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Effectiveness of Earthing System in Vertical Configurations

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***Abstract*—**This paper presents the measurement and simulation results by Finite Element Method (FEM) for earth resistance (R_{DC}) for interconnected vertical ground rod configurations. The soil resistivity was measured using the Wenner four-pin Method, and R_{DC} was measured using the Fall of Potential (FOP) method, as outlined in the standard. Genetic Algorithm (GA) is employed to interpret the soil resistivity to that of a 2-layer soil model. The same soil resistivity data that were obtained by Wenner four-pin method were used in FEM for simulation. This paper compares the results of R_{DC} obtained by FEM simulation with the real measurement at field site. A good agreement was seen for R_{DC} obtained by measurements and FEM. This shows that FEM is a reliable software to be used for design of earthing systems. It is also found that the parallel rod system has a better performance compared to a similar setup using a grid layout.

***Keywords*—**Earthing systems, earth electrodes, Finite Element Method, FEM, Genetic Algorithm, GA, earth resistances.

I. Introduction

THE effectiveness of earthing system depends on its earth resistance value. The earth resistance values depend on the soil resistivity and earth electrode. Knowledge of the characteristics of the soil resistivity which heavily influences the resistance of an earth electrode is therefore important in any design of electrode configuration grounding system.

Earthing systems can be used to dissipate the fault current into the ground so as to protect expensive electrical equipments, as well as comply with statutory safety regulations in relation to personnel safety against electrical risks [1]-[5]. The ground impedance is an important index when designing the earthing installation, as there is the need to ensure that the value of the system's resistance to be of 5 Ω or less as recommended by IEEE Std. 80-2000 [1] to dissipate the fault currents effectively to the ground.

Previous work has looked at the earthing performance in both homogeneous and non-homogeneous soil for an embedded single-rod vertical system, as well as that using a horizontal grid configuration [2], [4], [6]-[8]. The behavior of earthing systems on its R_{DC} is dependent on the configuration of the earthing system [1], [9], and the resistivity of the soil can vary with depth, as well as in the traverse direction, between one point to another.

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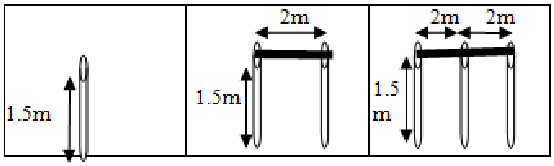
II. Measurement Set-Up

Three types of configurations have been used in this work which was carried out at Multimedia University. The 1.5 m long copper electrodes each of 16 mm in diameter were buried at a depth of 0.3 m below the earth's surface, and are interconnected with copper tapes (16 mm x 1.5 mm). The configurations used are shown in Fig. 1.



(a) (b) (c)

Fig. 1 Configurations of earthing systems in vertical for (a) 1 rod, (b) 2-rods, (c) 3-rods

A. Earth Resistance Measurement Set-up

To measure the R_{DC} for all earthing systems used in this study, the FOP method as outlined in IEEE/ANSI Std. 80-2000 [1] was used, where the measurements are initially carried out for the shorter distance (probe C1-P1) up to 90% of the total distance (C1-C2) with a 10% step interval in distance. FOP is the recognized method for measuring the resistance to earth of earthing system [6], [9]-[11]. From Fig. 2, probe C1 is the earth electrode under test, and probe P1 and C2 are two auxiliary electrodes placed at suitable distances from C1. When the current from the equipment is injected, it will pass between the electrodes C1 and C2, and the potential difference between probes C1 and P1 is measured. For current I and potential difference V, the quotient V/I will give the resistance value. Once all measurements have been made, the data is plotted with the distance from the electrode on the horizontal scale (X) and the measured resistance on the vertical scale (Y).

The curves for each data set should be smooth with no significant peaks or valleys. The curves will rise as the potential probe (P1) is moved away from the electrode, and level off just beyond the mid-point between the electrode (C1) and current probe (C2), and increases sharply when the potential probe approaches the current probe [1], [9], [10].

If the curves do not level off in the middle but have a small slope, the probes are only partially influenced by the electrode, and the resistance can be read from the curve at a point that is 61.8% of the distance to the current probe. The results and discussed in Section V of this present paper.

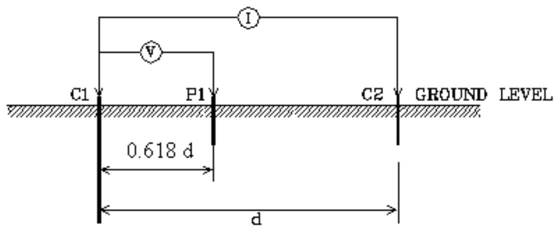


Fig. 2 FOP Set-up where: C1 – The earthing system under test, P1 – A potential/voltage probe, C2 – A current probe

B. Soil Resistivity Measurement Set-up

A homogeneous isotropic soil will have constant resistivity. However, in the case where the spacing of the grounding rods varies in an inhomogeneous soil, each set of measurement will give a different value of resistivity, known as the apparent resistivity. In this study, the apparent soil resistivity, ρ was measured using the Wenner four-pin method [1], [9], [11]-[13]. Fig. 3 shows the soil resistivity measurement set-up by Wenner method.

The set of measured values obtained from this exercise will later be interpreted to give an equivalent model representing the electrical performance of the soil in the grounding system. Here, the four rods are arranged with equal spacing, d in a straight line. In each set of measurement, a current, *I* is injected between the probes C1 and C2 and voltage V between probes P1 and P2 using Megger Tester. To obtain the apparent resistivity, ρ for every 'd' spacing, Ohm's law is applied whereby the earth resistance is taken as the ratio of the voltage of the earthing system and the current that flow into the earth via the earthing system [6], [9].

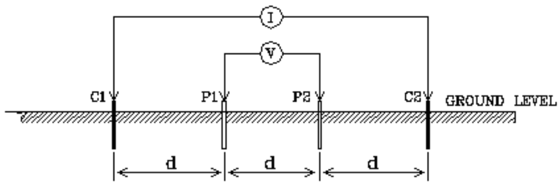


Fig. 3 Wenner four-pin Method Set-up

The apparent soil resistivity is then calculated using ρ = 2πdR, where ρ is the apparent resistivity (soil resistivity) in ohm-m (Ω-m), d is the distance between the electrodes in meter (m), and R is the digital readout of the resistance in ohms (Ω). Following this, ρ is interpreted as a 2-layer soil model using GA, as can be found in [8], [14], [15].

III. Interpretation Techniques by GA

Many studies have proposed a few methods on the interpretation of soil resistivity data into homogeneous, 2-layer or multi-layer soil model [16]-[19]. In this paper, the GA is utilised to interpret the soil resistivity data that are obtained by Wenner Method as presented in Section II *B* into 2-layer soil models. The GA method and formulae are obtained from [8], [14].

The applied GA starts with a randomly generated population for both the first and the second layer resistivities, as well as the thickness of the first layer. By applying the process of natural selection, the minimization problem is solved whereby the members with the lower values of the objective function are chosen. The algorithm minimises errors by repeating the iterations, and terminates this process only when the mean value of the optimization function is no longer improved.

The minimized function, *Fg* is given by [8]-[15]:

$$Fg = \sum_{i=1}^{N} \left| \frac{\rho_{\alpha i}^{m} - \rho_{\alpha i}^{c}}{\rho_{\alpha i}^{m}} \right| \tag{1}$$

where $\rho_{\alpha i}^{m}$ is the i^{th} measurement of the soil resistivity of the soil, using the Wenner method for a distance between two sequentially auxiliary electrodes equal to α , and $\rho_{\alpha i}^{c}$ is the calculated value of the soil at distance α between the auxiliary electrodes corresponding to the i^{th} pair of measurements. N is the total number of soil resistivity measurements.

The calculation of the soil resistivity is then made using (2)-(5) [8], [15]:

$$\rho_{\alpha}^{c} = \rho_1 \cdot \left(1 + 4 \cdot \sum_{n} K^{n} \cdot \left(\frac{1}{\sqrt{A}} - \frac{1}{\sqrt{B}} \right) \right) \tag{2}$$

where $n = 1 \ldots \infty$. K is the reflection coefficient:

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{3}$$

A and B are two parameters, which are given by:

$$A = 1 + \left(\frac{2 \cdot n \cdot h_1}{\alpha} \right)^2 \tag{4}$$

$$B = A + 3 \tag{5}$$

The convergence of two-layer earth parameters is presented in Appendix A.

IV. FEM Simulation

The steady state grounding impedance has been calculated using an FEM-based software, developed by [20] and [21]. The finite element approach has been adopted as it takes into account the heterogeneity of the different layers of soil and an arbitrary configuration of earthing systems. In this paper, the FEM software that was developed by [20] and [21] is used. This software has been tested and verified with many cases already [21], and the results are found to be similar to previous published work. However, the verification of FEM was done by [20], [21] based on [22] that was done by computational method. In this work, FEM software is compared to the experimental work. The electrodes analysed, each with a length of 1.5 m and a diameter of 16 mm, are placed 0.3 m vertically from the surface of the earth into the two-layer soil (interpreted using GA) as in Section III which have an upper- and lower-layer resistivities, ρ_1, and ρ_2, of 500.1 Ωm and 99.184 Ωm respectively. The height of the upper layer soil, h_1 is 1.094 m, and the fault current, I_f is taken as 10 mA, which is maximum value from Megger Digital East Tester instrument. The flowchart of the FEM simulation is shown in Fig. 4.

The process to calculate the R_{DC} values for earthing configurations as given in Fig. 1 as follows:

i) At initial stage, the parameters of earthing system as configuration, geometric of electrode (length *l* and diameter, *d*), the depth of earthing system and the resistivity of electrode (conductor) are as the input parameter in the software.

ii) Then, it is followed with placed input data such as electrical characteristic (fault current, I_f) and the soil resistivity of 2-layer soil (ρ_1, ρ_2 and h_1).

iii) The 3-D current field calculation is done by FEM to calculate the earthing resistance, R_{DC}

iv) Modification of earthing system will be applied for different configuration as in Fig. 1 (Section II) and continued which later complete the simulation with step (i) until step (iii) above then complete.

In the analysis, the field caused by the fault current flowing through the earthing system into the soil is expressed by Laplace's equation with set boundary conditions, which are then discretized into finite element quantities whose computed solution gives the relevant nodes making up the value of the needed R_{DC} [16], [17].

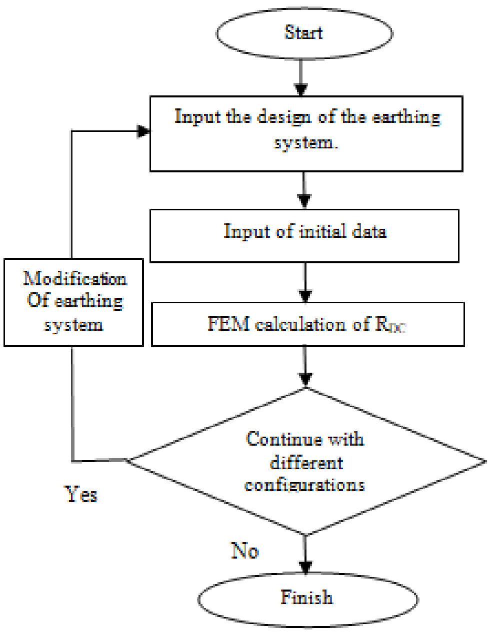


Fig. 4 Flowchart of the FEM simulation

IV. Results and Discussions

The simulation and experimental results are compared for all configurations of the earthing systems in this study, under steady state conditions.

The results of R_{DC} are recorded at 61.8 % of the C1-C2 (C1-P1 probe distance) as shown in Fig. 5. This is a slight adaptation – the "61.8 % Method"- of the FOP method for medium sized earthing systems.

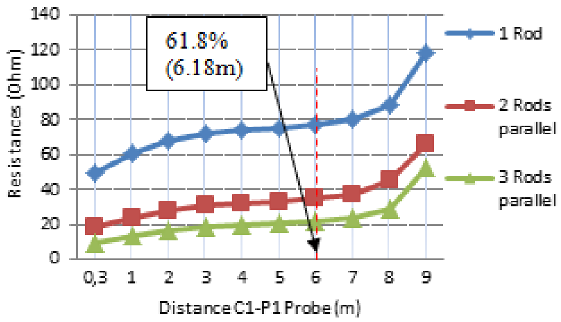


Fig. 5 Results of Earth Resistance, R_{DC}

The measurement and simulation results are shown in Table I. As expected, it can be seen that when only a single vertical rod is embedded into the soil, the value of the R_{DC} obtained is the highest, whereas the 3-rod set-up gave the lowest R_{DC} value.

TABLE I
Measured Earth Resistance Values

Comparison results	1 rod	2-rod system	3-rod system
Measurement at site	77.6 Ω	34.5 Ω	21.6 Ω
FEM software	63.92 Ω	33.61 Ω	20.51 Ω

The difference of reduction between R_{DC} by measurement and FEM is found to be less than 9%. The results also show that, an additional rod placed in parallel will reduce the earth resistance, by 55.54% in a 2-rod system, and 72.16% in a 3-rod system as compared to a single rod. This reduction is due to the arrangement of the electrodes in parallel. In contrast, [6] carried out measurements on a horizontal grid system and only managed to get a comparable R_{DC} as obtained in this work, at 1.8 m depth for their 3-rod system, and 1.2 m depth for their 4-rod system, indicating the potential of parallel rod placements compared to that of the more complicated grid one.

VI. Conclusions

Extended and electrodes in vertical configurations showed better R_{DC} values. Earth resistances value of 1, 2 and 3 rods earthing systems are obtained by measurement and FEM. For measurement methods, the FOP method was adopted. For FEM, soil resistivity was first obtained by Wenner Method which was followed by interpretation into a 2-layer soil model. The detail configuration of the earthing system was then incorporated in FEM. Close agreement was found between R_{DC} by measured and simulation methods. This shows that FEM can be utilised for difficult assessment of R_{DC} especially for existing substation.

APPENDIX A: INTERPRETATION OF SOIL RESISTIVITY IN TWO-LAYER

Site location at MMU has been used for experiment. The measurements of soil resistivity are presented in Table II whereas the results of GA application to the mentioned measurements are shown in Fig. 6. The parameters of the structure of soil resistivity and the thickness of the first layer, are, respectively, ρ1 = 500.1 Ωm, ρ2 = 99.184 Ωm and h1 = 1.094 m.

TABLE II
APPARENT RESISTIVITY, ρ_A AT SITE LOCATION IN MMU

a (m)	1	2	3	4	5	6	7	8	9	10
ρ_a (Ωm)	355	246	159	1267	112	100	100	102	103	110

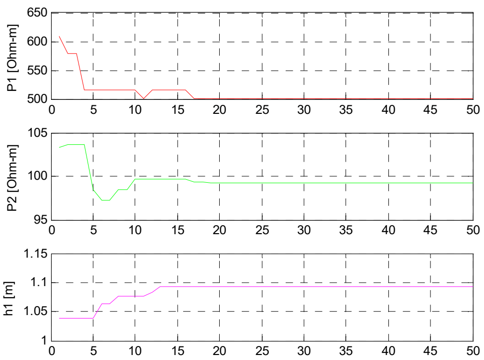


Fig. 6 Convergence of two-layer earth structure parameters

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