Grounding Resistivity Measurements Analysis of Sloped-Layered Soil

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How to correctly obtain the structure parameters of soil is the precondition of grounding system design to guarantee the safe operation of power systems. An efficient method for estimating soil structure from the test data by Wenner method is presented. The soil is supposed to be extended to two-layer structure with a sloped top layer. Numerical results are computed by the current source simulation method and the method of images. Curves representing measurement error are presented for different sloped angle of the top layer.

Keywords surface potential, step voltage, ground resistance, scale model, grounding grids

Introduction

The soil model and its parameters should be determined first in the simulation and the design of power system grounding grids, which are interconnected conductor bars buried under the power systems substations, stations transmission lines, etc. Usually, the soil structure is complex, since the resistivity of the soil varies horizontally and vertically. However, in order to achieve the numerical simulation of the grounding grids it is usually assumed that the earth is a horizontally stratified multi-layer model and in each layer the resistivity is a constant. However, the horizontal two-layer model is not able to reflect the property of the earth structure in some practical situation. Therefore, it is necessary to employ sloped two-layer models to face horizontal and the vertical variation of soil resistivity.

The grounding resistance is an important index of grounding systems for substations and power plants, and is also a parameter to measure the efficiency, safety of grounding systems, and to check whether the grounding systems meet the demand of design. Due to the nonuniformity of soil and measuring error of soil resistivity data and some other factors, which cannot be considered in simulating analysis, the designed value of grounding resistance must be checked by the field test after the grounding system is constructed [2], [3]. On the other hand, in order to examine the actual condition of the grounding system of an operating substation, the grounding resistance must be measured periodically. The measurement of the grounding resistance is routine work to ensure the safe operation of power systems in China [4].

How to simply and precisely measure the grounding impedance of a grounding system is an important problem in power systems [4], [5].

1. Wenner's Measurements Method

Fig. 1 shows the configuration of Wenner's four-probe measurement system [1]. In the system four probes are located in a straight line with an equal distance of . Half-spherical conductors can be employed as the probes which are buried in the earth and the end-surface of the half-sphere is on the earth surface. The outer pair of the probes are current electrodes from one of which a current is injected into the earth and collected from the other. The inner pair of probes are voltage ones to measure the earth potential rise or the voltage of the two points due to the current. By taking a fixed value of the injected current and different values of , a set of voltages can be obtained. The greater the values of , the deeper the current goes into the earth. Therefore, the structure and the parameters of the earth model can be inferred from the relationship between the current and the voltage with different probe distances. The determination of the structure and the parameters of the media from known exciting current sources and the potential distribution is just the solution of the electric field inverse problem.

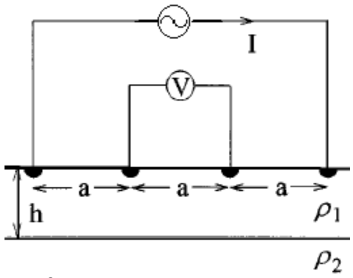


Fig. 1. Wenner's four-probe test system for a three-layer earth model.

2. Two layer apparent resistivity

A two layer soil model can be represented by an upper layer soil of a finite depth above a two layer of infinite depth. The abrupt change in resistivity at the boundaries of each soil layer can be described by means of a reflection factor. A resisitivity determination using the Wenner-method in two-layer soil result in an apparent resisitivity which is a function of the electrode separation, a in terms of the above parameters the apparent resistivity (ρ_a):

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

Where h : first layer;

ρ_1 : first layer resistivity Ω.m

ρ_2 : first layer resistivity Ω.m

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

3. Analytical Method

The analytical method used to calculate the surface potential profile and grounding resistance is based on division of grid conductors driven into the ground into a large number N of spheres. This replacement was adopted before [4,5], where the electric and magnetic fields created by the grid cylindrical conductors are replaced with the effect of equivalent spheres. For example, the electric field flux lines emanate from the outer portion of the expose surfaces of the spheres (away from the contact points) which is close to the cylindrical surface of the grid conductor. The grounding system is considered as equipotential surface [5-11] so that if each sphere diffuses a current I_j, the relationship between the voltage and current can be written as

$$\begin{bmatrix} V_1 \\ .. \\ V_2 \\ .. \\ V_3 \\ .. \\ V_4 \\ .. \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & \dots & \dots & R_{1N} \\ R_{21} & R_{22} & \dots & \dots & R_{2N} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ R_{N1} & R_{N2} & \dots & \dots & R_{NN} \end{bmatrix} \begin{bmatrix} I_{11} \\ .. \\ 0 \\ .. \\ 0 \\ .. \\ I_{41} \\ .. \end{bmatrix} \quad (1)$$

where I_i is the current of the ith sphere (i= 1, 2,…..,N) ,V_i is the voltage of the ith sphere, R_{mn} is the mutual resistance element, i.e. mutual resistance between sphere number m and sphere number n , R_{nn} is the self resistance of the nth sphere. For conducting (equipotential) surface $V_1 = V_2 = \ldots = V$, the voltage applied to the grid.

The elements of the resistance matrix are calculated [11-13] as equal to:

$$R_{mn} = \frac{\rho}{4\pi r_{mn}} \quad (2)$$

$$R_{nn} = \frac{\rho}{4\pi a} \quad (3)$$

Where r_{mn} is the distance between centers of m^{th} and n^{th} spheres and a is the radius of each sphere, which is the radius of the grid conductors**.** ρ is the resistivity of ground (water).

To account for the effect water surface, images of spheres are considered. If the spheres are at depth D under soil surface, they will have images at vertical distance D above the soil surface. Each image carries the same current as the original sphere, so the self and mutual resistances are expressed as :

$$R_{nn} = \frac{\rho}{4\pi}\left(\frac{1}{a} + \frac{1}{2D}\right) \quad (4)$$

$$R_{mn} = \frac{\rho}{4\pi}\left(\frac{1}{r_{mn}} + \frac{1}{r_{mn1}}\right) \quad (5)$$

Where, r_{mn1} is the distance between the mth and the image of the nth. The second term in equations (4) and (5) expresses the image effect.

$$\begin{bmatrix} I_{11} \\ .. \\ 0 \\ .. \\ 0 \\ .. \\ I_{41} \\ .. \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \dots & \dots & G_{1N} \\ G_{21} & G_{22} & \dots & \dots & G_{2N} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ G_{N1} & G_{N2} & \dots & \dots & G_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ .. \\ V_2 \\ .. \\ V_3 \\ .. \\ V_4 \\ .. \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} I \\ 0 \\ 0 \\ -I \end{bmatrix} = \begin{bmatrix} G^{\backslash}_{11} & G^{\backslash}_{12} & G^{\backslash}_{13} & G^{\backslash}_{14} \\ G^{\backslash}_{21} & G^{\backslash}_{22} & G^{\backslash}_{23} & G^{\backslash}_{24} \\ G^{\backslash}_{31} & G^{\backslash}_{32} & G^{\backslash}_{33} & G^{\backslash}_{34} \\ G^{\backslash}_{41} & G^{\backslash}_{42} & G^{\backslash}_{43} & G^{\backslash}_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \quad (3)$$

where $G^{\backslash}_{nm} = \sum_{i=n+n_b^{n-1},}^{n+n_b^{n}} \sum_{j=m+n_b^{m-1}}^{m+n_b^{m}} G_{ij}$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} R^{\backslash}_{11} & R^{\backslash}_{12} & R^{\backslash}_{13} & R^{\backslash}_{14} \\ R^{\backslash}_{21} & R^{\backslash}_{22} & R^{\backslash}_{23} & R^{\backslash}_{24} \\ R^{\backslash}_{31} & R^{\backslash}_{32} & R^{\backslash}_{33} & R^{\backslash}_{34} \\ R^{\backslash}_{41} & R^{\backslash}_{42} & R^{\backslash}_{43} & R^{\backslash}_{44} \end{bmatrix} \begin{bmatrix} I \\ 0 \\ 0 \\ -I \end{bmatrix} \quad (4)$$

As the resistance elements are known, the sphere currents can be calculated by the inversion of equation (1). Then, the resistance of the grounding is

$$Rg = \frac{V_2 - V_3}{I} \quad (6)$$

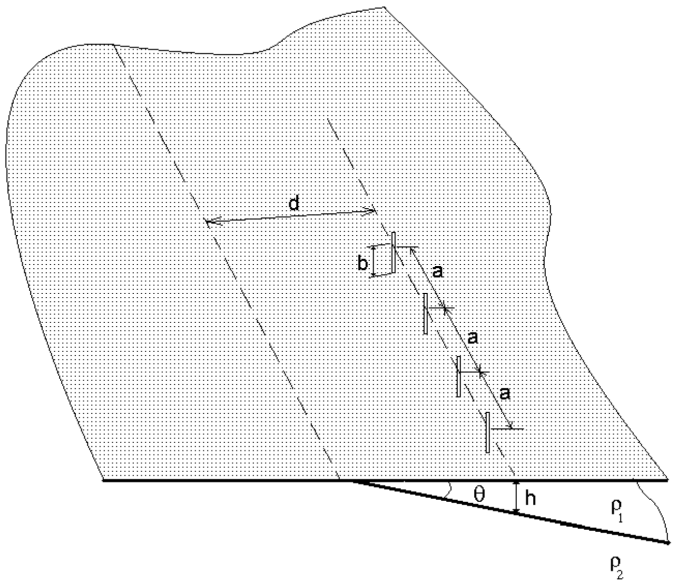


Fig. Measurement of the ground resistivity by using four probe method in sloped top layer ground

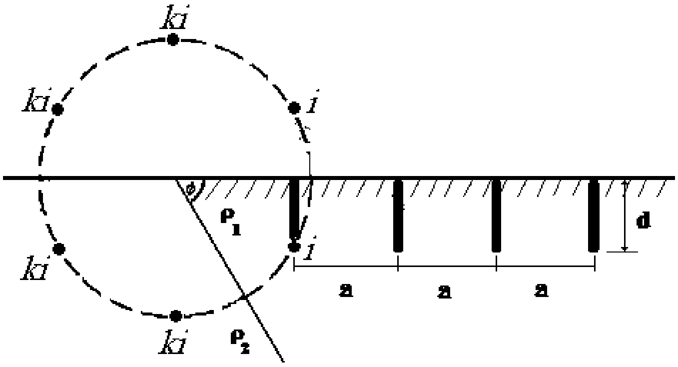


Fig. 2. Images of spherical elements for four electrodes in sloped top layer

Table 1 Studied cases

Case 1

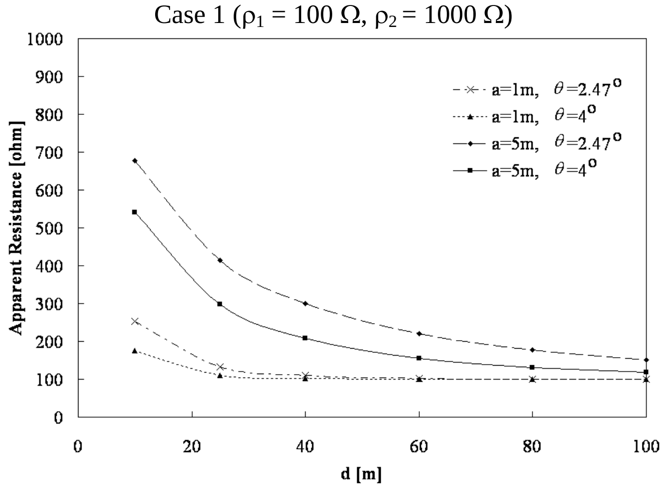
$\rho_1(\Omega.m)$	1000	$\rho_2(\Omega.m)$	100

Case 2

$\rho_1(\Omega.m)$	100	$\rho_2(\Omega.m)$	1000

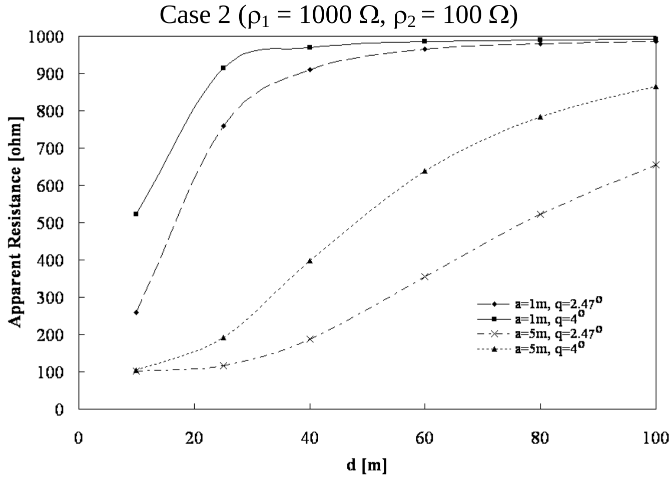
4. Results

Case 1 (ρ_1 = 100 Ω, ρ_2 = 1000 Ω)



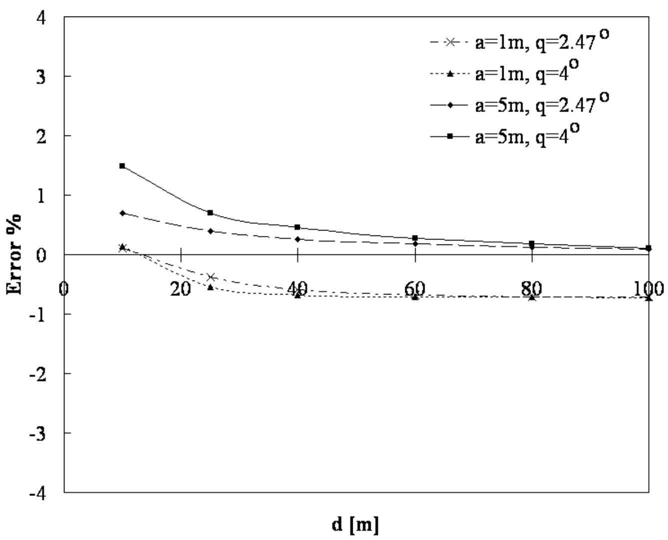
(a)

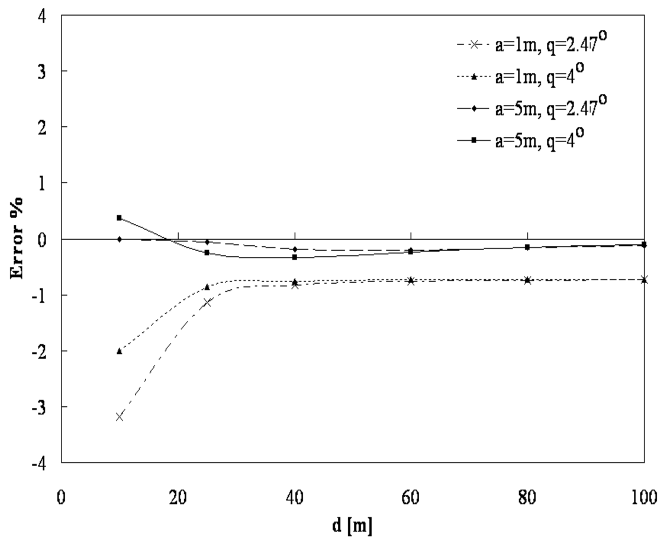
Case 2 (ρ_1 = 1000 Ω, ρ_2 = 100 Ω)



(b)

Apparent resistivity vs. distance from the intersection





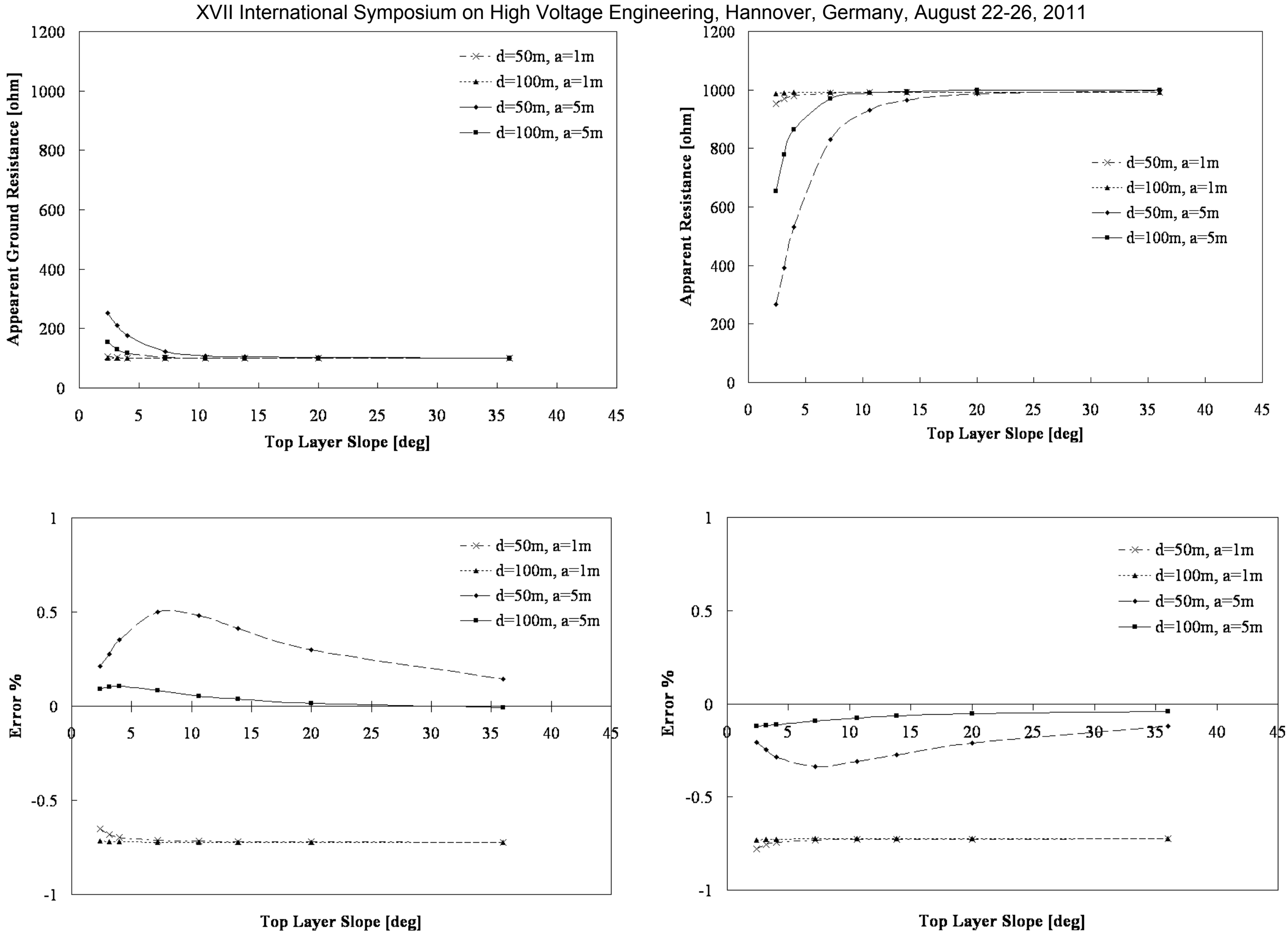


Fig. 4 Case 1– Error % of apparent resistivity vs. top layer slope

5. Discussion

6. Conclusions

From the present study, one can conclude the following:

References

[1] IEEE Guide for Safety in AC Substation Grounding, ANSI/IEEE Std.80, 2000.

[2] H. G. Sarmiento, R. J. Fortin, and D. Mukhekar, "Substation ground impedance: Comparative field measurements with high and low current injection methods," *IEEE Trans. Power App. Syst.*, vol. PAS-103, pp.1677–1683, July 1984.

[3] H. G. Sarmiento and R. Velazquez, "Survey of low ground electrode impedance measurements," *IEEE Trans. Power App. Syst.*, vol. PAS-102, pp. 2842–2849, Sept. 1983.

[4] "Grounding for AC Electrical Installations," China Electrical Power Industry Ministry, Beijing, China, DL/T621-1997, 1997.

[5] F. P. Dawalibi and D. Mukhedkar, "Resistance measurement of large grounding systems," *IEEE Trans. Power App. Syst.*, vol. PAS-98, pp. 2348–2354, June 1979.

[6] Hans R. Seedher, J. K. Arora," Estimation of two layer using finite wenner resistivity expressions", IEEE Trans. on Power Delivery, vol. 7, no. 3, pp. 1213-1217, July 1992.