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Seasonal Variation of Soil Resistivity and Corrective Factor for Optimal Substation Earth Grid Design in Eastern Cape

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Abstract—**Optimal Substation Earth Grid Design is a vital aspect of the electrical power system protection. The Seasonal Variation of Soil Resistivity mostly influences Earth Grid Design. Due to seasonal changes, there is an annual variation in the Soil Resistivity with no known correction factors that can be utilized. This has led to a need to ascertain annual "Seasonal Soil Resistivity Correction Factors" for utility application. The objective of this paper is to develop seasonal Soil Resistivity Correction Factors for Optimal Substation Earth Grid Design in a power distribution substation focusing on meeting the minimum safety requirements, which are the step and touch potentials. A case study site was used for this study in the Eastern Cape region based on a study carried out in the Gauteng province. Results obtained show that in winter, (June/July), the highest soil resistivity was reached and lowest value obtained in autumn season (March). The upper soil layer resistivity noticeably varies more than the lower layer. The corrective factors for the upper layer with probe spacing (0.5m-1m) is multiplied by 1.16; for the second upper layer probe spacing from (2m-5m) is multiplied by 1.02; while the lower layer with probe spacing (5m-50m) is multiplied by 1.01. The corrective factors are focused on July, which is the highest, for an Optimal Substation Earth Grid Design.**

Keywords— soil resistivity, seasonal variation, correction factor, earth grid

I. Introduction

An important input to earth grid design is soil resistivity. Its value depends on the moisture content, soil composition, dissolved substances, porosity of soil and temperature of the soil. Studies show that seasonal weather variations have an impact on soil resistivity. There appears to be no reliable data on seasonal variations in soil resistivity in the Eastern Cape and South Africa. The influence of these variations has not been quantified and could possibly render the designed earth grid unsafe at different times of the year, therefore the need for a corrective factor to compensate for all seasons. The ground resistance (Rg) is defined by the size of the grounding system and soil resistivity (ρ) within which the grounding system is embedded [1].

The electrical properties of the ground are characterised by the soil resistivity (ρ). Soil resistivity is the resistance between opposite faces of a cube of soil having sides of unit length 1m that is expressed in ohmmeter (Ωm) [2]. Soil resistivity data is used in the calculation to assess the increase of earth potential of the earthing system under earth-fault conditions. Increase of earth potential enables the determination of the transfer potentials (step and touch) [2]. The soil model is an electrical representation of the soil in which the earth electrode will be embedded and is an important input parameter in the design.

It should be noted that the soil model is an approximation of actual soil conditions. For this study, a site was selected which had to be void of the following limiting factors as they influence the results, namely: terraced soil (disturbed soil), underground services (pipes), no existing earth grids power lines, no boundary fences or platforms. A set of traverses were selected with the site location co-ordinates of 32°57'4.55"S and 27°56'5.89"E as shown in Fig. 6. The objectives of this case study are as follows:

- To determine the effects of seasonal changes in soil resistivity on Substation Earthing Grid Design.
- To develop a correction factor for Eastern Cape Distribution Substation Earth Grid for all Seasons.
- Evaluate and study the variations which will occur in applying the correction factor.

II. Literature Review

Two most important influential factors of soil resistivity are the moisture content and temperature. Fig. 1(a) shows the differences in terms of the moisture content by weight with the soil resistivity for various soil types: Clay B, Clay A, Soil residual and sandy soil. The temperature and resistivity for clay, silt, biotite granite, sand and gravel are shown in Fig. 1(b).

- The graph representation of the changes in humidity of the soil is shown in Fig.1 (a): Seasonal variation in rainfall and humidity will have an impact on the moisture content of soil. The soil resistivity may vary by a factor of ten in the dry season leading to a high resistivity and low values on the wet seasons [3] with better conductivity.
- The graphical representation of the changes in temperature is shown in Fig.1 (b). It shows that when the soil freezes, there is a multiple of ten or greater variance in the soil resistivity. This in consequence results in high soil resistivity values in the cold months of the year. The top layer of soil (0.1-1m depth) is where the effects of freezing are similar to those of dry soil conditions, which can increase the magnitude of the soil resistivity by one or two orders.

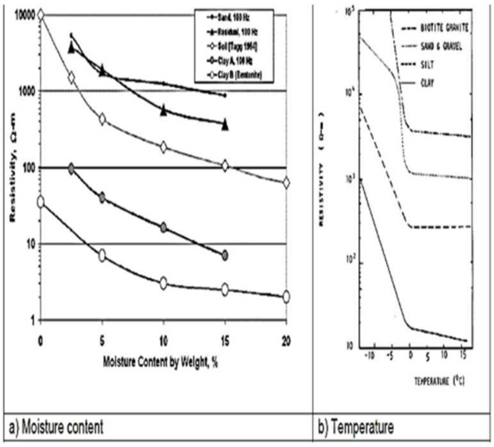

Fig. 1. Variation of soil resistivity [3]

South Africa is a relatively a dry country; with an average annual rainfall of about 464 mm. In winter, night-time temperatures can drop to freezing point or lower in some places. Soil resistivity being the basic parameter to the design of effective earthing or grounding of protection systems. It is imperative to measure the soil resistivity. The apparent resistivity is defined by eq. 1 using the Wenner method:

$$\rho_{\alpha w} = 2\pi d R \qquad (1)$$

Where $\rho_{\alpha w}$= represents apparent(Ωm), d = represents probe spacing (m) and R= represents measured resistance(Ω).

Fig. 2 shows diverse soil structures, which influences the electrical grounding system design.

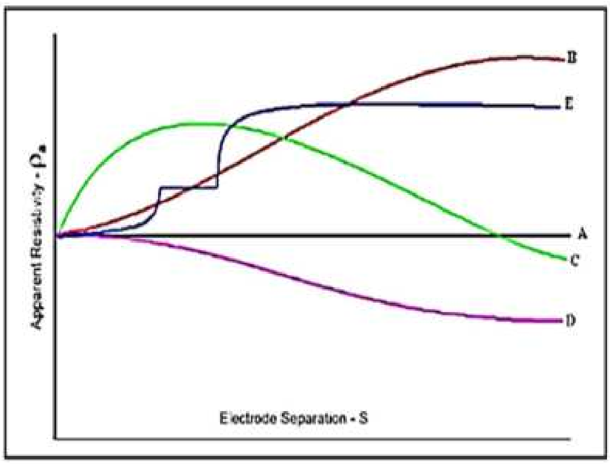

Fig. 2. IEEE 80 soil structure [5], [2]

The soil structure of Fig. 2 encompass of: curve A signifies homogenous resistivity; curve B signifies a low resistance layer overlaying a high resistivity layer; curve C signifies a high resistivity layer between two low resistivity layers; curve D signifies a high resistivity layer overlaying a lower resistivity layer; and curve E signifies a low resistivity over a high resistivity with vertical discontinuity.

The grounding of a substation comprises of the following elements: Earthing rods driven into the earth; Equipment ground mats [5]; Buried interconnecting grounding cables or grid [5]; Connecting cables connecting to the buried grounding grid to the metallic parts of structures and equipment [5]; Connections to the grounded system neutrals, as well as the material insulating the surface [5].

Within the substation, personnel may be exposed to five type of voltages, which are shown in Fig. 3. This includes the metal-to-metal voltage (Emm), step voltage (Es), touch voltage (Et), mesh voltage (Em), and transferred voltage (Etrrd). The threshold magnitude for the current and duration, at 50-60 Hz, should be below the ventricular fibrillation for 99.5% of the population.

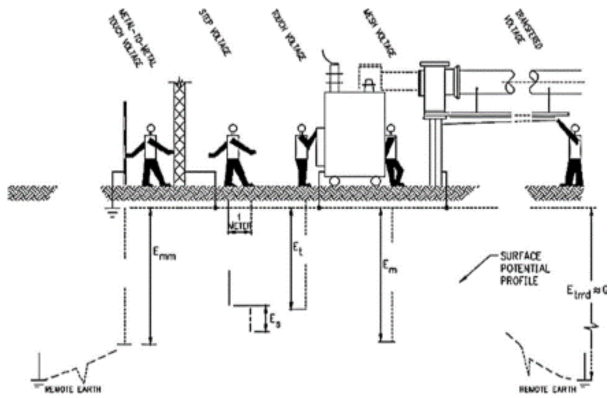

Fig. 3. Basic shock simulation [5]]

Step and touch voltages are standard voltages that need to be adhere to for ensuring a safe and optimal Substation Earth Grid Design. The lower the maximum touch and step voltages are, the harder it is to fulfil an adequate design. The faster the clearing time is, the less exposure of the fault current there is to the person. As per IEEE 80-2013, the resistance of the human body is R_B = 1000Ω and the body current associated with a person weighing 50kg or more. The following equations are used to calculate the allowable (safe) step and touch potential limits:

$$I_b = \frac{0.116}{\sqrt{t_f}} \qquad (2)$$

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

$$E_{step} = (R_B + 6\rho_s C_s) \cdot I_B \qquad (4)$$

$$E_{touch} = (R_B + 1.5\rho_s C_s) \cdot I_B \qquad (5)$$

Where:

E_{step} - Maximum allowable step voltage - V

E_{touch} - Maximum allowable touch voltage - V

I_b - Maximum expected RMS current in the grid conductor - A

R_B - Body resistance = 1000Ω

ρ_s - Resistivity of the surface material - Ωm

C_s - Surface layer de-rating factor

t_f - Fault clearing time - s

ρ - Soil resistivity in which the earth grid is buried under - Ωm

h_s - Thickness of the surface layer

A. Design Methodology

The flow-chart of a basic earth electrode design process applicable to the study is given in Fig. 4. This process flow is applicable irrespective of the design method being used, i.e. calculating all parameters by hand in accordance with IEEE 80 or by making use of appropriate finite element analysis software.

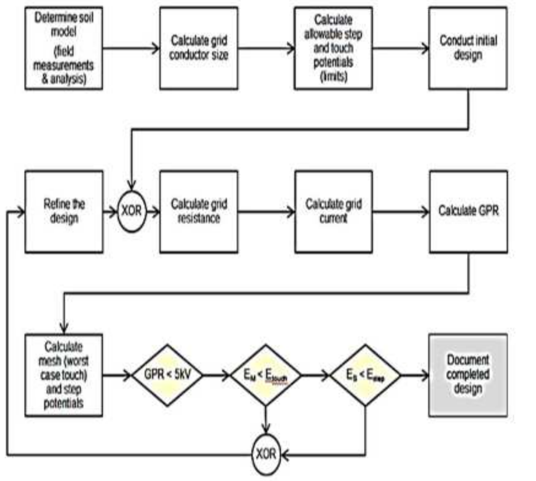

Fig. 4. Earth electrode desig process flow [6]

Soil model is an electrical representation of the soil in which the earth electrode will be installed and is one of the important input parameters in the design. It must be stressed that the soil model is only an approximation of the actual soil conditions and that a perfect match is improbable. The most accurate method in practice is the Wenner method. Current is passed through the earth between two current electrodes C1 and C2, and the resulting potential drop over a given distance is measured between two potential electrodes P1 and P2. All probes are in a straight line and equal distances apart. It is therefore necessary to move all four electrodes for each measurement. The probe spacing show in Fig. 5 were used 0.5m, 1m, 2m,3m,4m, 5m, 10m, 15m, 20m, 30m, 40m and 50m for field measurement and analysis.

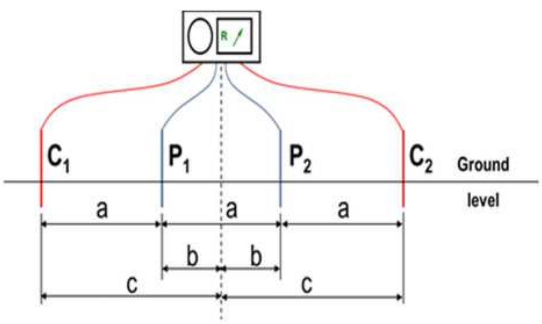

Fig. 5. Wenner foru-electrode method [7]

Soil models results are modelled out from June 2018 until July 2020. Soil resistivity measurements conducted on a monthly basis. The measurements were carried out as per the guidance provided in [8]. The following effects were not monitored during the investigation: the effect of temperature, moisture and geology. The main focus was on the variance of the seasons.1x10mm diameter annealed soft drawn round copper rod will be assumed as main earth grid conductor.

Fig. 6. Proposed measurements site

As presented in Fig. 6, the four terminal earth tester would be centred at the centre of the two 150m traverses. It is important to calculate and plot the resistivity results on the bi logarithmic graph paper concurrently while the measurements are carried out (i.e. on the fly) to ensure that discrepancies are identified while conducting the tests and reasons for it can be investigated while busy with the tests, or retested if necessary.

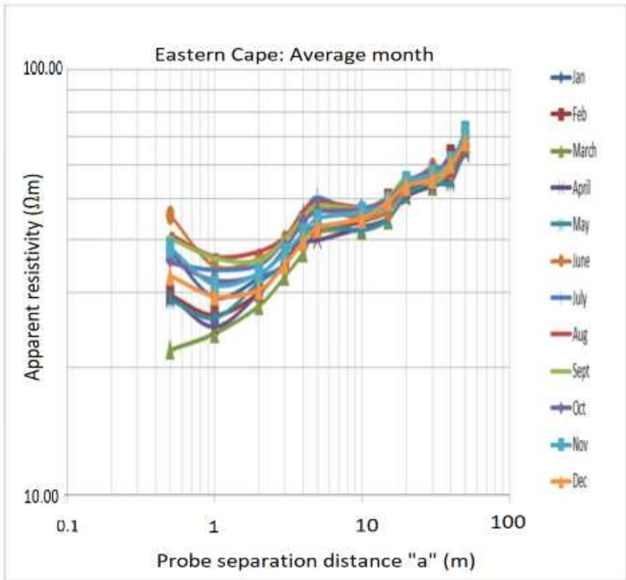

Fig. 7. Bi-logarithmic representation of results

B. Interpretation of results

There is a strong correlation between the two traverses measured on site. Bi-logarithmic representation from January 2019 until December 2019 of average values of the measured results of traverse 1 and 2 are shown in Fig. 7. From these results, it could be presented that there is a large variation of the soil resistivity with the seasonal changes. In winter, June/July, the highest soil resistivity was reached and the lowest was reached in Autumn (March). Maximum and minimum values measured over from January 2019 to December 2019 for the given probe distances are shown in Fig. 8. There are further observations of greater variances in soil resistivity for probe distances 0,5m, 1m and 2m (upper layer) compared to the larger probe distances 5m to 50m (bottom layer). From the results shown in Fig.8 it is evident that soil resistivity varies considerably over the changing seasons in the upper surface. An excellent style manual for science writers is [7].

From Fig. 8, conclusions can be arrived to that the soil is non-homogenous that is multiple layers of soil are present on the site, with each layer comprising of a different resistivity. The change in the soil resistivity average value is an indication of multi-layered soil. The variations in the soil resistivity values over the seasons justify the need to develop a seasonal soil resistivity correction factor. Correctional factor is defined as the mathematical adjustment to compensate for deviations in a sample or the method of measurement. Voltage gradient does not affect the soil resistivity unless the voltage gradient exceeds a certain critical value. The value somewhat varies with the soil material, but it usually has the magnitude of several kilovolts per centimetre [6]. Once the critical value is exceeded, arcs would develop at the electrode surface and progress into the earth so as to increase the effective size of the electrode, until gradients are reduced to values that the soil material can withstand [2]

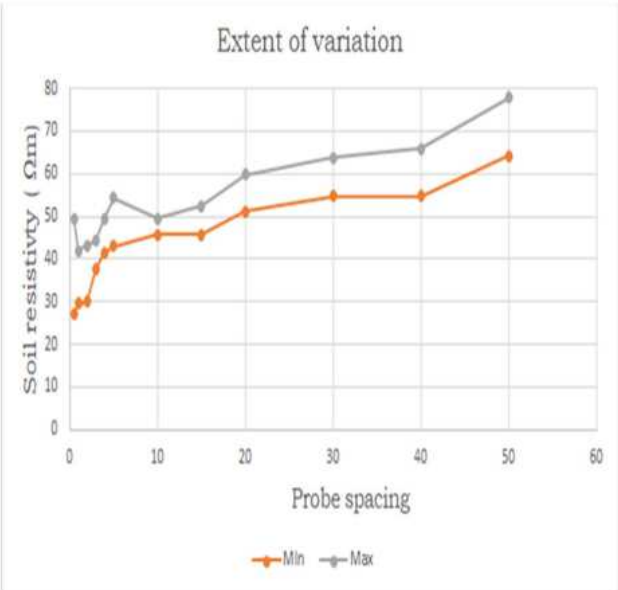

Fig. 8. Extent of soil resistivity variation

III. DERIVATION OF CORRECTION FACTOR

The measured results enable the extrapolation of the correction factors. Due to the variances in the upper and lower layer soil resistivity, distinct correction factors are extrapolated for the upper layer lower layer.

TABLE I. SEASONAL SOIL CORRECTIONAL FACTOR FOR EASTERN CAPE

	Seasonal Soil correctional factor for Eastern Cape		
Months	***Upper layer (<2m)***	***Lower Layer(2-5m)***	***Lower layer (>5m)***
January	1.20	1.16	1.04
February	1.43	1.17	1.03
March	1.75	1.25	1.09
April	1.48	1.21	1.10
May	1.46	1.16	1.09
June	1.00	1.04	1.04
July	1.16	1.02	1.01
August	1.03	1.00	1.03
September	1.05	1.03	1.02
October	1.18	1.08	1.00
November	1.15	1.11	1.00
December	1.29	1.18	1.03

Table I displays the extrapolated soil correction factors for each probe distance/depth. Mathematical adjustment made it possible to account for measurements done in other months. The observation of seasonal influence on the soil resistivity has led to the derivation of distinct correction factors for the upper and lower.

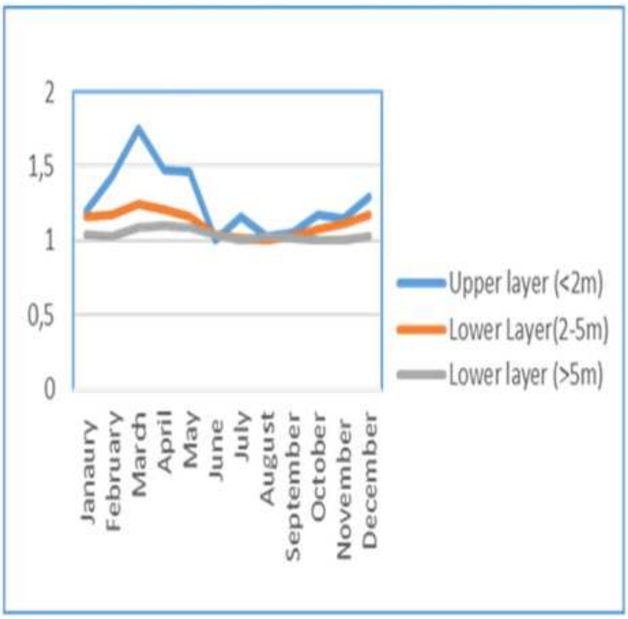

Fig. 9. Graphical representation of corrective factor

IV. DESIGN CALCULATION

Depending on the month during which the soil resistivity measurements are done, the measured values shall be multiplied with the values against that month for all measured values. Refer to Table II for an example of soil measurements taken in the month of July.

From Table II the values for probe separations < 2m lower layer 2-5m and >5m is multiplied by 1.16 lower layer 1.02 and the values associated with probe separations >5m to 50 m are multiplied with 1.01. The corrected soil resistivity is then as input to the design.

TABLE II. SOIL RESISTIVITY CORRECTION APPLICATION

Probe Separation (a)	Tester Reading (R)	Resistivity (= 2πaR)	Correction factor July	Correction Soil Resistivity
m	Ω	Ω*m*		Ω*m*
0,5	7,64	24,002	1,16	27,842
1	4,57	28,714	1,16	33,309
2	2,35	29,531	1,02	30,122
3	1,898	35,776	1,02	36,492
4	1,698	42,675	1,02	43,529
5	1,56	49,009	1,02	49,989
10	0,712	44,736	1,01	45,184
15	0,492	46,370	1,01	46,834
20	0,422	53,030	1,01	53,561
30	0,264	49,763	1,01	50,261
40	0,234	58,811	1,01	59,399
50	0,208	65,345	1,01	65,999

A. Design assumptions:

Select a design fault current of 15kA based on 10-year maximum value of 7.8 kA based on [7]. Two-layer model with the following shall be used:

TABLE III. TWO LAYER MODEL

Top soil layer thickness (h1):	4m
Top soil layer resistivity (ρ1):	24Ωm
Bottom/Top layer relationship (ρ2/ρ1):	2.5
Bottom soil layer resistivity (ρ2):	60Ωm

The earth grid will be buried at top soil layer for design purpose 24Ωm. Df = 1.091 will be used and based on a fault clearing time of 0.5 s and network X/R ratio of 30. Earth grid material will be standard 10 mm diameter round annealed soft-drawn copper. Earth tail material will be standard 50 mm x 3 mm flat copper bar.

The maximum expected magnitude of the current that will flow in earth grid conductor is based on number of earth tails and the current split factor per earth tail. For two earth tails, the current split is 80%: 20%. Therefore, the maximum expected current in the grid conductor for the chosen design earth fault current of 15 kA is [7]:

$$I_c = 0.4 I_F \quad (6)$$

$$I_c = 0.4\ X\ 15 = 6kA$$

$$A_c = I_C \frac{1}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_f \alpha_r \rho_r}\right) ln\left(\frac{K_O + T_m}{K_O + T_a}\right)}} \quad (7)$$

$$A_c = 16.8899mm^2$$

$$d_c = 2\sqrt{\frac{A_c}{\pi}} \quad (8)$$

$$d_c = 4.64mm$$

$$I_b = \frac{0.116}{\sqrt{t_f}} \quad (9)$$

$$I_b = 0.164A$$

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} = 0.692 \quad (10)$$

$$E_{step} = I_b(R_b + 6\rho_s\ C_s) \quad (11)$$

$$E_{step} = 2206V$$

The maximum allowable step potential for a duration up to 0.5 seconds is only 2,206 volt. Earth grid layout design must therefore ensure that the maximum expected step potential is limited to below this value.

$$E_{touch} = I_b(R_b + 1.5\rho_s C_s) \quad (12)$$

$$E_{touch} = 676V$$

The maximum allowable touch potential for a fault up to 0.5 seconds is 676V.

V. CONCLUSION

The objectives of this paper, which are outlined in the introduction of this paper, have been realized. The paper has revealed that in winter, which is June/July, the highest soil resistivity was reached and lowest soil resistivity was in autumn (March). The upper layer soil resistivity varies more noticeably than the lower layer. Based on the seasonal variations in the soil resistivity observed over a period of one year, a table of multiplicative correction factors is therefore proposed as shown in Table II above as a suitable guideline to be used for all earth grid designs within the Eastern Cape region of South Africa.

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