SOIL RESISTIVITY INVESTIGATIONS FOR SUBSTATION GROUNDING SYSTEMS IN WETLAND REGIONS – A CASE STUDY OF LAGOS STATE, NIGERIA

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ABSTRACT

Soil resistivity - a measure of how much the soil resists the flow of electricity is a critical factor in the design of safe and efficient grounding systems. Actual resistivity measurements are required to fully qualify soil resistivity and its effects on any proposed substation grounding system. This paper investigated the soil resistivity in three different sites in Lagos – a wetland region in Nigeria during the wet and dry seasons of 2016 in line with the relevant IEEE Standards and International best practices for determining resistivity levels for substation grounding system designs. To locate the soil of acceptable resistivity values that would ensure effective grounding system design for substations in the region, the Wenner Four-Pin Method was deployed. The findings show that soil resistivity in wetland areas varies according to seasons being significantly high during the dry seasons and significantly low during the wet seasons. The outcome of this study is useful for purposes of estimating the ground resistance and potential gradients including step and touch voltages of substation grounding installations and for computing inductive couplings between neighboring power and communication circuits within and around wetland regions.

Keywords: Earthing, Grounding systems, Soil Resistance, Soil Resistivity, Substation

INTRODUCTION

When designing and installing a vital subsystem of the electrical power system such as the substation, proper grounding is a necessity. A good grounding arrangement provides a low-impedance path for fault and lightning-induced currents to flow through earth thus ensuring maximum safety from electrical system faults and lightning. A properly installed grounding system helps to safeguard equipment and buildings from damages resulting from unintentional fault currents and lightning surges as well as protects human lives against any potential danger. Soil resistivity is one of the major factors that determine the effective performance of a grounding system. By ensuring low soil resistivity for a grounding system, its performance can be greatly enhanced. Different soils have different grounding resistivity, it is advisable therefore to always consider soil resistivity variations while designing for grounding systems. Soil resistivity varies significantly by region due to differences in soil type and changes seasonally due to variations in the soil's electrolyte content and temperature. It increases slowly with decreasing temperatures from 25°C to 0°C. Below 0°C, soil resistivity increases rapidly [1,2].

Soil resistivity measurements are useful for purposes of: (i) Estimating the ground resistance of a proposed substation or grounding installation, (ii) Estimating potential gradients

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including step and touch voltages, (iii) Computing the inductive coupling between neighboring power and communication circuits [1,3,4,5,6].

In most substations, the earth is used to conduct fault current when there are ground faults on the system. In single wire earth return power transmission systems, the earth itself is used as the path of conduction from the end customers (the power consumers) back to the transmission facility. In general, there is a limit above which the impedance of the earth connection must not rise, and some value of maximum step voltage which must not be exceeded to avoid endangering people and livestock.

Soil resistivity is influenced by the type of composition, moisture content and temperature. Soil is rarely homogenous; its resistivity varies geographically and according to different depths. Soil resistivity can change dramatically with changes in moisture, temperature, and chemical content. To determine the soil resistivity of a particular site, soil resistivity measurements need to be taken. Soil resistivity can vary both horizontally and vertically, making it necessary to take more than one set of measurements.

When designing an extensive grounding system for an electrical substation, it is often advisable to locate the area of lowest soil resistivity in order to achieve the most economical grounding installation. Actual resistivity measurements are required to fully qualify the resistivity and its effects on the overall power system infrastructure. Thus, soil resistivity measurement is best carried out at the site at the planning stage while designing for the grounding system [7].

This paper investigated the soil resistivity for substation grounding systems in three different locations during dry and wet seasons in Lagos state of Nigeria in 2016 using relevant IEEE Standards and International best practices for determining acceptable resistivity levels for such grounding system designs. The outcome of the investigation would be useful for purposes of estimating the ground resistance and potential gradients including step and touch voltages of substations or grounding installations and for computing inductive couplings between neighboring power and communication circuits within and around wetland regions.

Soil resistivity investigations

Soil resistivity is a measure of how much the soil resists the flow of electricity. It is a critical factor in design of systems that rely on passing current through the Earth's surface. An understanding of the soil resistivity and how it varies with depth in the soil is necessary to design the grounding system in an electrical substation, or for lightning conductors. It is needed for design of grounding (earthing) electrodes for substations and high-voltage direct current transmission systems.

The resistivity values for typical classes of soil are given in Table 1. Interpretation of the apparent soil resistivity based on field measurements is difficult. Uniform and two-layer soil models are the most commonly used soil resistivity models. The objective of the soil model is to provide a good approximation of the actual soil conditions. Interpretation can be done either manually or by the use of computer analysis. There are commercially available computer programs that take the soil data and mathematically calculate the soil resistivity and give a confidence level based on the test.

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Table 1. Classes of Soil and their Resistivity [8]

Class of Soil	Resistivity (Ω - m)
Paddy of Clay and Swamps	10 ~ 150
Farmland of Clay	10 ~ 200
Seaside Sandy Soil	50 ~ 100
Paddy or Farmland with Gravel Stratum	100 ~ 1,000
Mountains	200 ~ 2,000
Gravel, Pebble Seashore or Parched River Bed	1,000 ~ 5,000
Rocky Mountains	2,000 ~ 5,000
Sandstone or Rocky Zone	10^4 ~ 10^7

There are two ways to determine the resistivity of the soil at a certain site. The first is to actually measure the resistivity itself. The second is to drive a ground rod of known length and diameter into the ground and to measure its grounding resistance. That reading can then be used to calculate the resistivity of the surrounding soil [8].

The typical features of soils with certain resistivity values are shown in Table 2. Areas where the resistivity value exceeds 1,000 ohm-m are considered zones of high resistivity and grounding in such areas is very difficult. Generally, the earth is in layers and resistivity varies considerably depending on the layer or even at different depths within the same layer. Soil is therefore not consistent in resistivity values but rather unpredictable [8]

Table 2. Classification of Soil Resistivity [8]

Classification	Resistivity ρ[Ω - m]	Features
Low Resistivity Zone	$\rho<100$	Lowland at the mouths of rivers or by the sea. Usually abundant in water.
Medium Resistivity Zone	$100\le\rho<1,000$	Midland plains where ground water is not so difficult to obtain.
High Resistivity Zone	$\rho\ge1,000$	Hilly zones, piedmont districts and high lands, where drainage is good.

The soil resistivity value is subject to great variation, due to moisture, temperature and chemical content [9]. Typical values are:

I. Usual values: from 10 up to 1000 (Ω-m)
II. Exceptional values: from 1000 up to 10000 (Ω-m)

Electrical conduction in soil is essentially electrolytic and for this reason the soil resistivity depends on:

i) moisture content,
ii) ii) salt content,
iii) iii) temperature (above the freezing point 0 °C).

Soil resistivity is also one of the driving factors determining the corrosiveness of soil. Corrosion increases as resistivity decreases. The soil corrosiveness is classified based on soil electrical resistivity by the British Standard, BS 1377 as shown in Table 3 below:

Table 3. Soil Electrical Resistivity Classification [10]

Soil Resistivity (Ω-m)	*Soil Corrosivity*
<10	Severe
10-50	Corrosive
50-100	Moderately Corrosive
>100	Slightly Corrosive

THE STUDY AREA

The study area, Lagos lies in south-western Nigeria, on the Atlantic coast. It is located at longitude 2^0 42' E and 3^0 42' E and between latitudes 6^0 22' N and 6^0 42' N. On this stretch, lies the Lagos Lagoon with long coastal sand spits or sand bars. Badagry Creek flows parallel to the coast for some distance before finding an exit through the sand bars to the sea. The southern boundary of the state is formed by the 180-km long Atlantic Coastline while its northern and eastern boundaries are shared with Ogun state. Lagos is the most industrialised state as well as a commercial nerve-centre in Nigeria.

Wetlands are those areas where the water table is at, near, or above the land surface for a significant part of most years and the hydrologic regime is such that aquatic or hydro-phytic vegetation usually is established, although alluvial and tidal flats may be non-vegetated. Wetlands frequently are associated with topographic lows, even in mountainous regions. Examples of wetlands include marshes, mudflats, and swamps situated on the shallow margins of bays, lakes, ponds, streams, and manmade impoundments such as reservoirs [11].

The dominant vegetation in Lagos state is the Swamp forest consisting of the fresh water and mangrove swamp forest both of which are influenced by the double rainfall pattern of the State, which qualifies the environment as a wetland region.

Lagos state has two climatic seasons: Dry (November – March) and Wet (April – October). The wettest month is June with precipitation total 315.5 millimetres (12.42 in) while the driest month is January with precipitation total 13.2 millimetres (0.52 in) [12]. Figure 1 is the Map of Lagos showing the sites namely Surulere, Apapa and Victoria Island covered by this study.

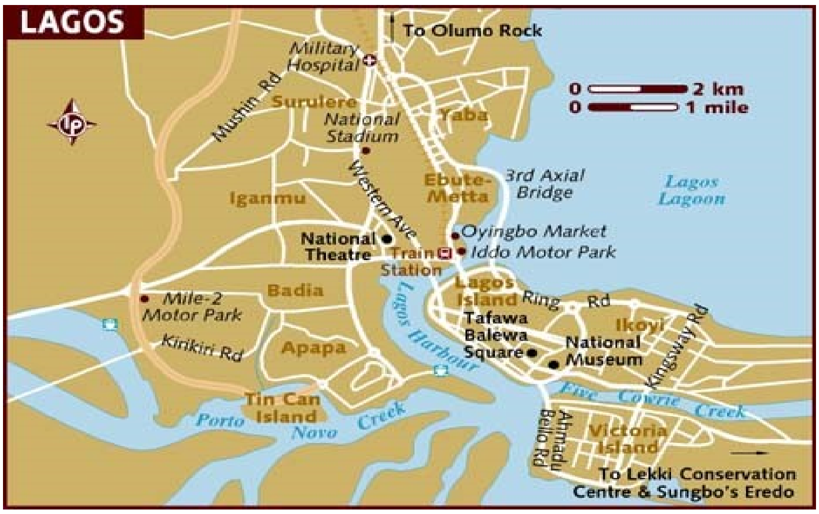

Figure 1: Map of Lagos [13]

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MATERIALS AND METHODS

The study employed the EM-4055 earth tester [14]. This is a digital, microprocessor controlled instrument that allows to measure the earth resistance and ground resistivity (using Wenner´s four-pin method), as well as to detect parasitic voltages present in the ground. The EM-4055 earth tester is suitable for soil resistivity measurements, in order to optimise the earth systems project. It is fully automatic and easy-to-operate equipment. Before starting each measurement, the equipment will check that conditions are within appropriate limits and will notify the operator in case any abnormality turns up (too high interference voltage, too much resistance in test spikes, very low test current, etc.). Then, it will look for the most suitable range and show measurement results in an alphanumeric display.

The instrument has four ranges that are automatically selected, covering measurements from 0.01Ω up to 20kΩ, which allows to obtain very accurate measurements for any kind of soils. During ground resistivity measurement, the operator determines the distance between spikes in order for the equipment to apply Wenner's formula and to show the resistivity value directly.

The Wenner four-pin method (Figure 2) is the most widely used and the most accurate method of testing soil resistivity. The method uses four electrodes which are embedded to the ground in straight line. Two of these electrodes are for current injection and two for voltage measurement. The two outer electrodes are current electrode and the two inner electrodes measure voltage drop due to resistance of soil path when current is passed between the outer electrodes.

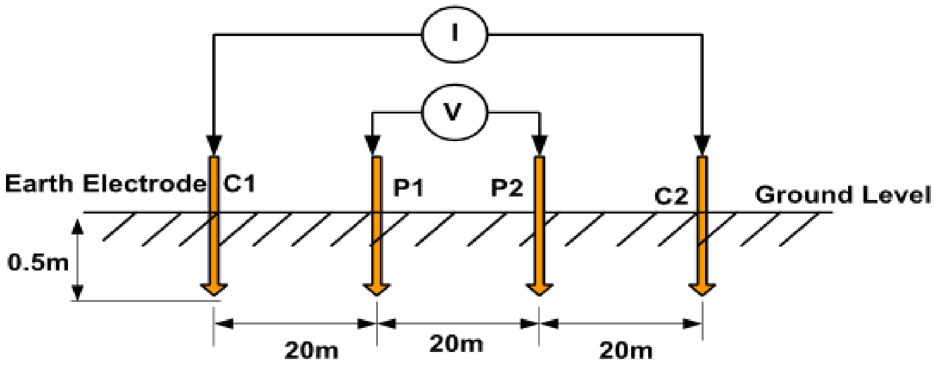

Figure 2: The Wenner Four-Pin Method

As best practice, the test is performed during different seasons of the year; the worst-case measured soil resistivity is then considered in order to design a grounding electrode system that will meet the resistance design goal throughout the year. The area indicating the lowest soil resistivity is often considered the optimum location for placement of the grounding (earthing) electrode system.

While carrying out the study, four probes are inserted in a straight line, equidistant from one another into the soil area being tested. The author ensured that the distance between the earth ground probes was at least three times greater than the depth into which the probes were inserted into the soil. A constant current generated by the earth ground tester was then allowed to flow through the two outer ground probes (C1 and C2) and consequently developed potential difference which was measured between the two inner ground probes (P1 and P2). The resulting resistance indicated by the tester was later used to calculate the soil resistivity according to Equation (1).

$$\rho = 2\pi AR \quad (1)$$

Where:

ρ = Soil resistivity (Ω.m)

π = Constant (3.1426)

A = Distance between the electrodes (m)

R = Resistance (Ω) measured from the test instrument

RESULTS AND DISCUSSION

Soil resistivity (ρ) is expressed in Ohm metres (Ω.m). This corresponds to the theoretical resistance in Ohms of a cylinder of earth with a cross-section area of 1 m^2 and a length of 1 m. By measuring it, you can find out how well the soil conducts electric currents. So the lower the resistivity, the lower the earth electrode resistance required at that location.

The findings of the study shows that resistivity varies significantly according to seasons and according to the level of humidity and the temperature. Soil resistivity decreases when the temperature increases. See Tables 4, 5, 6 and Figures 3, 4, 5. As temperature and humidity levels become more stable the further you go from the ground surface, the deeper the earthing system, the less sensitive it is to environmental variations. It is advisable to bury your earth electrode as deep as possible. The investigation has further revealed that the higher the air temperature, the lower the soil resistivity and the lower the humidity. Ideally, the earth surface potential should be flat in the area around the earth electrode. This is important for protection against electric shock, and is characterized by touch and step voltages. Rod electrodes have the most unfavourable surface potential distribution, while meshed electrodes have a much flatter distribution.

As shown in Tables 4, 5 and 6, the soil resistivity decreases while the air temperature and the depth in which the earth electrode is buried in the soil increases. This confirms the earlier findings of the independent studies carried out by Refs [15,16,17] which revealed that temperature variation of surface layer (≤ 20cm) contributes significantly to diurnal variation of soil resistivity.

Table 4. Resistivity, Humidity and Air Temperature Values in Victoria Island in 2016

Depth of Electrode (m)	*Resistivity (Ω.m)*											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1.0	280	154	122	180	147	95	100	115	149	162	173	200
3.0	211	144	100	152	133	64	78	97	132	158	165	184
5.0	98	62	48	86	74	29	31	36	47	69	75	88
7.0	72	46	37	67	53	23	28	30	38	45	53	61
9.0	51	33	30	41	37	17	20	26	30	31	37	48
Average Humidity (mmHg)	95	86	80	89	88	72	74	77	81	85	90	93
Mean Air Temperature (^{O}C)	25.1	31.2	32.5	30.8	31.4	34.1	34	33.9	33.7	32.2	30.7	27.4

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The outcome further justifies the preference of air temperature to ambient temperature of the earth electrodes in the investigation of the soil resistivity by the author. The ambient temperature, that is, temperature of the soil in which the earth electrode is buried was thus not considered in the study. Only the air temperature was measured in the course of the investigation.

The resistivity values were observed to be low during the wet season and lowest in June being the wettest month of the year. Conversely, during the dry season, resistivity values were observed to be high. The highest values were recorded in January which is the driest month of the year. These findings correlated in the three locations studied viz. Victoria Island, Apapa and Surulere areas of Lagos state.

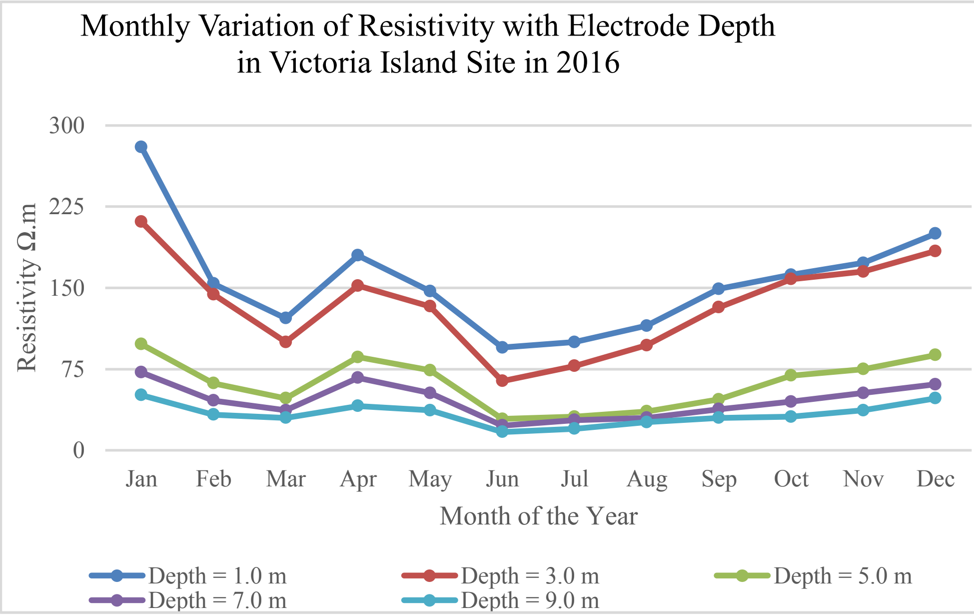

Figure 3: Resistivity variation with earth electrode depth in Victoria Island

Table 5. Resistivity, Humidity and Air Temperature Values in Apapa in 2016

Depth of Electrode (m)	*Resistivity (Ω.m)*											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1.0	452	240	143	260	219	98	113	120	164	182	180	327
3.0	335	178	124	204	199	72	97	114	153	170	165	256
5.0	218	169	67	98	85	32	34	38	57	76	93	197
7.0	116	98	48	64	72	26	30	32	35	58	69	108
9.0	87	54	36	47	44	20	23	27	31	36	47	62
Average Humidity (mmHg)	96	92	83	95	91.2	74	79	81	83	88	88	94.6
Mean Air Temperature (^{O}C)	25.0	26.2	27.1	31.2	32.8	35	34.7	34.5	34	33.1	26.5	25.4

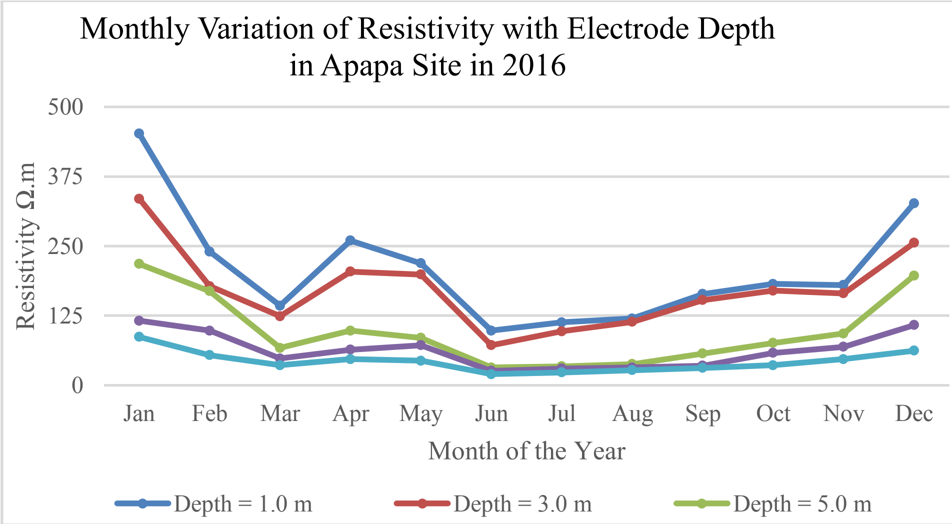

Figure 4: Resistivity variation with earth electrode depth in Apapa

Table 6: Resistivity, Humidity and Air Temperature Values in Surulere in 2016

Depth of Electrode (m)	*Resistivity (Ω.m)*											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
1.0	535	238	160	420	312	120	133	154	197	261	327	439
3.0	390	186	139	318	270	92	119	122	152	174	292	319
5.0	235	120	89	209	184	42	45	50	93	150	183	222
7.0	210	100	78	187	162	30	36	42	74	120	154	204
9.0	178	85	54	150	135	22	24	33	58	98	121	198
Average Humidity (mmHg)	96.2	90	87	97	94	82.6	83.4	84.2	86	91.5	94	95.1
Mean Air Temperature(^{o}C)	25	30	27	32.3	33.8	41.5	40.0	38.7	37.2	36.1	26.8	25.9

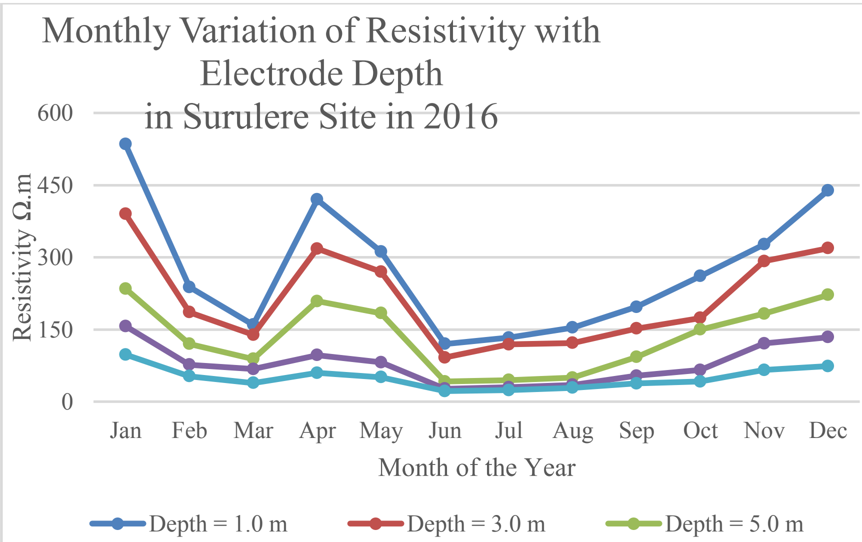

Figure 5: Resistivity variation with earth electrode depth in Surulere

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CONCLUSION

It is concluded that in wetland regions, soil resistivity varies seasonally and according to the level of humidity and the temperature. In the case of this study, during the month of June being the wettest month, the resistivity values were lowest while in January which is the driest month, the highest values of resistivity were recorded in the three locations studied. The investigation helped in ascertaining the soil corrosivity in the study area. The subsoil layers whose resistivity values are less than 10 Ohm-metre were classed as “very corrosive” whereas those whose resistivity values are within 10 and 50 Ohm-metre were classified as “corrosive.” Those geo-electric layers whose resistivity values range from 50 and 100 Ohm-metre were considered as “moderately and mildly corrosive” while those whose resistivity exceed 100 Ohm-metre were classified as “slightly or none corrosive.” The study further confirmed that the deeper the electrode rod is driven into the soil, the lower the soil resistivity.

The findings show also that soil properties are characterized by soil resistivity, which changes over a wide range from a few metres (m) up to few thousand metres (m), depending on the type of ground and its structure, as well as its humidity.

The study recommends use of copper-bonded electrode which is a molecularly bonded steel-cored copper ground rod in places where the layer is corrosive because of its comparative cost effectiveness. It is advised also that when designing large grounding systems such as for substations in wetland regions, the areas of lowest soil resistivity should be promptly located in order to maximize the overall system installation costs.

CONFLICTING INTERESTS

The researcher declares that no conflicting interests exist.

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