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**Citation:**
METHODS FOR FIELD MEASUREMENT OF THE FREQUENCY-DEPENDENT SOIL ELECTRICAL PROPERTIES: EVALUATION OF ELECTRODE ARRANGEMENTS THROUGH FEM COMPUTATIONS

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Abstract: The low radio-frequency electrical properties of soil (up to 3-5 MHz) are important for lightning transient and grounding system studies. Measurements of soil electrical properties are most commonly performed on undisturbed or reconstituted soil samples even though it is difficult to use these results for the representation of undisturbed ground in field conditions. This work presents an evaluation of several electrode arrangements for field measurement (in situ) of the frequency-dependent soil electrical properties at low radio-frequencies through FEM computations. The developed model is validated against results obtained theoretically and using grounding analysis software. A parametric analysis is performed by varying electrode dimensions, separation distances between electrodes and the excitation frequency (up to 100 kHz); several uniform as well as two-layer soil models were investigated. Results are compared and discussed based on deviations from the assumed hemispherical symmetry of the potential distribution in the ground around the injecting electrode taking into account the effects of excitation frequency and soil model parameters. The most appropriate arrangement for field measurements comprises a hemispherical and a ring electrode for current injection as well as two potential probes; for practical applications, the ring current-return electrode can be replaced by four ground rods in order to minimize the time and effort required for the setup of the electrodes. A preliminary investigation is conducted to assess the applicability of the measured apparent electrical properties of non-uniform soils to the computation of the impedance of ground electrodes. It is shown that using the apparent soil electrical properties as determined for an arbitrary distance between potential probes, may result in significant errors in the computed impedance of ground electrodes.

1 INTRODUCTION

The electrical properties of soil at low radio-frequencies are important for many engineering applications, including lightning transient studies and grounding system design and analysis. For such applications, soil can be characterized using the relative permittivity, $\varepsilon_r$, and the effective (equivalent) conductivity, $\sigma_{eff}$, that is, the sum of the DC and AC conductivity. $\varepsilon_r$ and $\sigma_{eff}$ are frequency-dependent owing to polarization phenomena in soil. Actually, at low radio-frequencies $\varepsilon_r$ decreases with increasing frequency due to the distributed relaxation of the interfacial polarization mechanism and $\sigma_{eff}$ increases as a result of the associated polarization losses.

For frequencies up to 3-5 MHz related to lightning phenomena, measurement of the frequency-dependent soil electrical properties is typically performed on undisturbed or reconstituted soil samples using two-, three- or four-terminal cells [1-4]. In this way, the actual electrical properties are obtained for the soil under test. However, due to the non-uniformity of soil, it is difficult to use these results for characterizing the electromagnetic behaviour of undisturbed ground in field conditions, thus also for determining an accurate soil model. This task requires field measurements to be conducted, analogous to those used for determining the apparent DC (or power frequency AC) soil resistivity, $\rho$. For DC soil resistivity measurement, several field methods and electrode arrangements have been proposed in literature, as also adopted by IEEE standards [5, 6]. However, for field measurement of the frequency-dependent soil electrical properties only Visacro and Alipio [7] have proposed a method.

This work presents an evaluation of several electrode arrangements for field measurement of the frequency-dependent soil electrical properties. This is accomplished through FEM computations using COMSOL Multiphysics software [8, 9]; the latter is commonly used in literature for the analysis of grounding systems [10-13]. A parametric analysis is performed considering different electrode dimensions and separation distances between electrodes, as well as several uniform and two-layer soil models. Results are compared and discussed considering the effects of excitation frequency and soil model parameters.
is shown that the most appropriate electrode arrangement for field measurements comprises a hemispherical and a ring electrode; for practical applications, the latter can be replaced by four equipotential ground rods.

2 FEM MODELLING USING COMSOL

2.1 General settings

The model employed in FEM computations was developed using the Electric Circuit and Electric Currents interfaces of the AC/DC module [9] of the COMSOL Multiphysics software [8]. The former interface was utilized to excite the evaluated electrode arrangements in the frequency domain through an External I vs. U node. The electrode arrangements were designed with the aid of the Electric Currents interface. The ground surrounding the electrodes consists of two concentric hemispheres. The subdomain between the hemispheres is characterised as an Infinite Element Domain; hence, the ground is considered as semi-infinite and the total dimensions of the model do not affect computation results.

The potential of the outer hemisphere surface was set to 0 V to simulate the remote earth. The Electric Insulation boundary condition was used at the ground-air interface: \( n \cdot J = 0 \), where \( n \) is the normal unit vector and \( J \) is the current density vector. The investigated electrodes were excited using a Terminal node by coupling the Electric Circuit and Electric Currents interfaces. Models were created in 3D and/or 2D axisymmetric geometries (where possible) so as to minimize simulation time and memory usage. The extremely fine physics-controlled mesh was used in all cases.

Several uniform and two-layer soil models were employed in computations; the relative permittivity, \( \varepsilon_r \), and resistivity, \( \rho \), values are given in Table 1. The electrical properties of soil were considered as frequency-independent since computations are performed in the frequency domain and each \((\varepsilon_r, \rho)\) set is employed for all investigated frequencies. The selected \( \varepsilon_r \) values of the uniform soil models (Table 1) decrease with increasing \( \rho \) values as expected for actual soils [1-4]. Extremely high \( \varepsilon_r \) values were deliberately chosen so as to consider cases with relatively high electric displacement currents. The two-layer soil models of Table 1 (soil cases 5 and 6) were implemented in COMSOL by modelling the upper layer as a disk with a diameter almost equal to the inner hemispherical subdomain and depth equal to that of the soil model (Table 1).

Initially, validation was performed for DC and AC excitation by simulating ground electrodes and a guarded two-electrode laboratory arrangement, respectively. The frequency values used in this work were lower than 100 kHz to fulfill the criteria for the quasi-static approximation at the highest frequency, taking into account the largest dimensions of the investigated electrode arrangements. The AC/DC module of COMSOL, which employs quasi-static analysis, is appropriate for problems with electrical size less than 0.1 [9].

2.2 Validation with DC excitation

In order to validate the model under DC excitation, several hemispherical electrodes and ground rods were simulated in uniform soils \((\rho = 10^{-6}-10^4 \, \text{Ωm}, \varepsilon_r = 10^6)\) considering both 3D and 2D axisymmetric geometries and using a Stationary Study. Each electrode was excited by DC current and the obtained ground resistance was compared with that calculated using well-known expressions [3] or computed with the XGSLab software [14]. Also, results of 3D and 2D axisymmetric geometries were compared. For all investigated cases, the obtained errors are less than 0.05%; typical results are shown in Figure 1.

2.3 Validation with AC excitation

Validation in the frequency domain was performed by simulating a guarded two-electrode laboratory arrangement used for soil electrical properties measurements in the frequency range from 42 Hz up to 1 MHz (Figure 2 of [4]). The arrangement was simulated in 3D geometry using a Frequency

<table>
<thead>
<tr>
<th>Soil Case</th>
<th>( \rho ) (Ωm)</th>
<th>( \varepsilon_r )</th>
<th>Depth, h (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10000</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Two-layer soil models</th>
<th>( \rho_{\text{upper}} ) (Ωm)</th>
<th>( \rho_{\text{lower}} ) (Ωm)</th>
<th>( \varepsilon_r )</th>
<th>Depth, h (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
<td>100</td>
<td>10000</td>
<td>0.3, 0.5</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>10</td>
<td>10000</td>
<td>1.0, 2.0</td>
</tr>
</tbody>
</table>

Figure 1: Ground resistance of a hemispherical electrode: (a) Calculation and 3D simulation and (b) 3D and 2D axisymmetric simulation; parameter: soil resistivity.
3 VISACRO AND ALIPIO METHOD

For field measurement of soil electrical properties in the frequency range up to 3-5 MHz the only available method has been proposed by Visacro and Alipio [7] (Figure 2). A low-voltage impulse generator is used to inject a current between a hemispherical electrode and four auxiliary rods. The developed potential difference between the hemisphere and a point on the ground surface is measured and the admittance in the frequency domain, $Y^*$, is obtained. The electrical properties of soil are calculated using (1), which is derived assuming hemispherically symmetric current and potential distributions in the ground:

$$Y^*(\omega) = \frac{2\pi \left( \frac{1}{\rho(\omega)} + j\omega\varepsilon_r,\varepsilon_0(\omega) \right)}{1 - \frac{\rho_1}{\rho_2}}.$$  

In (1) $Y^*$ is the admittance between $r_1$ (m) and $r_2$ (m) (Figure 2), $\omega$ (rad/s) is the angular frequency, $\varepsilon_r$ is the relative permittivity of soil, $\varepsilon_0$ is the permittivity of free space (8.854·10^{-12} F/m) and $\rho$ (Ωm) is the electrical resistivity of soil.

As evident from Figure 2, the current returns to the impulse generator on the auxiliary rods, which are not symmetrically positioned with respect to the hemisphere. Even though the rods are placed at a considerable distance from the hemisphere, the assumption of a hemispherically symmetric current distribution has to be investigated; from a relevant study on impulse ground impedance measurement it can be deduced that such a distribution may not always apply [15]. In addition, and most importantly, this method uses a three-terminal arrangement; therefore, measurement errors due to contact resistance and electrode polarization effects are inherent, as the hemisphere is used for both current injection and voltage measurements.

4 DESIGN AND EVALUATION OF ELECTRODE ARRANGEMENTS

Several electrode arrangements were designed in this work in order to achieve symmetric current and potential distributions in the ground and to eliminate measurement errors due to contact resistance and electrode polarization effects. A parametric analysis was conducted to evaluate arrangements using a hemispherical electrode for current injection in the ground and either a ring electrode or four equipotential ground rods as return electrodes (Figure 3). The voltage arising between two points on the ground surface due to the injected current is measured using two test probes. It is noteworthy that arrangements employing a ring electrode for the current return path have been used in ground impedance measurements in [15, 16].

4.1 Uniform soil models

The evaluated electrode arrangements of Figure 3 were simulated in uniform soils using 3D or 2D axisymmetric geometry. Different ring burial depths, $h$, hemisphere, $D_h$, ring, $D_r$, and conductor, $D_c$, diameters were investigated. It was found that the current and potential distribution symmetry in the ground is predominately affected by $D_h$; thus, the latter was considered as an influencing parameter in what follows. In simulations, the ring was placed at the ground surface taking into account the applicability of the arrangement; the hemispherical electrode and conductor diameters were selected 0.5 m and 6 mm, respectively.

Figure 4 shows the variation of the relative difference between the maximum and minimum potential on a hemispherical surface in the ground with its radius, $r$, for several values of $D_c$ (Figure 3a); this variation is a measure of the asymmetry in current and potential distributions in the ground. The potential can be considered as symmetrically distributed only close to the hemispherical electrode; potential difference values lower than 5% were obtained for $r < 0.18D_c$. Based on the results of Figure 4, a ring diameter of 60 m is

![Figure 2: Electrode arrangement of the Visacro and Alipio [7] method (not according to scale).](image)

![Figure 3: Investigated electrode arrangements for field measurements of the frequency-dependent soil electrical properties (top view). Current-return electrode: (a) Ring and (b) Four ground rods.](image)
adopted resulting in enhanced symmetry in the potential distribution. Figure 4 also includes the results referring to the Visacro and Alipio arrangement (Figure 2). It is evident that the potential distribution is symmetric for considerably shorter distances from the centre of hemispherical electrode as compared with the arrangement of Figure 3a for the corresponding case of $D_r = 60$ m. It is important that the results of Figure 4 are not affected by the electrical properties of the uniform soil model (Table 1) and the excitation frequency.

In order to evaluate the applicability of (1) to the adopted electrode arrangement ($D_r = 60$ m), the computed admittances between several points on the ground surface (radii $r_1$ and $r_2$ from the centre of the hemispherical electrode) were compared with those calculated by using (1). Figure 5 shows the variation of the absolute relative error of the computed admittance amplitude, $|\Delta Y/Y|$, with $r_1$ and $r_2$; these results are not influenced by the excitation frequency and the uniform soil model (Table 1). As evident from Figure 5, $|\Delta Y/Y|$ is constantly lower than 1%; for the phase angle of the admittance, errors are lower than 0.1%. Hence, (1) yields accurate results even when the potential difference is measured at a considerable distance from the hemispherical electrode.

Figure 6 shows the corresponding relative error values, $|\Delta Y/Y|$, for the Visacro and Alipio arrangement. Despite the fact that in their method $r_1$ is equal to the hemispherical electrode radius (Figure 2), in this work the positions of both $r_1$ and $r_2$ were varied along the axis connecting the hemispherical electrode with the auxiliary rods. Apparently, the error values of the computed admittance amplitude are almost 1 order of magnitude higher than those of Figure 5; for the admittance phase angle, errors were found comparable between the two arrangements. For the Visacro and Alipio arrangement, (1) can be used with confidence when both potential probes are in close proximity to the hemispherical electrode, where symmetry is acceptable (Figure 4). Alternatively, at least one potential probe should be placed at a very short distance from the hemispherical electrode where the potential rise on the ground surface attains its highest values, thus, dominating voltage measurements.

In light of the above, the electrode arrangement of Figure 3a has several advantages with respect to that shown in Figure 2. Specifically, by employing two potential probes the effects of contact resistance and electrode polarization are eliminated. Also, due to enhanced symmetry of the current and potential distributions, the potential probes can be placed at greater distances from the hemispherical electrode (Figures 5 and 6).

A simplified electrode arrangement has also been evaluated so as to facilitate electrode setup in the field. The ring electrode of Figure 3a is replaced by four equipotential ground rods symmetrically placed around the hemispherical electrode (Figure 3b) at a distance of 30 m. In order to assess the effectiveness of this simplified arrangement, the computed admittances were compared with those referring to the arrangement of Figure 3a for $D_r = 60$ m; typical results are shown in Figure 7. For all cases it was found that deviations are lower than -0.5% for both the amplitude and phase angle of the admittance when the potential probes are placed along an axis that connects the hemispherical electrode with a rod (Figure 3b).

### 4.2 Two-layer soil models

Two-layer soil models were also evaluated in order to better simulate field conditions. Figure 8 shows the potential distribution around the hemispherical
A preliminary investigation was conducted to assess the applicability of the apparent soil electrical properties obtained using the arrangement of Figure 3a to the computation of the impedance of a ground electrode. A ground rod (length: 2 m, diameter: 0.02 m) was simulated using the two-layer soils of case 5 (Table 1) and the uniform soils with the corresponding apparent electrical properties; the frequency spectra of the latter were determined from the arrangement of Figure 3a \((D_r = 60 \text{ m})\) for \((r_1, r_2) = (0.25 \text{ m}, 0.9 \text{ m})\). Figure 9 shows the variation of relative error values of the computed ground rod admittance with excitation frequency. Obviously, the apparent electrical properties do not satisfactorily describe the two-layer soils. This was found to apply also for the apparent electrical properties determined using the Visacro and Alipio arrangement.

Consequently, the use of the apparent electrical properties of non-uniform soils determined for an arbitrary distance between potential probes may result in significant errors in grounding system simulations. Further work is needed to develop appropriate methods for measurement results interpretation, so as to derive soil models representative of non-uniform field conditions.

5 CONCLUSIONS

Several electrode arrangements for field measurement of the frequency-dependent soil electrical properties have been evaluated through FEM computations. The developed FEM model has been validated against results obtained using theoretical expressions and grounding analysis software. A parametric analysis has been performed by varying electrode dimensions, separation distances between electrodes and the excitation frequency (up to 100 kHz); several uniform as well as two-layer soil models were employed in computations.
The most appropriate electrode arrangement for field measurements of the frequency-dependent soil electrical properties comprises a hemispherical and a ring electrode (diameters: 0.5 and 60 m, respectively) used for current injection; the ring electrode can be replaced by four equipotential ground rods to facilitate electrode setup. The voltage arising between two points on the ground surface due to the injected current is measured using two test probes. Therefore, measurement errors due to contact resistance and electrode polarization effects are eliminated.

The frequency-dependent electrical properties determined from field measurements performed on non-uniform soils are apparent values, varying with potential probe positions. Further work is needed to develop appropriate methods for measurement results interpretation, so as to derive soil models representative of non-uniform field conditions. In addition, investigation is required for frequencies higher than 100 kHz, considering in computations wave propagation effects.

REFERENCES


