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Research article

SOIL RESISTIVITY MEASUREMENT AND EVALUATION FOR POWER SYSTEM EARTHING A CASE STUDY OF RADIO NIGERIA PACESETTER F.M UMUAHIA NIGERIA

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ABSTRACT

Power system earthing plays a vital role to guarantee the safe, reliable operation of power systems and also ensure the safety of human being in case of any disturbance or fault in the system. In realization of this objective, the nature of soil, specifically the soil resistivity, strongly influences the performance of earthing system. This paper discusses the methods and tools used for carrying out extensive measurement of the soil resistivity at Radio Nigeria Pacesetter Fm Umuahia in the South Eastern Zone of Nigeria using the four electrode method. The soil resistivity measurements were conducted in 20 different locations at various depths of 0.5m, 0.8m, 1.2m, 1.5 meters and distance of 1, 2, 5 and 10 meters covering 120 by 240 square meters of the entire substation. The calculation was made to determine the average measured soil resistivity of all the layers of soil between the surface and depth and the results were shown as 0.709, 1.45, 0.0915 and 0.0715 Ohms respectively. These values helped to achieve good correlation between designs and measured earthing system performance of the soil resistivity. The soil resistivity near the surface varies significantly at eight different locations. The values obtained from four locations were radically high comparing to the other eight values. These values probably reflects differences in lithology, and water content in the upper soil layer due to local topography and drainage situation. With the help of Matlab program, graphs were plotted which confirmed the relationship between soil resistivity and grounding resistance and also the relation between the electrode diameter and grounding resistance respectively.

Keyword: MATLAB, Earth Electrode Resistance, Effective Grounding, Electrical Earthing Systems, Soil Resistivity.

1.1 INTRODUCTION

One of the key factors in any electrical protection scheme is earthing. If any acceptable measures of safety are to be attained, effective and efficient earthing design and application must be made. That is, it must provide a common voltage reference and low impedance fault current path to allow the protection system to reliably clear abnormal or fault conditions while limiting the grid voltage rise and transfer earth potentials to tolerable limits, thereby ensuring the safety of personnel and public in the vicinity of the installation**.** (Anup Kumar et al 2015). The design must also be practical, maintainable and easily constructible at minimal cost. An effective design will provide a margin of compliance with minimum performance criteria that is appropriate to uncertainties implicit to the design inputs. This is to ensure acceptable performance of the installed earthing system and avoid expensive remediation designs that may be required if actual and design performance do not correlate.

It is well known fact that the resistance of an earth electrode is heavily influenced by the resistivity of the soil in which it is driven and as such, soil resistivity measurements are an important parameter when designing earthing installations. A knowledge of the soil resistivity at the intended site, and how this varies with parameters such as moisture content, temperature and depth, provides a valuable insight into how the desired earth resistance value can be achieved and maintained over the life of the installation with the minimum cost and effort. One of the main objectives of earthing electrical systems is to establish a common reference potential for the power supply system, building structure, plant steelwork, electrical conduits, cable ladders and trays and the instrumentation system. To achieve this objective, a suitable low resistance connection to earth is desirable. (Saqer A. Khalil, l , 2007, ANSI/IEEE Std. 81-1983)

It is important to be able to respond to the numerous constraints with an efficient comprehensive soil resistivity test plan that will enable the designer to assess the level of uncertainty in the soil resistivity model used in the design process. This will ensure that a cost effective earthing system design can be developed and will meet minimum performance criteria. This paper highlights important considerations for an effective soil resistivity test plan. (Gabriel A, et al, 2011). Typical site constraints are identified and their influence of soil resistivity data discussed. Methods of best accommodating soil resistivity model uncertainties into the earthing designs are also discussed. (Lightning & Surge Technologies 2002)

1.2 Geoelecterical Resistivity Survey

Soil resistivity is a basic parameter and one of the most important methods for the design of effective grounding and lightning prevention or protection systems. In addition, resistivity profiling can yield information on characteristics (including depth) of different layers in the subsurface. The resistivity of rocks or soils is in general a complicated function of their porosity, permeability, ionic content of pore fluids, and mineralization. In most rock materials, the porosity and the ionic content of the pore fluid are more important in governing resistivity than the conductivity of the constituent mineral grains. In situations where the porous rocks lie well above the water table and the fraction of the pores filled with fluid is negligibly small, mineralization starts to contribute.

Igneous rocks tend to have higher resistivity than sediments. Lavas and tuffs have very high values ranging from 10^2 to 5×10^4 Ω m and from 2×10^3 to 10^5 Ω m, respectively, whereas unconsolidated wet clay is known to have resistivity as low as ~20 Ω m (Telford, Geldart, and Sheri, 1990).

1.3 Principles

Soil resistivity values in the Nigerian continent are widely varying depending on the type of terrain, e.g., silt on a river bank may have resistivity value in the order of 1.5Ωm, whereas dry sand or granite in mountainous country areas may have values higher than 10,000Ωm. Factors that affect resistivity may be summarized as:-

- Type of earth (e.g., clay, loam, sandstone, granite).
- Stratification; layers of different types of soil (e.g., loam backfill on a clay base).
- Moisture content; resistivity may fall rapidly as the moisture content is increased, however, after a value of about 20% the rate of decrease is much less. Soil with content greater than 40% do not occur very often.
- Temperature; above freezing point, the effect on earth resistivity is practically negligible.
- Chemical composition and concentration of dissolved salt.
- Presence of metal and concrete pipes, tanks, large slabs, cable ducts, rail tracks, metal pipes and
- Fences Topography;. Rugged topography has a similar effect on resistivity measurement as local surface resistivity variation caused by weathering and moisture. Table 1 to Table 3 show how typical values alter with changes in soil, moisture and temperature.

Table 1: Resistivity values for several types of soils and water

Type of Soil or Water	*Typical Resistivity Ωm*	*Usual Limit Ωm*
Sea water	2	0.1 to 10
Clay	40	8 to 70
Ground well & spring water	50	10 to 150
Clay & sand mixtures	100	4 to 300
Shale, slates, sandstone etc	120	10 to 100

Peat, loam & mud	150	5 to 250
Lake & brook water	250	100 to 400
Sand	2000	200 to 3000
Moraine gravel	3000	40 to 10000
Ridge gravel	15000	3000 to 30000
Solid granite	25000	10000 to 50000
Ice	100000	10000 to 100000

Table 2: Variations in soil resistivity with moisture content

	Typical resistivity Ωm	
Moisture % by weight	*Clay mixed with sand*	*Silica based sand*
0	10 000 000	-
2.5	1 500	3 000 000
5	430	50 000
10	185	2 100
15	105	630
20	63	290
30	42	-

Table 3: Variations in resistivity with temperature for a mixture of sand and clay with a moisture content of about 15% by weight

Temp. C	*Typical resistivity Ωm*
20	72
10	99
0 (water)	138
0 (ice)	300
-5	790
-15	3300

1.4 Types of Earth Electrodes

Earth electrodes must ideally penetrate into the moisture level below the ground level. They must also consist of a metal (or combination of metals) which do not corrode excessively for the period of time they are expected to serve. Because of its high conductivity and resistance to corrosion, Copper is the most commonly used material for earth electrodes. Other popular materials are hot-galvanized steel, stainless steel, aluminum and lead. Earth electrodes may be rods, plates, strips, solid section wire or mats. (Lightning & Surge Technologies 2002, Nigel Johnson, .J, 2006)

Three types of copper rods are commonly available.

- Solid Copper
- Copper clad steel rod (copper shrunk onto the core)
- Copper Bonded steel core (copper is molecularly bonded to nickel plated steel rod)

Solid copper rods not prone to corrosion, but are expensive and difficult to drive into hard ground without bending. A steel cored copper rod is used for this reason, however those rods that are simply clad are prone to the cladding tearing away from the core when driven in rocky ground, or when bent. This exposes the internal steel core to corrosion. The most cost effective solution is the copper bonded electrode which is a molecularly bonded steel cored copper ground rod.

2. MATERIALS AND METHODS

Numerous methods have been developed to determine the resistivity of soil and variations thereof in a specific plane (e.g. vertically). They are Wenner Array, Schlumberger, Driven rod and four electrodes Method. The method adopted for this paper is the four electrodes method and study was carried out within the month of August 2014 and February 2015. This period was chosen because they represent the dry and the rainy seasons. (Saqer A. Khalil, l, 2007).

In this method four small electrodes (probes) are inserted in the soil with equal distances and equal lengths also the distance D is more than five times the probes length (L) as shown in the below figure :

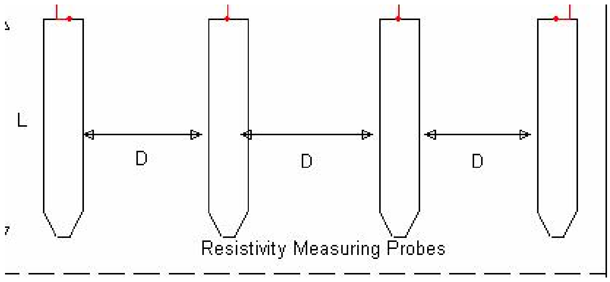

Fig 1: Resistivity measuring probes using four electrodes

In order to measure the soil resistivity , the four small electrodes (probes) method will be used. In case of one electrode , four probes equal in distances and diameters and D>5*L), are used This method is uses a current source between the outer probes and a voltmeter between the inner probes as shown in the following figure :

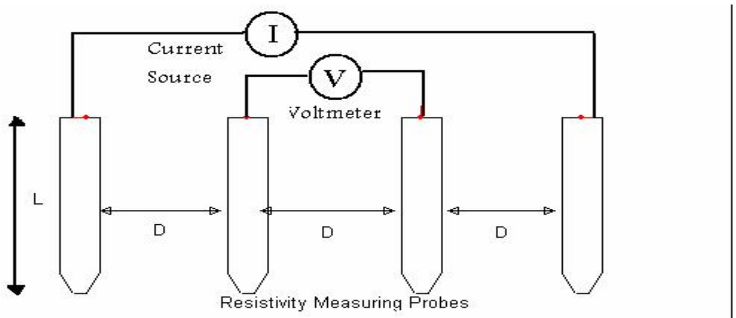

Fig 2: Resistivity measuring probes with current and voltage source

The current source is constant and known from the design. Also the probes length and diameter are known too , The measured volts will indicate the soil resistivity according to the relation : The Fig.3 shows the general measurement setup. The four earth probes should be driven into the ground in a straight line, at a distance ‘a’ meters apart and driven to a depth of ‘P’ cm.

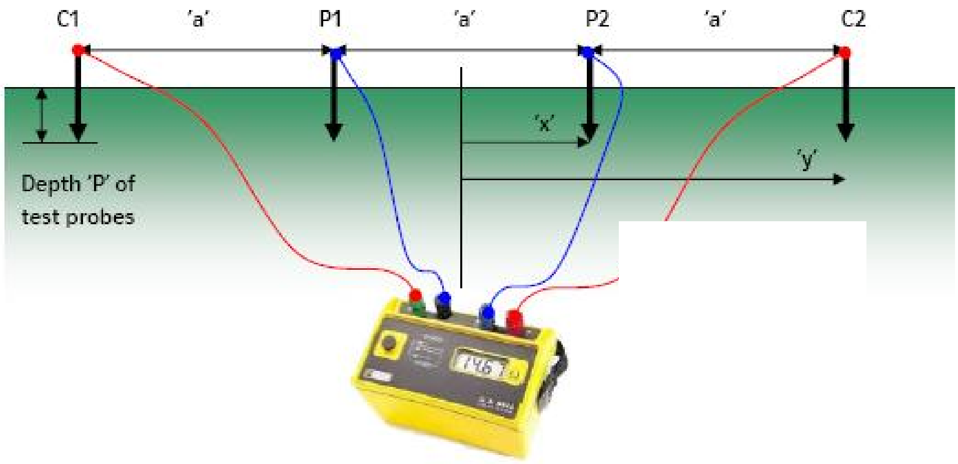

Fig 3: General measurement setup of the four earth probes

The four probes should be connected to the tester, with the outer probes connected to the C1 and C2 terminals, and the inner probes to the P1 and P2 terminals. (Dharmendra Prajapati, 2012). The instrument is being kept in a central position and a series of resistance measurements made as the four electrodes are moved out in equal distances from the central point. A calculation is made to determine the average soil resistivity of all layers of soil between the surface and a depth 'd' which is taken to be ¾ of the separation distance 'a'. The meter should be left on to allow the built in filters to operate and the value after 30 seconds should be taken.

2.1 Required test equipment and Supplies

The required test equipment and supplies for performing a soil resistivity test are as follows:

- A 4-Pole Digital Meter – (Megger Earth Tester)
- Four probes
- Four insulated wire conductors
- Small sledge hammer
- Tape measure
- Safety glasses
- Gloves

2.2 Field work and Instrumentation

The field work was conducted between August 2014 and February 2015 with Digital Meter – (Megger Earth Tester) resistivity instrument. The four probe electrode configuration was used to obtain the apparent resistivity values, with aim of four electrodes in each configuration. Soil resistivity was measured with sets of electrode spacing's per location to obtain the depth profile of the soil resistivity. The spacing's of the probes, were selected to be 1, 2, 3, 5 and 10 m, to provide uniform sampling on a logarithmic scale, in order to deduce properties of both upper and lower layers. The depth of each electrode is set to be about 1m to 5m depending on the brittleness of surface soil.

2.3 Measuring at various Depths

The soil is typically not homogenous from the surface to the depth being tested and resistivity varies at different depths. Because of this, the four-point test (performed at various depths and at various locations throughout the site) is used to provide a composite result of the soil resistivity. The testing depth of a soil resistivity test is determined by the spacing between the four test rods which correspondingly connect to tester terminals C1, P1, P2, and C2. The recommended practice is to test the soil at various depths in order to determine the best depth for the grounding (earthing) electrode system. For example, if the test rods are 1.52 m (5 ft.) apart, the measurement will be an average of the soil from the surface down to 1.52 m (5 ft.). As the spacing between the rods is increased, results for correspondingly deeper samples are directly obtained. Table 4 lists the soil depths measured for different rod spacing distances.

Table 4: Soil depth measured as a Function of rod spacing

Rod Spacing	Soil Depth Measured
1.52 m (5 ft.)	1.52 m (5 ft.)
3 m (10 ft.)	3 m (10 ft.)
6.1 m (20 ft.)	6.1 m (20 ft.)
9.1 m (30 ft.)	9.1 m (30 ft.)
12.2 m (40 ft.)	12.2 m (40 ft.)

3. Mathematical Modelling

Soil resistivity is defined as the resistance between the opposite faces of a cube of soil having sides of length one meter and can be expressed in Ohm-metres. Soil resistivity is the key factor that determines what the resistance of the charging electrode will be and to what depth it must be driven to obtain low ground resistance. The resistivity of the soil varies widely throughout the world and changes seasonally. (Dawalib F.P and, Ma, J (2002), Resistance is that property of a conductor which opposes electric current flow when a voltage is applied across the two ends. Its unit of measure is the Ohm (Ω) and the commonly used symbol is R. Resistance is the ratio of the applied voltage (V) to the resulting current flow (I) as defined by the well known linear equation from Ohm's Law:

$$V = I \times R \qquad (3.1)$$

where: V *Potential Difference across the conductor (Volts)*
I *Current flowing through the conductor in (Amperes)*
R *Resistance of the conductor in (Ohms)*

"Good conductors" are those with a low resistance. "Bad conductors" are those with a high resistance. "Very bad conductors" are usually called insulators. The Resistance of a conductor depends on the atomic structure of the material or

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it's Resistivity (measured in Ohm- m or Ω -m), which is that property of a material that measures its ability to conduct electricity. A material with a low resistivity will behave as a "good conductor" and one with a high resistivity will behave as a "bad conductor". The commonly used symbol for resistivity is ρ (Greek symbol rho). The resistance (R) of a conductor, can be derived from the resistivity as:

$$R = \frac{\rho \times L}{A} \qquad (3.2)$$

where ρ *Resistivity (Ω-m) of the conductor material*
L *Length of the conductor (m)*
A *Cross sectional Area (m^2)*

Resistivity is also sometimes referred to as "Specific Resistance" because, from the above formula, Resistivity (Ω-m) is the resistance between the opposite faces of a cube of material with a side dimension of 1 meter. Consequently, Soil Resistivity is the measure of the resistance between the opposite sides of a cube of soil with a side dimension of 1 meter. In the USA, a measurement of Ω-cm is used. (100 Ω-cm = 1 Ω-m)

3.1 Ground (Soil) Resistance:

The mathematical relation that describes the resistivity of the soil and the grounding resistance is

R=[ρ/(2π*L)]*[ln(4*L/D)] -------------------------- (3.3)

where :
R : Resistance of soil in ohm.
ρ : Resistivity of soil in ohm-meter.
L : Length of electrode in meter.
D : Diameter of the electrode in meter.

NOTE: The above relation consider only one electrode for the grounding system

ρ=2*π*D*(I/V). ------------------- (3.4)

Where :
ρ: Resistivity of soil in ohm-meter., D : Distance between probes in meter. I: Current source value in ampere. V: The measured voltage in volt.

4. Simulation

A software model of the system was created in order to assist in algorithm development and to provide parameter inputs to calculate the resistivity of the soil according to the above relation in measuring soil resistivity. Due to the high level of unbalance and asymmetry on this circuit, it would not be acceptable to use conventional program utilizing sequence components, for this reason a high performance language for technical computing with graphic user interface (MATLAB/SIMULINK) Program is used. (Saqer A. and Khalil, l , 2007), The simulated circuit consists of transformer, resistors, capacitors, zener diodes, inveter, Transistor and Voltage regulator. A simplified illustration of the Simulink model is shown in Figure 4 below.

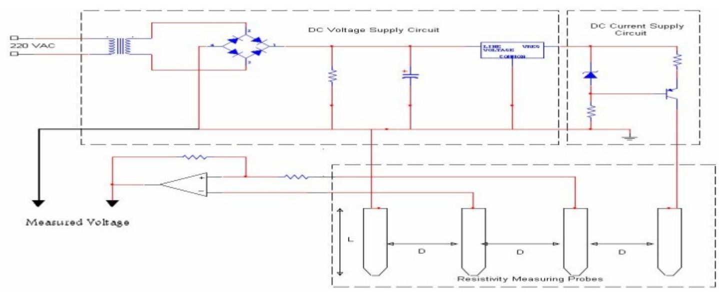

Fig 4: Electronic circuit measuring the soil resistivity

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After measuring the drop voltage we can calculate the resistivity of the soil was calculated according to the above relation used in measuring soil resistivity section. A simple circuit to activate an alarm if the soil resistivity is over the desired value as shown in the Figure 5. Below:

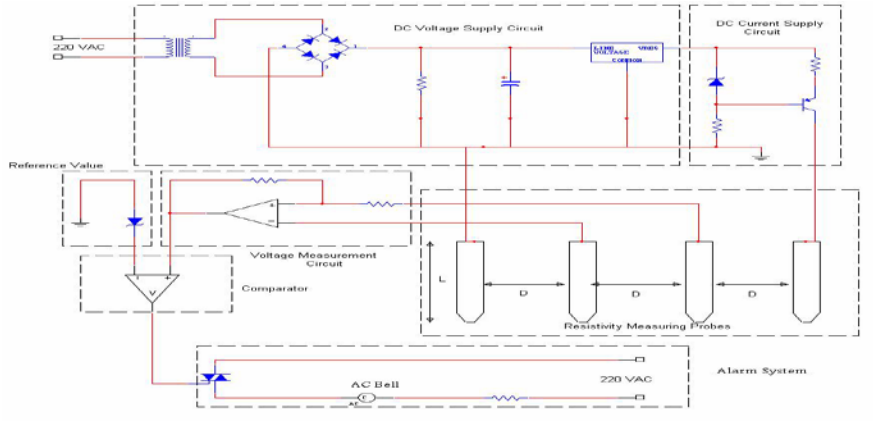

Fig.5: Electronic Circuit for Ground Alarm

4.2 Testing

The purpose of resistivity testing is to obtain a set of measurements which may be interpreted to yield an equivalent model for the electrical performance of the earth, as seen by the particular earthing system. However, the results may be incorrect or misleading if adequate investigation is not made prior to the test or the test is not correctly undertaken. To overcome these problems, the following data gathering and testing guidelines are suggested.

An initial research phase is required to provide adequate background, upon which to determine the testing program, and against which the results may be interpreted. Data related to nearby metallic structures, as well as the geological, geographical and meteorological nature of the area is very useful. For instance the geological data regarding strata types and thicknesses will give an indication of the water retention properties of the upper layers and also the variation in resistivity to be expected due to water content. By comparing recent rainfall data, against the seasonal average, maxima and minima for the area may be ascertained whether the results are realistic or not.

4.3` Field work and Instrumentation

The field work was conducted between August 2014 to February 2015 with Digital Earth resistivity instrument called “Megger Earth Tester”. The four electrodes method configuration was used to obtain the apparent resistivity values, with aim of Four electrodes in each configuration as indicated in Figure 3. Soil resistivity was measured with four sets of electrode spacing’s per location to obtain the depth profile of the soil resistivity. The spacing’s of the probes, were selected to be 1, 2, 5 and 10 m to provide uniform sampling on a logarithmic scale, in order to deduce properties of both upper and lower layers. The depth of each electrode is set to be about 1m to 5m depending on the brittleness of surface soil.

5 Result

The result of the simulation showed the graphs that described the relationship between the soil resistivity and grounding resistance, also the relation between the electrode diameter and the grounding resistance as presented in figures 5,6 and 7 and tables 5 and 6 respectively.

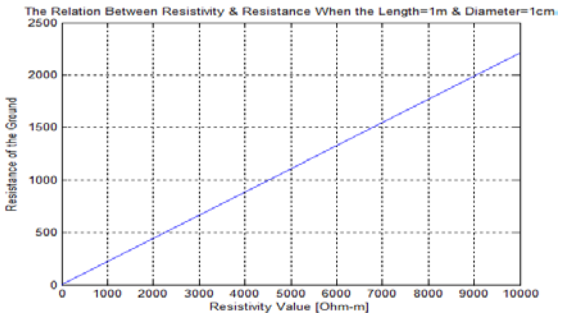

Fig 5: The graph of ground resistance vs resistivity

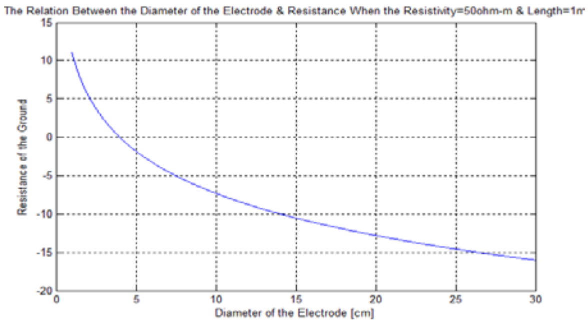

Fig 6: The graph of ground resistance vs Diameter of the electrode

Table 5: Test Report of Soil Resistivity Measurement

Location No.	Measured Soil Resistance (in Ω)			
	with d=1 mtr.	with d=2 mtr.	with d=5 mtr.	with d=10 mtr.
1	2.17	0.53	0.02	0.03
2	2.40	0.63	0.02	0.03
3	0.21	0.07	0.06	0.03
4	2.17	0.33	0.06	0.05
5	2.12	0.22	0.06	0.05
6	0.54	0.27	0.12	0.08
7	0.33	0.18	0.12	0.08
8	0.31	0.20	0.12	0.08
9	0.27	0.12	0.06	0.08
10	0.34	0.23	0.08	0.07
11	0.38	0.23	0.08	0.08
12	0.27	0.18	0.12	0.08
13	0.31	0.20	0.12	0.11
14	0.27	0.17	0.08	0.08
15	0.23	0.17	0.10	0.08
16	0.27	0.17	0.12	0.09
17	0.23	0.16	0.12	0.09
18	0.27	0.19	0.12	0.06
19	0.87	0.19	0.12	0.11
20	0.22	0.12	0.13	0.07

Table 6: Average Soil Resistivity of the substation

Average Soil resistivity of the Substation (in Ω-m)			
With d=1 m	With d=2m	With d=5 m	With d=10m
0.71	1.45	0.09	0.72

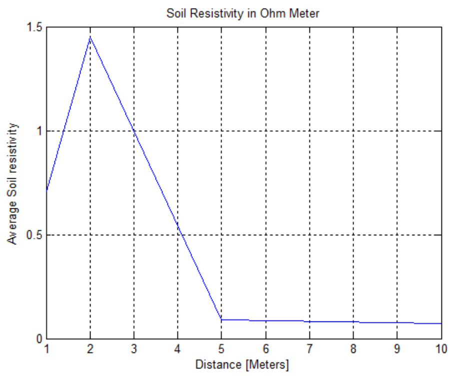

Fig: 7: The graph of average soil resistivity against distance

6.0 CONCLUSION

This paper has discussed the Earthing system design of 33kV transmission Substation of Pacesetter FM Umuahia in the South Eastern Zone of Nigeria. The earth resistance measurements were carried out at selected points covering 120 by 240 square meters of its perimeter fencing in 20 different locations of the Substation. The selected points include clay terrains and marshy areas. The average earthing resistance profile varied between 0.709 Ohms and 1.45 Ohms at various distance of 1,2,5 meters and 10 meters apart. Broad engineering soil identifications as well as programmed intensive field measurements of soil resistivity and earthing systems at some selected sites proved that soil resistivity values depend on the type of soil. For good grounding of electrical systems the soil resistivity should be improved for effective earthing of systems. In addition, in clay area the best result can be obtained by digging a trench of approximately 17m deep and 4m wide to bury the earth mat and electrodes. In addition, a PVC pipe of 1 inch in diameter should be vertical buried inside the pit before covering it with loamy soil or fine sand in order to obtain lower soil resistivity and enable low earth electrode resistance. The essence of the PVC pipe is to give an access of pouring water into the ground of the earth mat and electrodes during dry season to insure restoration moisture

The graph of the Soil resistivity test was plotted during measurements in order to identify possible inaccuracies that can be reduced by further testing at or near the test site using MATLAB tool. The earthing grids are tied by multiple conductors to reduce overall resistance which is calculated to be 2 ohms after tiding both grids. The overall grid resistance can further be reduced by designing auxiliary mat nearby and tiding it to grounding grid of switchyard. More effective method to reduce overall grid resistance is to tie earth mat to Penstock. Thus reduction in overall grid resistance helps to restrict touch and step potential within tolerable limit during heavy fault and lightning condition.

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