Factors Affecting the Apparent Soil Resistivity of Multi-Layer Soil

O.E. Gouda1, G.M. Amer2 and T.M. EL-Saied2*
1Electric Power and Mach., Faculty of Eng Cairo Univ., Egypt;
2Benha high institute of technology, Egypt
*E-mail: tamer18@hotmail.com

Abstract: The accuracy of power system grounding analysis is critically dependent on the actual resistivity of local surrounding system. In this paper the factors affecting the apparent soil resistivity of multilayer soil are investigated. Such these factors are:-
(1) The number of layers of soil structure (double and three layers are considered in this paper) and their arrangement.
(2) The thickness of each layer.
(3) The reflection factor between each layer.
The studies are done for different types of soil such as clay, sand and rocks, different formulas are used. An experimental model is used in the laboratory to study experimentally the effect of the above factors on apparent soil resistivity. A scaling factor is used into consideration due to the differences between model measurements. These differences are:-
(i- The layers thickness.
ii- The distances between the electrodes used in testing.
iii- The compactness between soil grains in the field is more than that in the laboratory.
The obtained experimental result are compared with the calculated values and also with the results obtained by the others.

Key Words: Soil resistivity; Apparent soil resistivity; Multilayer; Reflection factor

INTRODUCTION
To design the most economical grounding systems for large substations it is necessary to obtain accurate value of the resistivity on the site. The soil at the most sites is non-uniform. Different methods are used to compute the apparent resistivity of multi-layer soil structure and compared to actual measurement[1-4]. IEEE suggested formula to calculate the apparent soil resistivity seen by the earthing system, in case of there are two layer soil environment with upper layer thickness H, in which ground rods penetrate the more conductive lower layer, that is for \( \rho_1 > \rho_2 \) and the grid is buried in the upper layer \( \rho_1 \), but the ground rods are partly in \( \rho_2 \) and partly in \( \rho_1 \) the apparent soil resistivity \( \rho_a \) could be calculated by the relation[1]

\[
\rho_a = \frac{I_2(\rho_2,\rho_1)}{(\rho_2(H-h) + \rho_1(l_2 + h - H))} \tag{1}
\]

Where \( l_2 \) is the average value of rod length, \( \rho_1 \) and \( \rho_2 \) are the soil resistivity of upper and lower layers and H is the thickness of upper layer. According to IEEE[1-5] the ground resistance of rods and the mutual resistance between the grid and rods are calculated with the use of an apparent soil resistivity. Fig(1,2) shows the relation between the upper layer thickness and the apparent soil resistivity, rods resistance (R2) , mutual resistance (R12) between the grid and rods and the grounding system resistance (Rtotal).

From this figure it is noticed that increasing the upper
layer thickness from 1 to 7 meter increases the apparent soil resistivity, rods resistance, mutual resistance between the rods and connecting grid and the grounding system resistance in case of $\rho_1 > \rho_2$ by 90%.

In case of $\rho_1 < \rho_2$ increasing the upper layer thickness from 1 to 7 meter reduces the apparent soil resistivity, rods resistance, mutual resistance between the rods and connecting grid and the grounding system resistance in case of $\rho_1 > \rho_2$ by 60%.

To investigate the effect of the reflection factor on the apparent soil resistivity, rods resistance, mutual resistance and grounding system resistance, the value of $p_1/p_2$ is changed between 5 and 0.2 and the reflection factor $k$ is calculated according to relation

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

(2)

Fig. (3) shows the relation between the reflection factor and the apparent soil resistivity, rods resistance, mutual resistance between the grid and rods, also the ground resistance seen by the grounding system, these values are calculated according to IEEE(7).

$$R_1 = \left( \frac{\rho_1}{\pi l_1} \right) \left( \ln \left( \frac{2l_1}{h} \right) + k_1 \left( \frac{l_1}{\sqrt{A}} \right) - k_2 \right)$$

(3)

$$R_2 = \left( \frac{\rho_2}{2n \pi l_2} \right) \left( \ln \left( \frac{8l_2}{d_2} \right) \right) - 1 + 2k_1 \left( \frac{l_1}{\sqrt{A}} \right) \left( \sqrt{n} - 1 \right)$$

(4)

$$R_{12} = \left( \frac{\rho_2}{\pi l_1} \right) \left( \ln \left( \frac{2l_1}{l_2} \right) + k_1 \left( \frac{l_1}{\sqrt{A}} \right) - k_2 + 1 \right)$$

(5)

$$R_g = \frac{R_1 R_2 - R_{12}^2}{R_1 + R_2 - 2R_{12}}$$

(6)

Where $R_1$ and $R_2$ are resistance of all ground rods and grid conductors respectively and $R_{12}$ is the mutual resistance between the group of grid conductors and group of ground rods, $n$=number of ground rods placed in parallel in area A, $d_2$ is the diameter of the driven rods in meter, $A$= area covered by the rods in m², $K_1, K_2$ are constants related to the geometry of the system and could be calculated from the relations where $X$ is length to width ratio

$$K_1 = 1.41 - (0.04) X$$

(7)

$$K_2 = 5.5 + (0.15) X$$

(8)

From this figure it is noticed that increasing the reflection factor from -0.7 to 0.7 increases the apparent soil resistivity, rods resistance, mutual resistance between the rods and connecting grid and the grounding system resistance by 500%.

To study the effect of depth of laying of grid on the ground to apparent soil resistivity, mutual resistance and rods resistance. The laying depth of the grid is changed between 0 and 1.5 m. Fig. (4) shows the relation between the ground resistance, apparent soil resistivity, the mutual resistance and rods resistance and the laying depth of the grid.

$$R_g = \frac{R_1 R_2 - R_{12}^2}{R_1 + R_2 - 2R_{12}}$$

(9)

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From this figure it is noticed that increasing the depth of laying grid slightly changes rod resistance and mutual resistance but it makes enormous reduction to the total resistance of ground system 64% (from 0.196 Ω to 0.069 Ω) and also reduces the apparent soil resistivity seen by the grounding system by 7%

II. Multi-layer Case

In the analysis carried out in this paper any number of layers could be reduced to two layers. As example in 3-layers, two layers will be reduced to one layer as follows:
Evaluating initial apparent soil resistivity between first and second layer represented by \( \rho_{12} \) could be calculated by the relation [8-11]

\[
\rho_{12} = 2(\rho_2 - (\rho_2 - \rho_1)e^{-j\delta}) - (\rho_2 - (\rho_2 - \rho_1)e^{-2j\delta})
\]  

(9)

Where \( J = \frac{\delta}{2H} \), \( \delta = \frac{\ln(\rho_1/\rho_2) - \ln(0.0176)}{3.5} \)

\( \rho_1 \) and \( \rho_2 \) are the resistivity of first and second layer respectively, \( s \) is the space between probe electrodes of measuring the soil resistivity and \( H \) is thickness of first layer.

From the experimental work done by the authors it is found that the best space between electrodes is between 10m to 15m as given in Fig.(5)

![Fig.(5) Soil resistivity of three layer soil](image)

To obtain the apparent soil resistivity of the three layers consider \( \rho_{12} \) is resistivity of one layer and then obtain the total apparent soil resistivity

\[
\rho_a = l_2(\rho_{12} - \rho_1)/(\rho_1(H' - h) + \rho_{12}(l_2 + h - H'))
\]  

(10)

Where \( H' \) is the thickness of first and second layers. The relation between the reflection factors and apparent soil resistivity, grid resistance, mutual resistance and rods resistance is given in Fig.(6). The reflection factor is defined in this case as

\[
K' = \frac{\rho_1 - \rho_{12}}{\rho_1 + \rho_{12}}
\]  

(11)

![Fig.(6) Relation between reflection factor and the apparent soil resistivity, rods resistance, mutual resistance and the grounding system resistance](image)

From this figure it is noticed that there are proportional relation between reflection factor and the apparent soil resistivity, rods resistance, mutual resistance between the grid and rods and the grounding system.

Changing the reflection factor from -0.7 to 0 increase the apparent soil resistivity by 300% and changing the reflection factor from 0 to 0.7 increase the apparent soil resistivity by 200%

Similar relation is obtained between grid depth in first layer and apparent soil resistivity, grid resistance, mutual resistance and rods resistance, Fig.(7) shows this relation

![Fig.(7) Relation between depth of laying of grid and R2, R12, Rtotal and pa (\( \rho_1=60, \rho_2=50, \rho_3=10 \) to 250 Ω.m, \( H=2, H'=4 \))](image)

From this figure it is noticed that increasing the depth of laying grid slightly changes rod resistance and mutual resistance but it makes enormous reduction to the total
resistance of ground system 64% (from 0.228 Ω to .083 Ω) and also reduces the apparent soil resistivity seen by the grounding system by 3%

CONCLUSIONS
(1) There are proportional relation between apparent soil resistivity and upper layer thickness in case of $\rho_1 > \rho_2$ and the relation become inverse proportional in case of $\rho_1 < \rho_2$.

(2) Increasing the depth of buried grid reduces the total ground system resistance by 64% and slightly affect the apparent resistance.

(3) Change in reflection factor affects the apparent soil resistivity especially when it changes from negative to positive value for 3 layer soil.

(4) Apparent soil calculated and measured are very close to each other.

REFERENCES