac{m_J - c_J}{m_J} \right)^2 \tag{5}$$

Where:

$$m_J = \ln(\rho_J^{-}) \tag{6}$$

$$c_J = \ln[\rho_J(\rho_1, \rho_2, h)] \tag{7}$$

n: Number of electrode spacing for which apparent resistivity measurements are made.

ρ_J^{-}: Measured apparent resistivity for Jth electrode spacing.

ρ_J: Apparent resistivity at the Jth electrode rode pacing computed by using finite expression (2).

A developed computer program is used to determine the equivalent two-layer earth model from the measured apparent resistivity data obtained by the equally-spaced four point (Wenner) method. It is based on the (Finite Wenner Resistivity Expression) method in the case of $\rho_2 < \rho_1$. The program flow chart is shown in Figure (2).

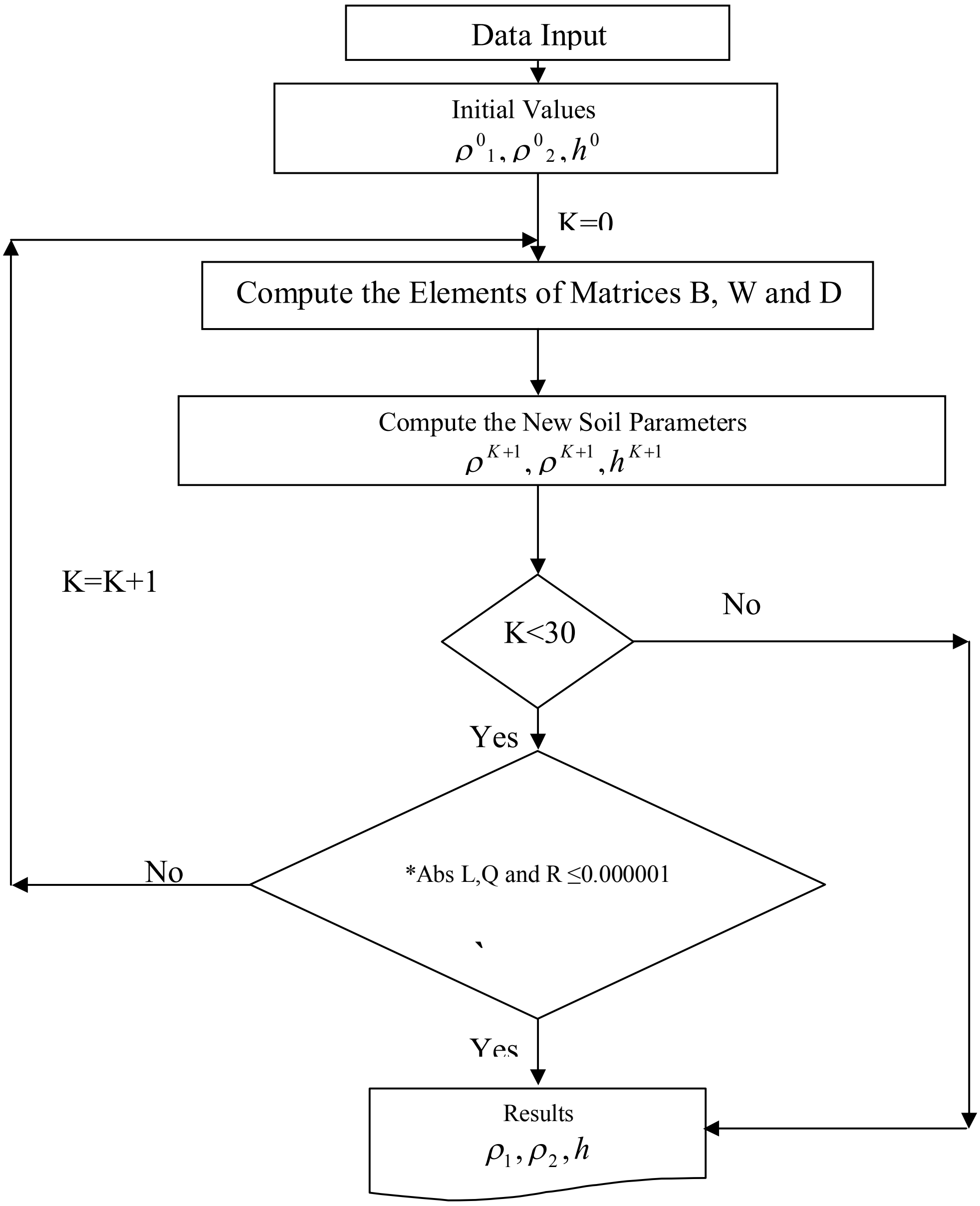

Fig. 2.Flow chart of the developed program

The proposed program has been used for the field data of ALKHOMS substation shown in Table (1). The results were as following:

Table 2: the soil modeling results

Site	Site #1	Site #2	Site#3	Site#4
Soil Resistivity of First Layer, ρ_1 $(\Omega.\mathrm{m})$	81.0381	122.4538	167.4151	149.3732
Soil Resistivity of second Layer, ρ_2 $(\Omega.\mathrm{m})$	5.0335	16.1376	29.1927	11.1966
Depth of First Layer, $h_1(m)$	4.2190	1.8364	1.0442	6.2365

The measured values are compared with the calculated values and the percentage error is estimated. Collective results appear in Tables (3), (4), (5) and (6) for site #1, site #2, site #3 and site # 4 respectively. The measured and calculated resistivity values are sketched on the same graph for each site .The results appears in Figures (3),(4),(5) and (6).

Table 3:Soil resistivity measured and calculated values for site #1

Spacing (m)	Resistivity measured values $\Omega.\mathrm{m}$	Resistivity calculated values $\Omega.\mathrm{m}$	Error (%)*
1	87.3522	80.4219	8.6174
1.5	83.2208	79.0912	5.2213
2	72.7593	76.8081	-5.2713
3	65.9734	69.6020	-5.2134
4	60.3186	60.1730	0.2420
5	48.3805	50.2443	-3.7095
6	38.8301	41.0204	-5.3395
7	35.1858	33.0863	6.3455

Spacing (m)	Resistivity measured values $\Omega.m$	Resistivity calculated values $\Omega.m$	Error (%)*
8	28.1487	26.5912	5.8572
9	23.1850	21.4456	8.1108
10	16.9646	17.4588	-2.8307
	Objective function F=0.0327		RMS Error**=5.3937%

$$\text{*Error }(\%) = \frac{Meas.value - cal.value}{cal.value} \times 100 \,, \quad \text{**RMS Error} = \sqrt{\frac{\sum_{i=1}^{N} Error^{2}(i)}{N}}$$

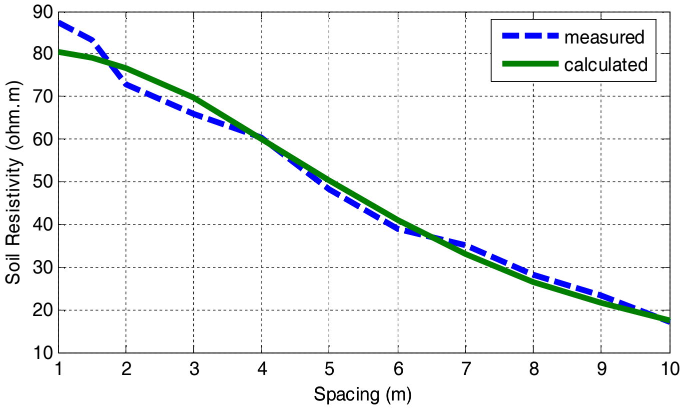

Fig 3. Soil resistivity measured and calculated values for site #1

Table 4:Soil resistively measured and calculated values for site #2

Spacing (m)	Resistivity measured values $\Omega.m$	Resistivity calculated values $\Omega.m$	Error (%)
1	125.0354	114.4253	9.2725

1.5	108.6677	101.8217	6.7235
2	85.3257	86.6126	-1.4858
2.5	69.4292	71.7808	-3.2761
3	55.4177	58.9220	-5.9474
4	37.4478	40.4419	-7.4035
5	30.7876	29.7888	3.3529
6	26.0124	23.9665	8.5365
7	22.8708	20.8189	9.8559
8	16.0850	19.0948	-11.5728
9	17.5301	18.1222	-3.2673
10	16.3364	17.5502	-6.9162
	Objective function F=0.0798		RMS Error=7.118 1%

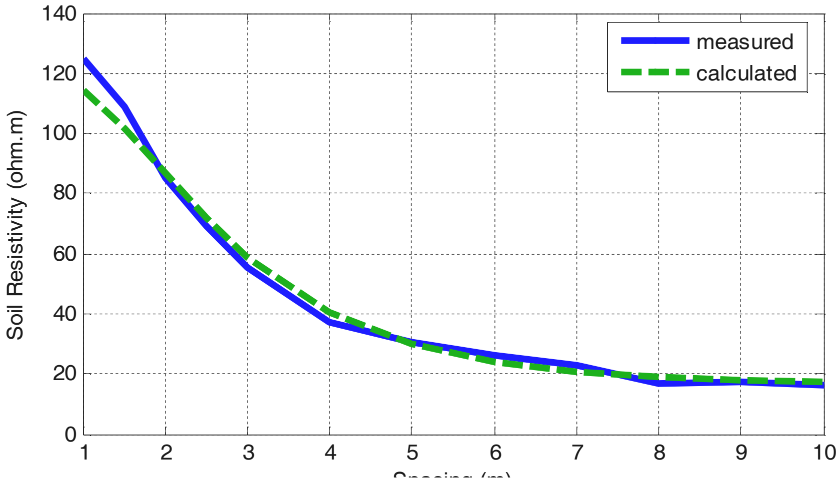

Fig.4. Soil resistively measured and calculated values for site #2

Table 5: Soil resistively measured and calculated values for site #3

Spacing (m)	Resistivity measured values Ω.m	Resistivity calculated values* Ω.m	Error (%)
1	133.9628	131.4985	1.8740
2	72.5080	72.7981	-0.3985
3	45.0504	45.9893	-2.0416
4	36.9451	36.2853	1.8184
6	28.6513	31.2450	-8.3012
8	29.6566	30.1699	-1.7014
	Objective function F=0.0093		RMS Error=3.7182%

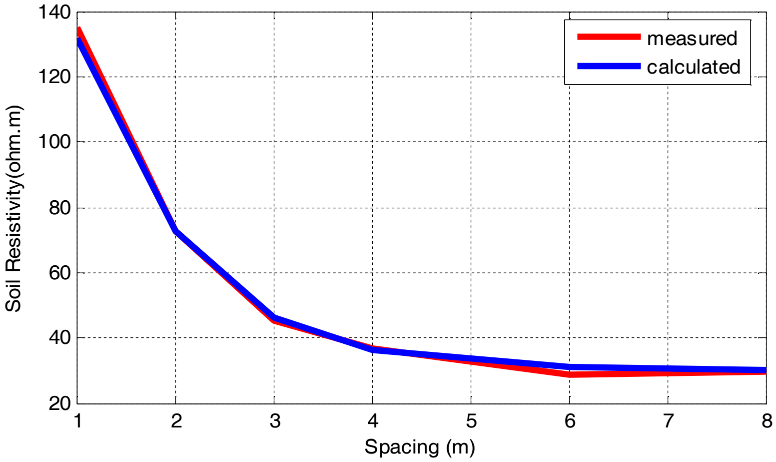

Fig.5. Soil resistively measured and calculated values for site #3

Table 5: Soil resistively measured and calculated values for site #4

Spacing (m)	Resistivity measured values Ω. m	Resistivity calculated values Ω. m	Error (%)
1	150.2938	149.0196	0.8551
2	146.0212	146.7449	-0.4932
4	130.1876	133.1537	-2.2276
6	111.9664	110.7144	1.1308
7	99.8398	98.5370	1.3221
9	78.0372	75.8024	2.9482
10	64.7168	65.9522	-1.8732
11	59.4389	57.2868	3.7567
	Objective function F=0.0034		RMS Error=2.0999%

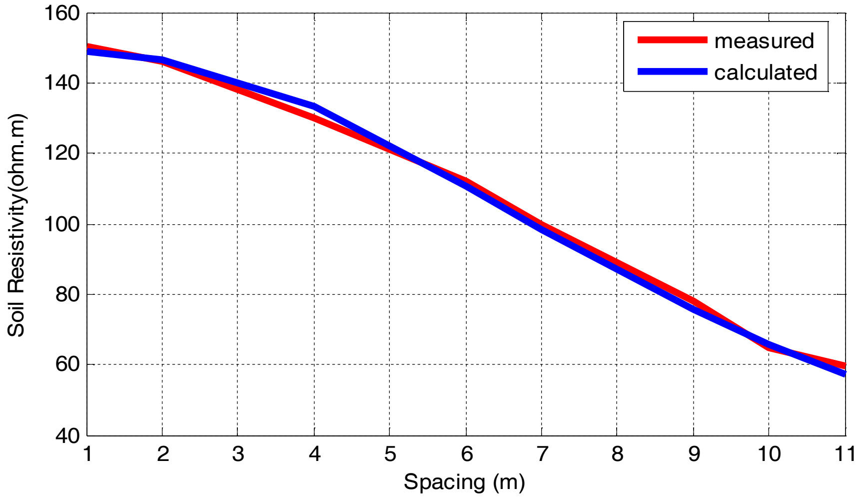

Fig .6. Soil resistively measured and calculated values for site #4

1.4 Formula for Calculating Ground Resistance

One of the important steps in determining the size and basic layout of a grounding system for an ac substation is the estimation of ground resistance of the grounding grid.

1.4.1 One-Layer Soil Model

According to the IEEE std. 80-2000 edition, the Schwarz's equation gives a simple formula for calculating the ground resistance in the uniform soil at a substation. The equations used in calculation of the horizontal electrode (ground grid), vertical electrode (ground rods), and mutual ground electrodes are repeated below [4]:

Schwarz's equation:

$$R_1 = \frac{\rho}{\pi L_C}\left[\ln\left(\frac{2L_C}{\sqrt{dh_g}}\right) + \frac{K_1 L_C}{\sqrt{A_g}} - K_2\right] \tag{8}$$

$$R_2 = \frac{\rho}{2\pi n_r l_r}\left[\ln\left(\frac{4l_r}{a}\right) - 1 + \frac{2K_1 l_r}{\sqrt{A_g}}\left(\sqrt{n_r} - 1\right)^2\right] \tag{9}$$

$$R_m = \frac{\rho}{\pi L_C}\left[\ln\left(\frac{2L_C}{l_r}\right) + \frac{K_1 L_C}{\sqrt{A_g}} - K_2 + 1\right] \tag{10}$$

$$R_{t-one} = \frac{R_1 R_2 - R_m{}^2}{R_1 + R_2 - 2R_m} \tag{11}$$

Where:

R_1 :One-layer soil ground resistance of grid conductors in ohm.

R_2: One-layer soil ground resistance of ground rods in ohm.

R_m: One-layer soil mutual ground resistance between the grid conductors and ground rods in ohm.

R_{t-one}: One-layer soil substation ground resistance in ohm.

ρ: Uniform soil resistivity in ohm.m.

L_C: Total length grid conductors in m.

d: Diameter of grid conductor in m.

h_g: Depth of ground grid conductor in m.

A_g: Total area enclosed by ground grid in m^2

n_r: Quantity of ground rods placed in area.

l_r: Length of ground rod at each location in m.

a: Radius of ground rod in m.

And:

$$K_1 = 1.41 - 0.04\frac{L}{W} \qquad (12)$$

$$K_2 = 5.5 + 0.15\frac{L}{W} \qquad (13)$$

$$\rho = \sum_{i=1}^{n} \frac{\rho_i}{n} \qquad (14)$$

Where:

ρ_i: Measured soil resistivity data in ohm.m .

n: Number of measurements.

L: Length of area occupied by the ground grid in m.

W: Width of area occupied by the ground grid in m.

1.4.2 Two-Layer Model

For grounding system in two-layer soil model with ρ_1 & ρ_2, the reflection factor K and two-layer soil resistivity can be simplified as one-layer apparent soil resistivity as follows:

$$\rho_a = \frac{\rho_1}{\left[1 + \left(\frac{\rho_1}{\rho_2} - 1\right)\left(1 - e^{\frac{1}{K\left(h_r + 2h_g\right)}}\right)\right]} \qquad \text{For } \rho_1 > \rho_2 \qquad (15)$$

$$\rho_a = \frac{\rho_2}{\left[1 + \left(\frac{\rho_2}{\rho_1} - 1\right)\left(1 - e^{\frac{-1}{K\left(h_r + 2h_g\right)}}\right)\right]} \qquad \text{For } \rho_2 > \rho_1 \qquad (16)$$

Where:

ρ_a : Apparent soil resistivity in ohm.m.

ρ_1: Upper-layer soil resistivity in ohm.m.

ρ_2: Lower-layer soil resistivity in ohm.m.

h_r: Depth of the reflection boundary in m.

h_g: Depth of ground grid conductor in m.

To simplify the two-layer soil model with a one-layer structure; the one-layer apparent soil resistivity will depend upon the parameters of the two-layer soil resistivity. The ground resistance after simplification can be calculated using the following equations [4]:

Sverak's equation :

$$R_g = \rho_a\left[\frac{1}{L_C} + \frac{1}{\sqrt{20A_g}}\left[1 + \frac{1}{1 + h_g\sqrt{\frac{20}{A_g}}}\right]\right] \qquad (17)$$

Empirical equation

$$R_g = \rho_a\left[\frac{1}{L_C} + \frac{1}{\sqrt{20A_g}}\left(1 + \frac{1}{1 + h_g\sqrt{\frac{20}{A_g}}}\right)\right] \times 1.52\left[2\ln\left(L_P\sqrt{\frac{2}{A_g}} - 1\right)\right]\frac{\sqrt{A_g}}{L_P} \qquad (18)$$

Where:

$$h_1 < 0.2\sqrt{A_g}$$

$$h_g < h_1$$

$$h_0 = C_f\sqrt{\frac{A_g}{2\pi}}\left[\ln(1-K)\right]\frac{K-1}{2K} \tag{19}$$

$$\Delta\ell = \sqrt{\Delta\ell_X . \Delta\ell_Y}$$

(20)

And:

$\Delta\ell_X$: Single mesh length in X direction in m.

$\Delta\ell_Y$: Single mesh length in Y direction in m.

h_1: Height of the upper earth layer in m.

C_f : Area shape factor.

All necessary data for calculating Ground Resistance are listed in Table 6:

Table 6: Input data

Symbol	**Quantity**	**Values**
A_g	Total area enclosed by ground grid	$200\times200\ m^2$
h_g	Depth of ground grid conductor	$0.5\,m$
ρ_S	Soil resistivity at the surface	$2500\,\Omega.m$
h_S	Thickness of the surface layer	$0.1m$
D	Maximum distance between any two points on the grid	$50\ m$

Symbol	Quantity	Values
I_f	Maximum earth fault current	$40KA$
C_f	Area shape factor	0.9[28]
ρ_1	Upper-layer soil resistivity	$130\Omega.m$ *
ρ_2	Lower-layer soil resistivity	$15.4\Omega.m$ *
ρ	Uniform soil resistivity	$63.7709\Omega.$
h_1	The height of the upper earth layer	$3.3m$ *
h_r	Depth of the reflection boundary	$h_r = h_g$ [22]

1.5 Discussion of Results

Table7:Calculation of ground resistance at ALKOMAS substation using one- and two – layer soil model

A=208.8712 mm^2	Type of Soil Model			
	One-Layer Model	Two-Layer Model		
Parameter	Sverak's	Grid Buried in Upper Layer Soil	One-Layer simplification	
			Sverak's	Empirical
Rg (Ω)	0.1737	0.1022	0.0675	0.0789

- As seen from Table (7) the cross section area of grid conductor is 208.8712 mm^2 then select A=240 mm^2 and the diameter of grid conductor is 17.5 mm.
- The grounding conductor which the copper wire is connecting the system grounding and

equipment grounding to the grounding grid must be having 240×240 mm^2 cross section area.

- Schwarz's equation (11) is used to calculate the grid resistance with rods.
- In the case of one-layer model Sverak's equation (17) is used to calculate the grid resistance without rods with uniform soil resistivity.
  - The reflection factor in the case of one-layer soil model can be calculated from the following equation [2]:

$$K_{one} = \frac{\rho - \rho_S}{\rho + \rho_S} \qquad \textbf{(21)}$$

Where:

ρ **:** Uniform soil resistivity in ohm.m**.**

ρ_S : Soil resistivity at the surface in ohm.m**.**

  - Uniform soil resistivity can be calculated from equation (14).
  - Since the upper–layer soil resistivity at ALKHOMS substation is greater than the lower-layer soil resistivity, it can use equation (15) to calculate the two-layer soil model simplified with the one-layer apparent soil resistivity.
  - For both types of soil models, the ground resistance at ALKHOMS substation are computed as listed in Table (7).

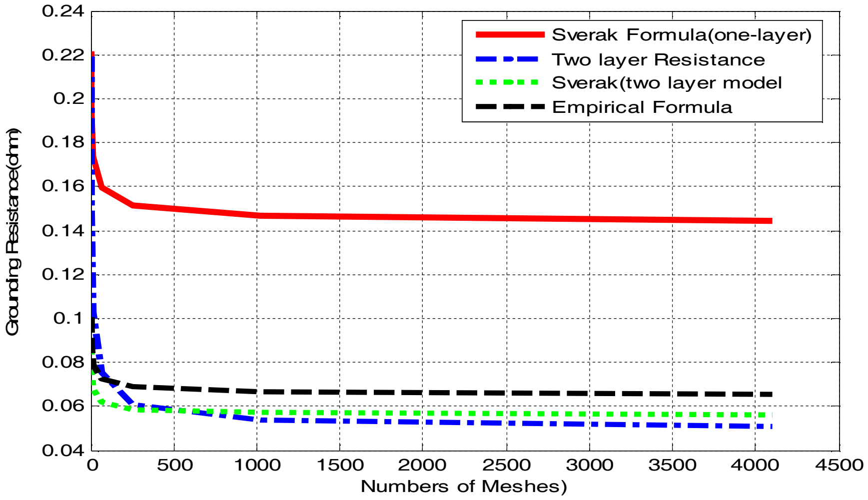

Fig.7.Ground resistance versus the numbers of meshes within the grounding grid

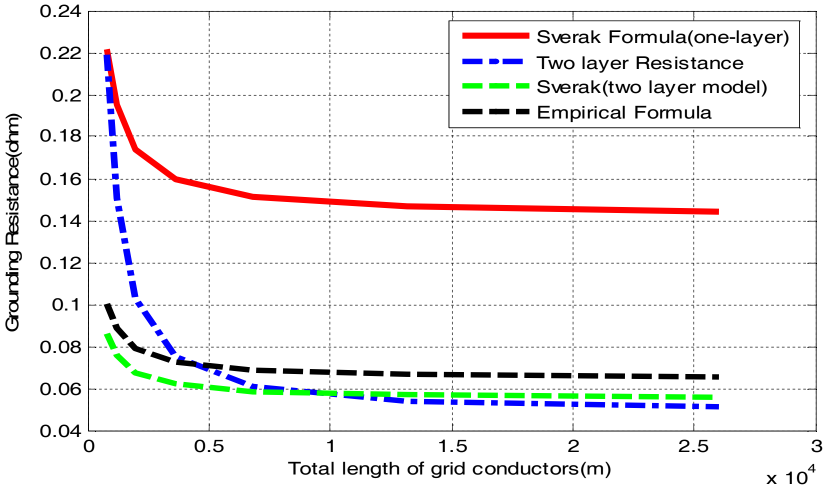

Fig .8.Ground resistance versus the total length of grid conductors

1.6 CONCLUSIONS :

The most accurate representation of a grounding system should be based on the actual variations of soil resistivity present at the substation site. Apparent resistivities obtained in the field tests must be modeled as a uniform soil model or as non-uniform soil model based on the resistivity varies with respect to depth. Finite expressions for Wenner apparent resistivity for two layer soil model have been developed.

Resistance is less than that of the same grounding system in uniform soil with resistivity

References :

[1]. Mohamad Nor, R.Rajab and K.Ramar, Validation of the calculation and measurements techniques of earth resistance values, American journal of applied sciences, 5(10): 1313-1317, 2008.

[2]. Practical Applications of IEEE Standard 80-1986 "Guide for Safety in Ac Substation Grounding "

[3]. H. R Seedher and J.K .Arora , Estimation of two-layer soil parameters using finite Wenner resistivity expression , IEEE Transactions on Power Delivery, Vol.7, No.3, July 1992,PP.1213-1217.

[4]. Cheng-Nan Chang and Chien-Hsing Lee, "Computation of Ground Resistances and Assessment of Ground Grid Safety at 161/23.9 KV Indoor-Type Substation", IEEE Transactions on Power Delivery, Vol.21, No.3, July 2006.