RESEARCH ARTICLE OPEN ACCESS

Soil Resistivity Measurement and Interpretation Technique

Dr. Mahadev Unde*, Vishal Tathe**
Department of Electrical Engineering, Zeal College of Engineering & Research, Pune
Corresponding Author: Dr. Mahadev Unde

ABSTRACT
Soil resistivity is one of the important key parameters which affects the performance of substation grounding system. It is a function of depth. The substation grounding performance parameters like ground resistance, ground potential rise (GPR), touch and step voltages, all are dependent on soil resistivity. Therefore, soil resistivity measurement is very essential at the site of all generating stations and large substations to develop suitable soil model which is like actual one. In this paper, various soil resistivity measurement techniques are discussed. Experimentation has been carried out for measurement of soil resistivity. Further, it modelled for various soil layer using various techniques. Modelling of soil structure makes the substation grounding cost effective by means of optimizing length of ground rods. It also enhances the safety of the substation operators and equipments.

Keywords **-**Soil model, Soil resistivity, Grounding, Ground rod, Wenner method.

Date of Submission: 28-04-2020 Date of Acceptance: 11-05-2020

I. INTRODUCTION

Electrical conduction in soils is essentially electrolytic. The surface soil layer consists of clay mixed sand and often mixed with decayed vegetable matter also. When dry this soil may not conduct much electricity. However, in the presence of moisture, ionic conduction takes place according to the type of slots present in the water contained soil [1]. Soil resistivity is dependent on physical and chemical composition of soil, grain size, soil compactness, porosity, moisture content and temperature. Resistivity of soil can vary within extremely wide limits, between 1 Ω m and 100,000 Ω m. It depends on type and nature of the soil [2-4].

The grounding performance parameters like ground resistance, GPR, touch and step voltages, all are dependent on soil resistivity. Therefore, soil resistivity measurement is very essential at the site of all generating stations and large substations to develop suitable soil model which is like actual one [5]. The most popularly used method is equally spaced four probe Wenner's method. It is necessary that the measurements are made by increasing probe spacing geometrically from small values up to about extent of substation grounding grid. The measurement should carry out at various profiles so that it covers entire substation area [6,7].

The shallow depth soil resistivity is a concern of surface potential whereas the deep level resistivity is a function of grounding grid resistance. It is necessary to plot the graph of soil resistivity against the inter electrode spacings. By visual inspection, the rough estimate of number of layers, their resistivities along with layer depth is possible. However, computer with software simulation should be used to obtain the desired accurate soil model which is close to actual true soil resistivity data [8 ,9]. Soil resistivity varies horizontally as well vertically. It varies region to region and within the same substation. Soil resistivity also changes season to season. During dry season, it increases whereas it decreases during rainy season. In mountain and hilly areas, during winter due to ice fall, moisture in the soil freezes and soil resistivity increases dramatically high. Therefore, substation grounding grid designed in one season which is safe, may become unsafe in another season [10].

Based on soil resistivity measured data, soil models have been obtained. The result revels that for a given data four-layer soil model is the most suitable. The safe and cost-effective substation grounding is possible if the ground rods reaches the low soil resistivity third layer. The paper is organized as follows. The introduction followed by methodology is given in section II where the soil resistivity measurement methods are elaborated. The soil resistivity measurement has been depicted in III whereas soil modelling has derived in section IV. The concluding remarks are drawn in section V.

II. METHODOLOGY

Soil resistivity is one of the important key parameter which affects the performance of grounding system. Many tables on soil resistivity are available in the literature which shows the range of resistivity for various types of soils and rocks. But it yields rough information on resistivity. Further, resistivity of soil changes geographically from one region to other. Therefore, actual measurement of soil resistivity is imperative. It is very essential to know the soil resistivity at substation site for good estimation of soil structure and hence the design of substation grounding [11].

2.1 WENNER METHOD

Dr. Wenner's equally spaced four electrode/probe method is most popularly used for soil resistivity measurement. The four probes must be inserted at equal distances along the straight line known as profile. The arrangement is as shown in figure 1. The battery-operated meter circulates the current I between the outer probes C_1 and C_2. The current (I) is injected into ground through probe C_1 and it is collected at probe C_2. The potential generated is measured between inner probes P_1 and P_2 . The earth tester directly reads the ratio of V and I that is resistance R and not the resistivity. The outer electrodes C_1 and C_2 are known as current electrodes whereas the inner two electrodes P_1 and P_2 are designated as potential electrodes [12].

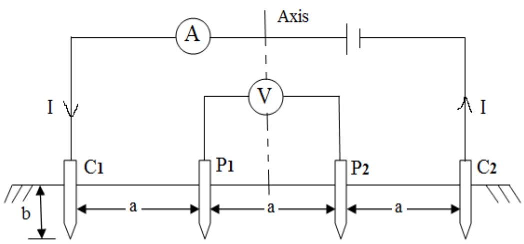

Figure 1. Equally spaced four probe Wenner method

If the probe spacing is 'a' and depth of probe in the earth / ground is 'b' as shown in figure 1, then the apparent soil resistivity is given by

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \tag{1}$$

However, the depth of installation of electrodes / probes is very small as compare to their separation. It should not exceed 0.1 a. Then, the user can assume b=0 and equation (1) will become

$$\rho_a = 2\,\pi\,a\,R \tag{2}$$

It is necessary to take the number of readings at exponentially increasing probe spacings from a small value to up to the extent of the grid electrode. To speed up the measurement process, put the potential probes at half the desired probe spacing and current probes at 1.5 times the probe spacing away from reference center axis. The method gives the information of soil resistivity at a depth equal to probe spacings.

2.1.1 Interpretation

The current tends to flow near the surface of earth for the small probe spacing, whereas more of the current penetrates deeper soils for large spacing. Since, grid is generally buried near to the surface of the soil, few readings are important at a small probe spacings. Further, for effective use of ground rods, the knowledge of deeper soil resistivity is important [13]. The soil resistivity should be measured along number of profiles at different locations, so that whole substation area is covered. The measurement should be carried out at exponentially increasing probe spacings. The question may come in once mind that how many readings are sufficient and to what extent must be the probe spacings? Answer to this question is very simple ie there must be at least two profiles at one location. Typically, if the extent of substation is say 240 -300 m, then the probe spacing may be 0.5 m, 1 m, 2 m, 3 m, 5 m, 7 m, 10 m, 20 m, 30 m, 50 m, 70 m, 100 m, 200 m, 300 m and may be up to 500 m.

While hammering the probes into hilly area, it's contact with soil may become loose. To have a firm contact it is advised to pour 100- 200 ml of water around the probes. If the probe spacings becomes more than 100 m, the current probes can be replaced by multiple probes to reduce probe earth contact resistance. If two probes are used, they may be inserted one meter apart & short circuited by thick copper wire. They can also be arranged in triangular position one meter apart.

According to principle of reciprocity theorem, the user can exchange current and potential electrode positions as shown in figure 2. When the potential electrodes are moved outside and current electrodes inside; the measured result will not be altered [14].

The test wires should be insulated and should not have joints. There should be firm contact to test probes and terminals of the earth tester. As far as possible, wires from potential terminal may not run parallel to the current terminal wires. Otherwise, meter will read additional resistance known as mutual resistance.

A set of readings taken at different profiles can be gathered together to find the arithmetic average of resistivity at the same probe spacings. When the apparent resistivity plotted against probe spacings yields valuable rough information like different soil layers, thickness of layers and resistivities.

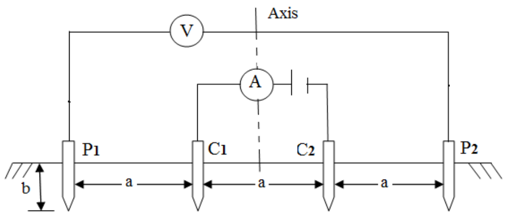

Figure 2. Interchanging current and potential probes, Wenner method

2.1.3. Derivation

If current probes are hemispherical then, the potential at any arbitrary point (x), from current source is given by

$$V_{(x)} = \frac{\rho I}{2\pi x} \tag{3}$$

Since, the size of current electrode is much smaller as compared to inter electrode spacing, the current distribution in the ground may be considered as a radial. During soil resistivity measurement, the current discharged into earth from electrode C_1 is I and that collected at electrode C_2 is –I. As a result, the voltage is induced at electrodes P_1 and P_2. Referring the figure 2, the potential generated at electrode P_1 is given by

$$V_1 = \frac{\rho I}{2\pi}\left(\frac{1}{a} - \frac{1}{2a}\right) \tag{4}$$

Similarly, the potential at electrode P_2 is

$$V_2 = \frac{\rho I}{2\pi}\left(\frac{1}{2a} - \frac{1}{a}\right) \tag{5}$$

Then, potential difference between P_1 and P_2 is given by

$$V_{12} = \frac{\rho I}{2\pi}\left(\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right) \tag{6}$$

$$V_{12} = \frac{\rho I}{2\pi}\left(\frac{1}{a}\right) \tag{7}$$

Where, V_{12} =Potential difference between electrodes P_1 andP_2.

$$\frac{V_{12}}{I} = R = \frac{\rho}{2\,\pi\,a} \tag{8}$$

$$\rho_a = 2\,\pi\,a\,R \tag{9}$$

Where, $\rho = \rho_a$ is the apparent resistivity. It is an average weighted resistivity at a depth equal to electrode spacing ‘a’.

2.2 Schlumberger- Palmer Method

One of the drawbacks of Wenner method is; while measuring the soil resistivity at large spacing, the voltage between potential probes decreases very rapidly and instruments are unable to measure such low voltage. Therefore, to measure the apparent soil resistivity at large spacing / depth, the unequal spacing four probes Schlumberger - Palmer method is recommended.

In this method, the potential probes are placed close together, and current probes are placed farther apart as shown in figure 3. The Wenner method requires all four probes to be reinstalled for each soil resistivity measurement whereas; Schlumberger- Palmer method requires only the outer probes to be reinstalled for measurements [15]. If the depth of burial of probes is small, as compare to their spacing a and c, and $a > 2c$, then apparent soil resistivity is given by

$$\rho_a = \pi R a[a + c]/c \tag{10}$$

Equation (10) indicates the soil resistivity at the approximate depth of (2a+c) / 2 which is the distance of current probe from centre axis.

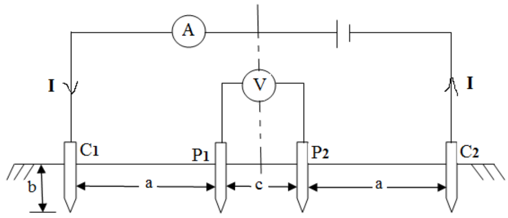

Figure 3. Unequally spaced Schlumberger-Palmer method

2.2.1 Derivation

If the current probes are hemispherical,
The potential at probe P_1

$$V_1 = \frac{\rho I}{2\pi}\left(\frac{1}{a} - \frac{1}{a + c}\right) \tag{11}$$

Similarly, the potential at electrode P_2 is

$$V_2 = \frac{\rho I}{2\pi}\left(\frac{1}{a + c} - \frac{1}{a}\right) \tag{12}$$

Then, potential difference between P_1 and P_2 is given by

$$V_{12} = \frac{\rho I}{2\pi}\left(\frac{1}{a} - \frac{1}{a + c} - \frac{1}{a + c} + \frac{1}{a}\right) \tag{13}$$

Where, V_{12} =Potential difference between electrodes P_1 and P_2.

$$\frac{V_{12}}{I} = R = \frac{\rho}{\pi}\left(\frac{c}{a[a+c]}\right) \tag{14}$$

$$\rho_a = \pi R a[a + c]/c \tag{15}$$

III. Experimentation

The soil resistivity has been measured by using Wenner’s four probe method at Ahmednagar near MIDC and results are listed in table 1. The apparent soil resistivity Vs probe spacing curve has depicted in figure 4. For the uniform soil model analysis, the average soil resistivity ρ_a=156.12 Ω m. Based on this resistivity, grid resistance, touch and step voltages are calculated using IEEE STD 80 - 2013 empirical formulae

Table 1: Soil resistivity measured data using Wenner method

Sr. No	Probe spacing 'a'(m)	Probe depth 'b'(m)	Resistance 'R' (Ω)	Resistivity 'ρ' (Ω-m)
1	0.30	0.10	140	263.76
2	0.60	0.10	37	139.47
3	1.0	0.10	22	138.16
4	2.0	0.10	12	150.72
5	3.0	0.15	7.46	140.54
6	4.0	0.15	6.0	150.72
7	5.0	0.15	5.0	157.0
8	7.5	0.15	4.0	188.5
9	10	0.15	3.0	188.5
10	12.5	0.20	2.0	157
11	15	0.20	1.29	121.52
12	17.5	0.20	1.0	109.95[av1 56.12]

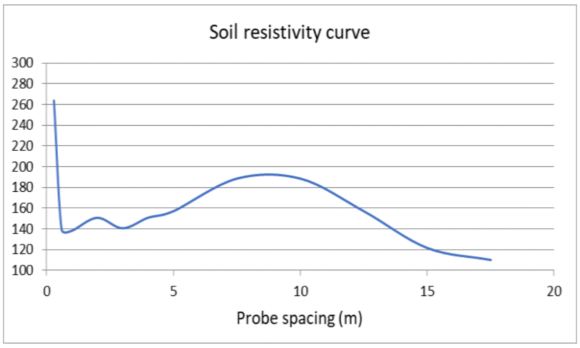

Figure 4. Variation of apparent soil resistivity with probe spacing

IV. SOIL MODEL

After successfully conducting the test for soil resistivity measurement at the various profiles in the substations, it is necessary to determine the arithmetic average resistivity corresponds to each probe spacings. Thus, a table is to be prepared showing probe spacing 'a' and average measured apparent soil resistivity. The graph of average apparent soil resistivity against probe spacing (ρ-a curve) gives us a visual aid to find the number of soil layers. The number of soil layers equal to number of points at which the slope of apparent soil resistivity curve changes greatly. The numbers of graphical and numerical methods are available in the literature to determine the soil models.

4.1 Multilayer Soil Model

A typical multilayer soil model is as shown in figure 5. The numbers of numerical methods for the analysis of multilayer soil model suggested by different authors are available in the literature as per the methodology used. The method includes least square method, using Greens function based on Bessel's function of first kind, Gauss Newton's method, Simpsons rule, Fredholm's equation. Zhang et al. presented the multilayer soil structure analysis by using complex image method.
The $\rho - a$ curve that obtained from the actual soil resistivity measurement data reflects the distinct number of layers. The predefined standard curves based on calculated apparent soil resistivity of different soil structures having number of layers are stored in the computer. Then actual number of layers can be determined by comparing he measured data with standard curves. For example, figure 6 indicate the different kinds of curves for three-layer soil model.

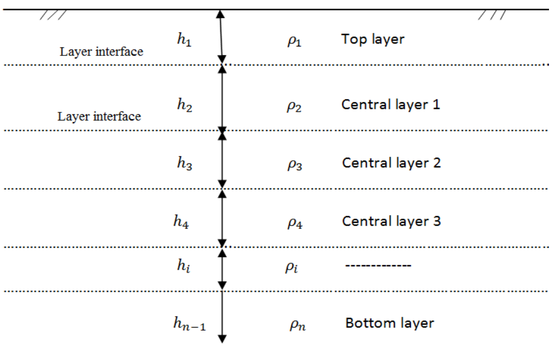

Figure 5. Typical multilayer soil model

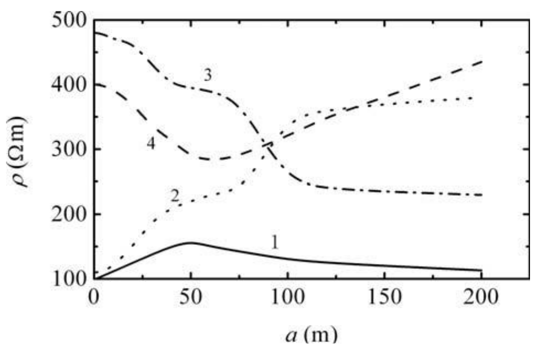

Fig 6. Typical three-layer soil resistivity curves (16)

The characteristics of three-layer curves can be distinguished as follows.
Curve 1: Initially increases, reaches to maximum and then decreases $K_1 > 0, K_2 < 0$
Curve 2: Increases continuously with probe spacing $K_1 > 0, K_2 > 0$
Curve 3: Decreases continuously with probe spacing $K_1 < 0, K_2 < 0$

Curve 4: Initially decreases, reaches to minimum and then increases $K_1 < 0, K_2 > 0$
Where,

$$K_1 = (\rho_2 - \rho_1)/(\rho_2 + \rho_1) \quad (16)$$

Where,
$\rho_1 =$ resistivity of top layer up to depth h_1
$\rho_2 =$ resistivity of second layer up to depth h_2

$$K_2 = (\rho_3 - \rho_2)/(\rho_3 + \rho_2) \quad (17)$$

ρ_3 is the resistivity of third layer up to depth h_3
The soil model having n layers, need to determine (2n-1) number of soil model parameters. The depth of n^{th} layer is infinity. The two sets of apparent soil resistivity data using least square method can be presented as [16]

$$\Psi(\rho_1, \rho_1, \dots \rho_N, h_1, h_2, \dots . h_{n-1}) = \sum_{i=1}^{k} \left[\frac{\rho_{mi} - \rho_i}{\rho_{mi}}\right]^2 \quad (18)$$

ρ_{mi} measured apparent soil resistivity for k number of probe spacing and ρ_i calculated apparent soil resistivity for k number of probe spacing.
The parameters ρ_i, h_i can be obtained by minimizing function Ψ. This is a unconstrained nonlinear least square optimization technique.
By putting $\rho_i = {\rho'_i}^2$ and $h_i = {h'_i}^2$, it is possible to change the nonlinear unconstrained optimization problem into nonlinear constrained optimization problem. Thus,

$$\Psi(\rho'_1, \rho'_1, \dots \rho'_N, h'_1, h'_2, \dots . h'_{n-1})$$

$$= \sum_{i=1}^{k} \left[\frac{\rho_{mi} - \rho_i}{\rho_{mi}}\right]^2 = min \quad (19)$$

The resistivities at different soil layers and their depth obtained are depicted in table 2.

Table 2. Various soil models for figure 4.

Model	Layer	Resistivity (Ω-m)	Thickness (m)
Uniform	---	156	--
Two layers	Top	348.84	0.18
	Bottom	140	∞
Three layers	Top	348.84	0.19
	Central	128.50	0.94
	Bottom	143.32	∞
Four layers	Top	348.83	0.212
	Central $_1$	119.07	2.37
	Central $_2$	296.85	6.00
	Bottom	33.11	∞

V. Conclusion

Various soil resistivity measurement techniques are demonstrated. The curve of soil resistivity against probe spacing clearly reflects the four distinct layers without knowing the soil resistivity of each layer and its depth. However, use of multilayer soil model, provides all the information of soil resistivity and its depth for each layer. The result table shows that the four-layer soil model is best suited for given soil resistivity data.

The knowledge of multilayer soil model has paramount importance while design of substation grounding grid. The most stringent safety criterion such as touch & step voltages are the functions of top layer soil resistivity whereas ground resistance and GPR depends on low soil layer resistivity. The optimum length of ground rods can be obtained so that they can reach to the low soil resistivity layer and discharge large fault current resulting in reduction in touch & step voltages, reduction in ground resistance, GPR which enhances of safety of substation operators & costly control equipments. This research will be useful to researchers and power engineers working in electrical utility and industries.

References

[1]. IEEE Standard 80-2013, *IEEE Guide for Safety in AC Substation Grounding*, IEEE, New York, USA.
[2]. J. K. Arora, Earthing systems – An overview, *Proceedings on earthing systems, Central Board of Irrigation and Power*, New Delhi, 2008, 1-7'
[3]. F. Dawalibi, N. Barbeito, Measurements and computations of the performance of grounding systems buried in multilayer soils, *IEEE Transactions on Power Delivery, 69(4)*, 1991, 1483-1490
[4]. F. P. Dawalibi, J. Ma, R. D. Southey, Behaviour of grounding systems in multilayer soils: a parametric analysis, January' *IEEE Transactions on Power Delivery, 9(1)* , 1994, 334-342.
[5]. Unde M.G., Kushare B.E., *Parametric Analysis of Grounding of EHV/UHV A.C. Substations in Multilayer, Non uniform Soils. A Ph.D. Thesis*, Savitribai Phule Pune University, Pune, Sept 2016
[6]. Takehiko Takahashi and Taro Kawase, Calculation of earth resistance for a deep-driven rod in a multi-layer earth structure, *IEEE Transactions on Power De1ivery, 6(2)* ,1991, 608-614.
[7]. B. Zhang, X. Cui, L. Li, J. L. He, Parameter estimation of horizontal multilayer earth by

complex image method, *IEEE Transactions on Power Delivery, 20(2)*,2003, 1394–1401.

[8]. ANSI / IEEE Standard 81-1983, *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System* , IEEE, New York 1983.

[9]. Jinliang He, Rong Zeng, Bo Zang, *Methodology & Technology for Power System Grounding*, John Wiley & sons Singapore, 2013,254-263.

[10]. Unde, M.G. and Kushare, B.E., Impact of seasonal variation of soil resistivity on safety of substation grounding system, *in Proc. IET Conference*, 2013,173-181.

[11]. Farid Dawalibi and Dinkar Mukhedkar, Survey on power system grounding design practices, *IEEE Transactions on Power Apparatus and Systems, 99(4),* 1980,1396-1405.

[12]. ANSI / IEEE Standard 81-2012, *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System* , IEEE, New York 2012.

[13]. Unde, M.G. and Kushare, B.E., Cost effective design of grounding grid using ground rods- a case study, in *Proc. Fifth IEEE Power India Conference,* Delhi 2012, 1-6

[14]. Wenner, F., A *Method of measuring resistivity, National Bureau of Standards, Scientific Paper,* Report no. 258, (1293), 1916, 469–482.

[15]. Palmer, L. S., *Examples of geo electric surveys*, *IEE*, *vol. 106*, part A, June 1959

[16]. B. Zhang, X. Cui, L. Li, J. L. He, Parameter estimation of horizontal multilayer earth by complex image method, *IEEE Transactions on Power Delivery, 20(2),* 2003, 1394–1401.

Kavita Joshi. “A Survey on Real Time Image Stitching.” *International Journal of Engineering Research and Applications (IJERA*), vol.10 (05), 2020, pp 25-30.