High frequency response of grounding electrodes: effect of soil dielectric constant

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Abstract: Grounding electrodes have an important role in electric power transmission and distribution systems. They are used to prevent excessive hazardous voltages due to ground potential rise in the case of system faults or lightning surges. The electrical properties of soil, which vary substantially with geographical location and time of year, affect the process considerably along with the properties of the grounding electrode itself, such as its dimensions. To have an accurate estimation of the induced overvoltages due to lightning strike, one has to take into account the effect of the value of the soil electrical parameters, such as the electrical conductivity and dielectric constant. This study investigates the high frequency behaviour of the grounding electrodes by solving a full-wave electromagnetic problem using the finite element method. The focus of this paper is on the effect of the variation of soil relative permittivity on the induced transient voltage in grounding electrodes. This allows an evaluation of the response of grounding systems due to seasonal changes, which would cause its electrical properties to vary significantly. This study demonstrates the importance of considering the variation of relative permittivity of the soil especially in the modelling of electrodes buried in highly resistive soil.

1 Introduction

Vertical and horizontal rods are commonly used in power systems as a type of earth termination to provide a path for the lightning current to flow in to the earth [1]. An effective grounding system directs lightning intensive currents to the earth with a low potential rise of the grounded system, which may be hazardous to personnel or sensitive electrical equipment. Negative first strokes have been traditionally known to produce the worst stress on the system insulation. The subsequent negative strokes have considerably lower peak currents but have a higher frequency content, up to a few MHz [2]. The dynamic behaviour of grounding electrodes in case of fast varying currents, such as lightning strokes, is different from their low frequency response [3]. There has been a significant number of research that aimed at high frequency modelling of grounding electrodes.

In general, the problem of modelling grounding electrodes is solved using (i) theoretical, (ii) numerical, and (iii) experimental [4–6] methods. The theories are either based on the circuit [7–9] or transmission-line formulations [10–14]. Full-wave electromagnetic modelling, using numerical techniques are based on finite element method (FEM) [15–18], method of moments [19–22], finite-difference time-domain method [23–25], and partial electric equivalent circuit [26, 27]. These methods can be considered as the most rigorous and accurate modelling procedures over a wide frequency range.

In lightning studies on grounding systems, the electrical parameters of the medium in which they are buried have a high importance and they need to be determined accurately. It has been shown through experiments that the conductivity and dielectric constant of soil are both very dependent upon the moisture content of the soil which is known to vary from 4 to 30% of the total soil weight over the greater part of the year [28]. Moreover, as the frequency of the waves penetrating in-to the ground increases, the dielectric constant of soil plays a more important role in determining the effect of the earth on the wave propagation. Due to these facts, the importance of evaluating the effects of the variation of the electrical parameters of the soil, particularly the dielectric constant in the whole permissible range, on the high-frequency response of grounding electrodes has to be studied. In the published literature, the dielectric constant of the soil is commonly assumed equal to 10 and its variation is not considered, although this value may vary between 3 or 4 for dry soil up to 30 for very moist soil, depending on the nature of the soil [10, 28].

The other characteristic of soil is the frequency dependence of its electrical parameters (resistivity and permittivity). There are several available frequency dependent models for the soil which are driven based on experimental data, such as, Messier [29], Visacro and Portela [30], Portela [31], Visacro and Alipio [32]. In it shown in such models that both the resistivity and permittivity of the soil decrease as the frequency increases, leading to a decreased grounding impedance [16, 33]. The frequency dependence of soil electrical parameters is disregarded in this paper, therefore the results are applicable for a conservative estimate of the upper bound of the grounding impedance and this can be considered as an assumption on the safe side. However, it is straightforward to consider this effect in the transient analysis of grounding electrodes using the simulation model proposed in this paper [16].

The objective of this paper is to investigate the response of vertical and horizontal grounding electrodes in the context of lightning currents considering a wide range of conductivity (0.1–0.0001 S/m) and relative permittivity (3–30) of the soil in the frequency range of 1 kHz–20 MHz. This frequency range has been selected because the major frequency content of the first and subsequent lightning currents have been shown to be below 10 MHz [2] and the behaviour of grounding electrodes is purely resistive below a frequency of 10 to 100 kHz (as will be shown in this paper). In this paper, we develop a full-wave electromagnetic model that is solved using the FEM [34, 35]. Solving the full-wave Maxwell's equations in the proposed model enables the consideration of long grounding electrodes. The frequency-domain impedance of the grounding electrodes is calculated using the proposed model with a focus on the effect of soil dielectric constant on the performance of grounding electrodes. Furthermore, the numerical simulation results are compared with those obtained using other modelling approaches. Unlike the Fourier-transform based approaches, the frequency-domain simulation results of this work can be directly incorporated in EMT-type simulators. Also, time-domain electrode voltages due to both the typical first and subsequent return strokes are calculated and the effects of the soil parameters on the time domain waveforms are investigated. This

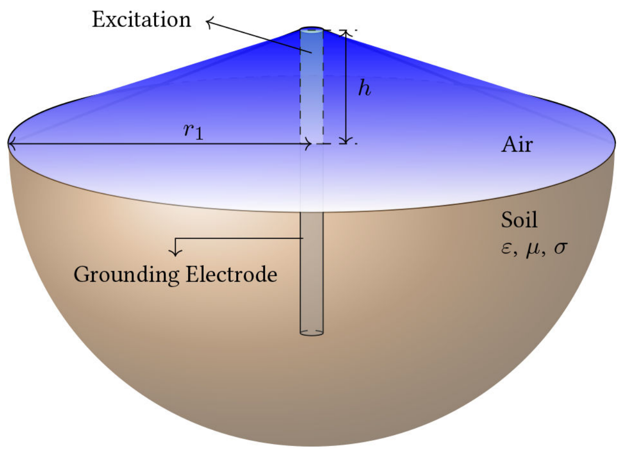


Fig. 1 *Proposed FEM model for the calculation of the grounding impedance. The air region is represented by the blue cone of height h, the brown hemisphere with radius r_1 is representing the ground region, and a rectangular port is defined for the excitation*

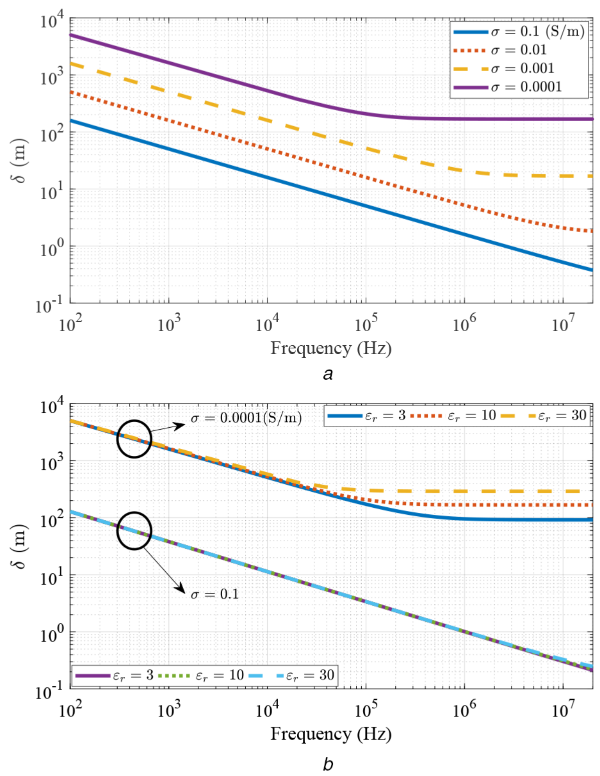


Fig. 2 *Skin depth in soil as a function of frequency, considering*
(a) Varying conductivity and $\varepsilon_r = 10$, ***(b)*** $\varepsilon_r = 3, 10, 30$

will allow one to have an accurate estimation of the grounding impedance variations in different soil conditions.

2 Determination of grounding impedance

Consider a grounding electrode buried in a soil with conductivity σ, permittivity ε, and permeability μ. In order to find the grounding impedance, an exciting voltage source $V(j\omega)$ is applied to the top of the grounding electrode whose other terminal is connected to a remote ground. By calculating the injected current into the grounding rod $I(j\omega)$, its input impedance in the frequency domain, also known as harmonic impedance [3], is obtained using

$$Z(j\omega) = \frac{V(j\omega)}{I(j\omega)}. \tag{1}$$

To determine $I(j\omega)$, a commercial finite-element full-wave electromagnetic solver [ANSYS HFSS] is employed to solve the wave equation in the frequency domain that is given by [36]

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \boldsymbol{E}(x,y,z)\right) - k^2\,\boldsymbol{E}(x,y,z) = \boldsymbol{0} \tag{2}$$

where

$$k = \omega\sqrt{\varepsilon\left(1 - j\frac{\sigma}{\varepsilon\omega}\right)}$$

and $\boldsymbol{E}(x,y,z)$ is the electric field vector. The finite simulation space is enclosed by perfect electric conductor (PEC) boundary condition that also creates a return path for the current. This boundary condition requires the tangential component of the electric field ($\boldsymbol{E}_t$) and the normal component of the magnetic field ($\boldsymbol{H}_n$) to be zero as given by [36]

$$\boldsymbol{E}_t(x,y,z) = 0 \tag{3a}$$

$$\boldsymbol{H}_n(x,y,z) = 0. \tag{3b}$$

The soil region is modelled as a hemisphere of radius r_1. However, any other symmetrical geometry can be used to represent the boundary of the ground as long as it is large enough [16]. The air region is modelled as a finite-length conical transmission line of length h, a lower radius r_1, and an upper radius equal to the radius of the grounding electrode. Using the conical transmission line results in higher cut-off frequencies for the non-TEM modes [37, 38]. The cut-off frequency for higher order TE and TM modes depends on the cone half angle and the radial distance in the spherical coordinate system from the cone apex [37]. As a result, these two parameters should be chosen carefully to avoid reflections from the outer PEC boundary of the air region in the frequency range of interest. A schematic view of the proposed model is shown in Fig. 1. The excitation is provided by means of a numerical port defined as a rectangle with a width equal to the electrode's diameter and a length of h. The numerical port will introduce a parasitic inductance. Selecting $h = 10$ mm results in the parasitic impedance to be negligible compared with the grounding impedance [16].

In (2), as the frequency increases the term $\sigma/\varepsilon\omega$ decreases, that means the effect of soil conductivity on the propagation of electromagnetic waves in the ground is less significant. As a result, at high frequencies ($\sigma/\varepsilon\omega \ll 1$), the dielectric constant will play a prominent role in determining the effect of the earth on the propagation of the electromagnetic wave [10].

2.1 Size of the computational domain

Considering a relative permittivity of $\varepsilon_r = 10$ for the soil, the dependence of skin depth on soil conductivity over a frequency range of 100 Hz to 20 MHz is shown in Fig. 2*a* [10]. As the conductivity of the soil decreases from 0.1 to 0.0001 S/m, the skin depth increases. Knowing the skin depth at a given frequency, one can determine the size of truncation radius of the ground. The variation of permittivity has no influence in the low frequency region (i.e. < 100 kHz) regardless of the soil conductivity, as shown in Fig. 2*b*. However, at high frequencies (i.e. > 100 kHz) and for soil of low conductivity, the skin depth is larger for soil with a higher permittivity. It can be concluded from Fig. 2 that if a specific value for the truncation radius of the ground accurately simulates the low frequency case, it can be assured that it also simulates the high frequency propagation with no error due to the truncation. Fig. 3 shows the results of the FEM electrostatic analysis, where vertical grounding electrodes are buried in a soil with conductivity of 0.1 S/m. As shown in this figure, for modelling a 1 m vertical grounding electrode, a truncation radius (r_0) of 50 m is sufficient for the ground to achieve an error of less than 1% in the value of the DC resistance (R_{DC}) with reference to the case of a 600 m radius. Similarly for 3 and 5 m electrodes a truncation radius of 55 and 70 m is sufficient, respectively.

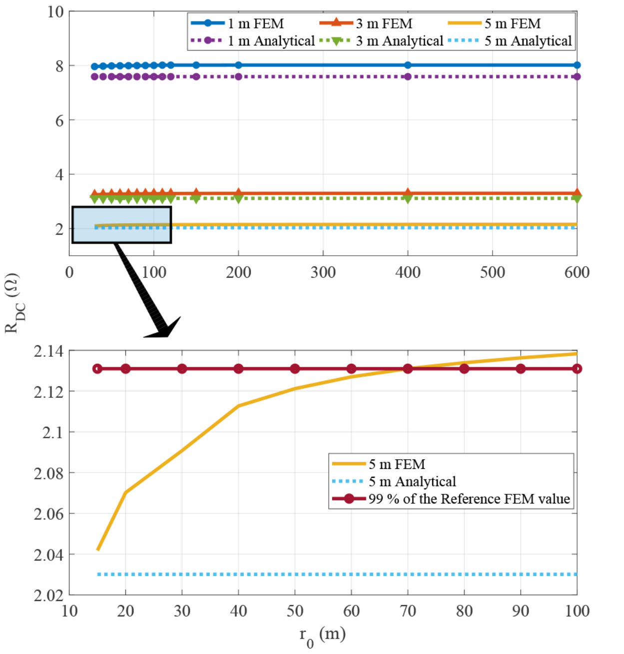


Fig. 3 *Electrostatic analysis of a vertical electrode buried in a homogeneous soil with conductivity of* $\sigma = 0.1$ S/m *as a function of ground radius obtained with FEM, and analytical formulae [10]*

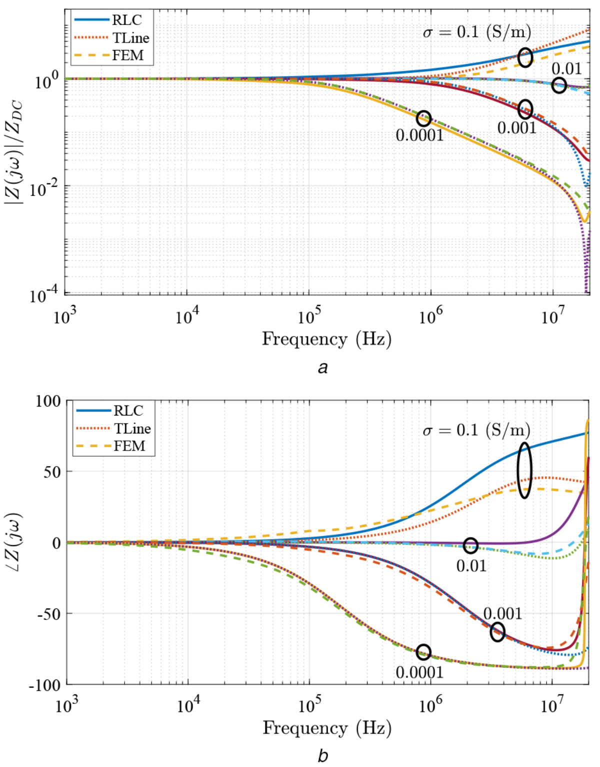


Fig. 4 *Grounding impedance of* 1 m *vertical electrode for* $\varepsilon_r = 10$

(a) Normalised magnitude, ***(b)*** Phase angle

2.2 Soil electrical parameters

2.2.1 Electrical conductivity: Soil conductivity is determined by measuring the resistance of a sample at very low frequencies, often DC to 20 Hz. It is shown that the soil conductivity is nearly constant in this frequency range [32]. The value of conductivity at higher frequencies can be estimated by knowing either its low frequency resistivity or water content. In general, clay soils have a high conductivity of 0.11 S/m and above, loam and chalk soils with an average value of about 0.1 S/m, while soil of a sandy or gritty nature gives a much lower conductivity value. The lowest values were obtained on solid granite or slate subsoils with conductivity of the order of 0.0001 S/m [28].

2.2.2 Dielectric constant: Relative dielectric constant (ε_r) expresses the ability of a material to polarise under an electric field. To measure this quantity, the material is placed in an alternating electromagnetic field, and the time it takes for the wave to travel through the material is measured [39–41]. Measurements have shown that the variation of dielectric constant with moisture content depends on soil types [42]. The dielectric constant increases slowly with soil's water content up to a transition point, beyond which a rapid increase occurs. It was also observed that the dielectric constant of soils with different water contents (from dry soil to 30% of moisture content) ranges between 3 to near 30, with its trend being dependent on the soil type or texture [28, 40]. In another measurement, where precautions were taken to remove all the moisture from a sample of soil, the minimum observed dielectric constant of 2 and conductivity of 5.5×10^{-5} S/m were measured [43]. As reported in [44], there have been several soil samples of highly resistive soils ($\sigma = 0.00008$ to 0.0005 S/m) which had a high low frequency (10 kHz) permittivity of 20 to 30. These soil samples had a volumetric water content of 0.2 up to 35%. From these measured data, it can be seen that the variation of conductivity and dielectric constant in a frequency range are related to each other [40], however, at low frequencies such correlation cannot be easily validated from the measurements.

2.2.3 Magnetic permeability: Magnetic permeability is determined by measuring magnetic susceptibility of soil samples under a weak magnetic field [41, 45]. In the study of electromagnetic pulse propagation in soil, the relative magnetic permeability of rock and soil is less important than its conductivity and dielectric constant. For most earth materials it is only slightly greater than unity (between 1.0006 and 1.001) [46]. Due to this fact, the permeability of soil is considered equal to 1 in all studies involving the ground.

3 Numerical results

In this section, the normalised magnitude of the impedance, $|Z(j\omega)|/Z_{\text{DC}}$, of vertical and horizontal grounding electrodes of lengths 1, 3, and 5 m in the frequency region of 1 kHz to 20 MHz are calculated. The electrodes have a radius of 12.5 mm. The conductivity of the soil is assumed to be in the range of 0.0001–0.1 S/m, and the values considered for soil relative permittivity are 3, 5, 10, 20, and 30.

3.1 Frequency response of grounding electrodes

The results determined by the full-wave electromagnetic approach ('FEM') are compared with those obtained using the circuit theory ('RLC') [10] and transmission-line theory ('TLine') [47, 48]. The harmonic impedance of 1, and 5 m vertical grounding electrodes with $\varepsilon_r = 10$ are shown in Figs. 4 and 5.

Any termination to ground presents resistive, inductive, and capacitive effects. The current that is injected into a grounding electrode has two components: a longitudinal current (I_L) transferred along the length of the electrode and a leakage transversal current (I_T) dispersed into the soil [10], as shown in Fig. 6. The response of grounding electrodes is practically constant up to a certain frequency, which is called the characteristic or the break frequency f_c [49]. This is due to the fact that at low frequencies, the voltage drop along the length of the electrode caused by the longitudinal current ($j\omega L_1 \simeq j\omega L_2 \simeq 0$) and the capacitive current dispersed into the soil are negligible ($j\omega C_1 \simeq 0$). In such a condition, the behaviour of the electrode is governed by the value of conductance G_1. Note that R_1 and R_2 are very small, because the grounding electrodes are made of highly conductive materials to have a better dispersion of excessive currents into the soil. Above the characteristic frequency, the electrode has either an inductive or a capacitive response based on the length of the electrode and the soil conductivity. To justify the high frequency

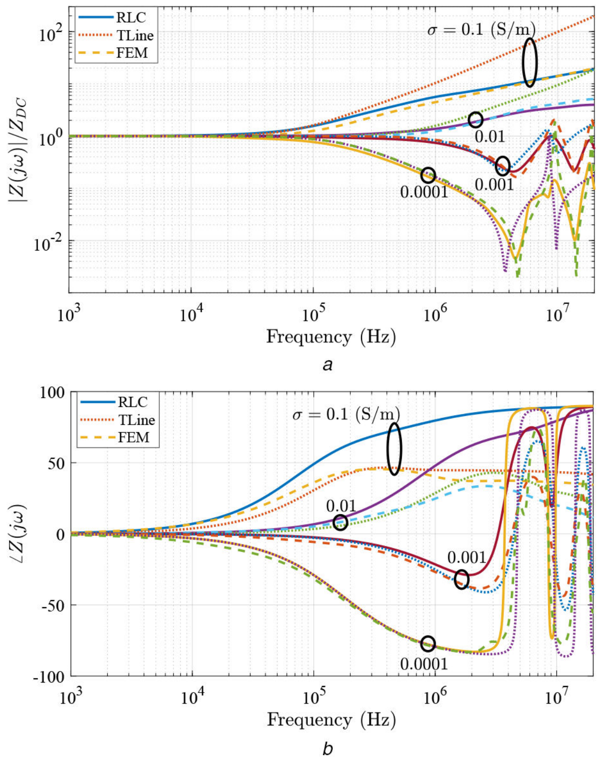


Fig. 5 *Grounding impedance of* 5 m *vertical electrode for* $\varepsilon_r = 10$
(a) Normalised magnitude, ***(b)*** Phase angle

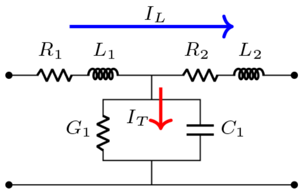


Fig. 6 *Equivalent circuit for a grounding electrode showing the transversal and longitudinal current components*

behaviour, one should consider the affecting parameters on the leakage transversal current, also known as displacement current. The ratio of leakage current to the longitudinal current (I_T/I_L) increases as the frequency, the dielectric constant, or the earth resistivity increases. As the conductivity increases, the effect of ground displacement current becomes less important and an inductive behaviour is seen in the high frequency region, as shown in Figs. 4 and 5. This can also be quantitatively described in terms of the ratio $\sigma/\omega\varepsilon$. Another influencing parameter is the length of the electrode which causes the resonant region to start at a lower frequency for longer electrodes. The vertical and horizontal grounding electrodes of the same length have almost a similar high frequency response (results for the horizontal grounding impedance are not shown here).

Comparing the results obtained by the three approaches, one can see that the theoretical models lead to very small errors up to the MHz frequencies, especially in the case of the highly resistive earth and shorter electrodes. When the injected current has only low frequency components, the electrode can be approximated by a conductance (G_1). This way, the electrical potential remains the same along the length of the electrode and the theoretical approaches that assume a constant potential are valid. Nevertheless, the highest amount of variation between the theoretical modelling approaches and numerical simulation results is seen in the regions of resonant behaviour, where they predict resonances of much higher peaks.

Regarding the effect of soil electrical permittivity on the harmonic impedance of the grounding electrodes, Figs. 7*a* and *b* show the variation of high frequency impedance of a vertical grounding electrode of length 1 m as the soil relative permittivity is

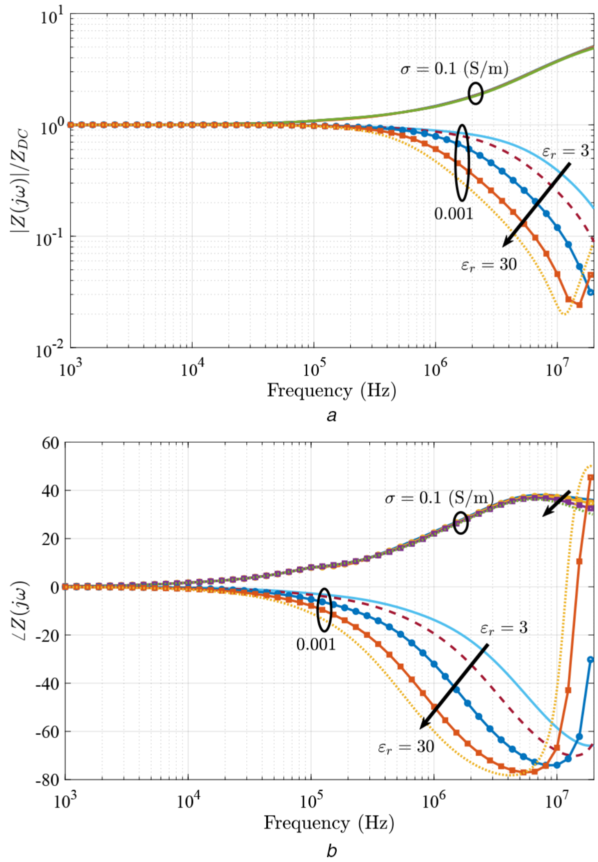


Fig. 7 *Normalised magnitude and phase angle of harmonic impedance of a* 1 m *vertical grounding electrode for ground conductivity* $\sigma = 0.1$ *and* 0.001 S/m *and relative permittivity* $\varepsilon_r = 3, 5, 10, 20, 30$
(a) Normalised magnitude, ***(b)*** Phase angle

changed from $\varepsilon_r = 3$ to 30. The variation of soil electrical permittivity (i.e. its water content) has no significant effect on the the impedance of the vertical grounding electrodes in a low resistivity soil (10 and 100 Ωm). Mathematically, the ratio of $\sigma/\varepsilon\omega$ in (2) determines whether the effect of soil permittivity is significant or not. In a highly resistive soil (1000 and 10000 Ωm) and low frequency range, the performance of the grounding electrode does not change significantly as the permittivity varies. However, beyond a threshold frequency of around 10 kHz, increasing the relative permittivity from 3 to 30 results in a significant reduction of at least 50% in the magnitude of impedance due to the capacitive effect. This decrease continues up to a frequency of 10 MHz after which an oscillatory behaviour is observed in soil of very high permittivity.

3.2 Characteristic frequency

The frequency limit for the resistive behaviour of grounding electrodes was termed as the characteristic frequency f_c by Gary [49]. In this paper, the grounding impedance is considered to be resistive if its phase angle is in the range of ±5°. The range of resistive behaviour depends on the value of the inductance (L_1, L_2) and capacitance (C_1) of the electrode. As we decrease the length of the electrode, both the capacitance to remote ground and self-inductance of the electrode decrease. Also decreasing the soil conductivity makes the capacitance smaller in value, and it makes no change to the electrode's self-inductance. For this reason, decreasing the length of the electrode or the earth conductivity increases the leakage current, the frequency band of resistive behaviour, and the characteristic frequency. This effect is demonstrated in Figs. 4 and 5.

Fig. 7 shows that the harmonic impedance of grounding electrodes buried in a more conductive earth (i.e. $\sigma = 0.1$ S/m) is inductive and not much dependent on the earth permittivity. However, a grounding electrode in highly resistive soil (i.e.

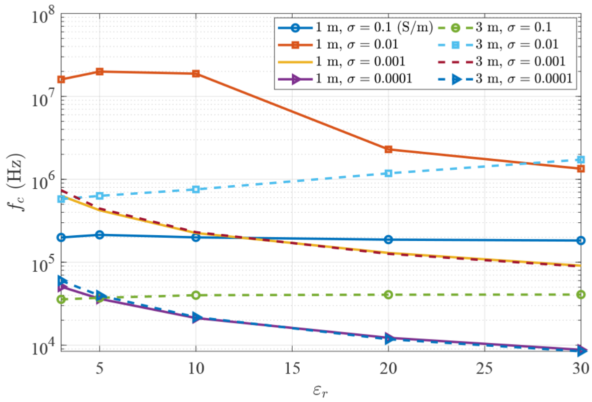


Fig. 8 *Dependence of the characteristic frequency (f_c) on the dielectric constant and frequency for a vertical electrode of length 1 and* 3 m

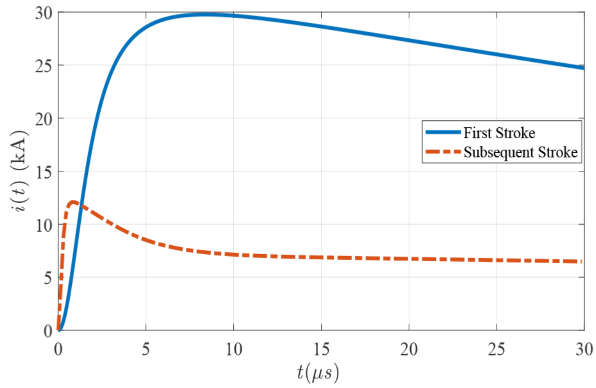


Fig. 9 *First and subsequent return stroke current waveforms*

$\sigma = 0.001$ S/m) shows a capacitive high frequency response ($\angle Z(j\omega) < 0$), and increasing the soil permittivity makes its capacitive behaviour more pronounced. As such, in this case, increasing the permittivity of the ground will result in a reduced characteristic frequency. In contrast, increasing the soil permittivity of soil with a small resistivity increases the characteristic frequency. The dependence of the characteristic frequency for vertical 1 and 3 m – long electrodes on the ground permittivity for various values of earth conductivity is plotted in Fig. 8. As it can be seen, the characteristic frequency is more affected by the soil permittivity in highly resistive grounds. Furthermore, the two lengths of the electrode have a similar variation of characteristic frequency as the permittivity is increased in a highly resistive soil, while its different in a lower resistive soil.

4 Time domain analysis

In this section, the influence of soil permittivity on the potential rise of grounding electrodes is analysed in the time domain. A lightning surge current pulse is applied to the electrode and the potential rise with reference to remote earth is determined. The lightning current waveforms of first and subsequent strokes employed in this work are approximated by Heidler's formulation [2, 50, 51] and plotted in Fig. 9. They have a rise time of 4.61 μs and 0.49 μs, respectively, as defined in [52]. To determine the potential rise of grounding electrodes, $v(t)$, directly in the time domain, Vector Fitting [53] is employed to approximate the impedance of grounding electrodes with rational functions. Recursive convolution method [54] is then used to obtain the time domain potential rise of grounding electrodes, $v(t)$. In Fig. 10, the voltage of a vertical electrode of length 1 m buried in soil with a conductivity of $\sigma = 0.001$ S/m and a varying relative permittivity is shown. The important characteristics of the induced overvoltage in the grounding electrode $v(t)$ include the peak and the rise time (or the front time) [52]. The rise time influences the withstand capability of an insulator. The initial change in the voltage is called the surge region and corresponds to the high frequency response of

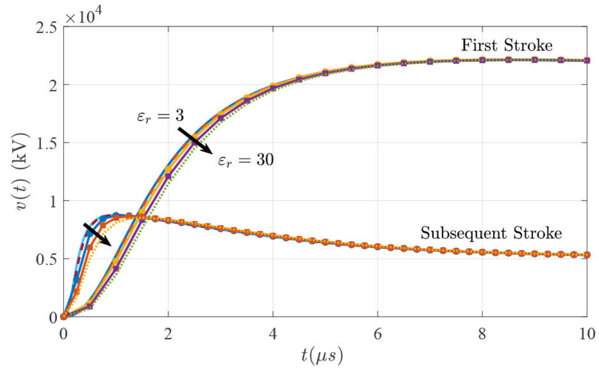


Fig. 10 *Grounding electrode potential rise of a* 1 m *vertical electrode in a soil with a conductivity of* $\sigma = 0.001$ S/m *and relative permittivity of* $\varepsilon_r = 3$, *5, 10, 20, and 30 due to the first and subsequent stroke currents*

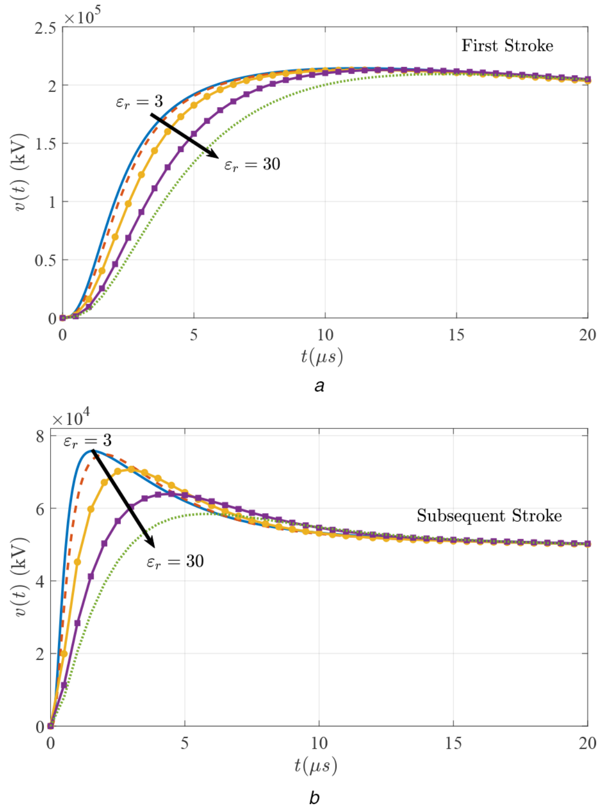
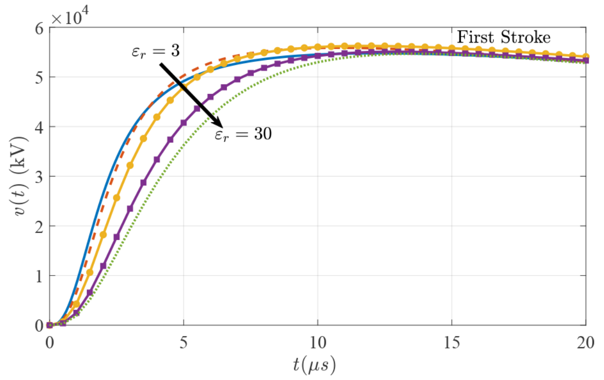


Fig. 11 *Grounding electrode potential rise of a* 1 m *vertical electrode in a soil with a conductivity of* $\sigma = 0.0001$ S/m *and relative permittivity of* $\varepsilon_r = 3$, *5, 10, 20, and 30 due to*
(a) First stroke current, ***(b)*** Subsequent stroke current

the electrode and the lightning current. Once the peak of the voltage is passed, the stationary period is reached where the behaviour of the grounding electrode can be estimated by its low frequency resistance. As such, the difference between the magnitude of the voltage in the stationary region is almost the same for all values of relative permittivity. Nevertheless, one can see for a conductivity of $\sigma = 0.001$ S/m the dependence of the peak and rise time on the relative permittivity is not significant. Fig. 11 shows the potential rise of grounding electrode for a less conductive ground ($\sigma = 0.0001$ S/m) where the peak and rise time show a very strong dependence on the relative permittivity of the ground. As the conductivity is reduced, there are two major effects on the voltages with varying soil permittivity: first, the peak of the voltage is considerably reduced as the relative permittivity varies from $\varepsilon_r = 3$ to $\varepsilon_r = 30$, especially in the case of the subsequent stroke. The percentage of variation in the peak is 3.5 and 24.9% for the first (Fig. 11*a*) and subsequent (Fig. 11*b*) strokes, respectively. Similar variation for the case of $\sigma = 0.001$ S/m is 2 and 6% only.



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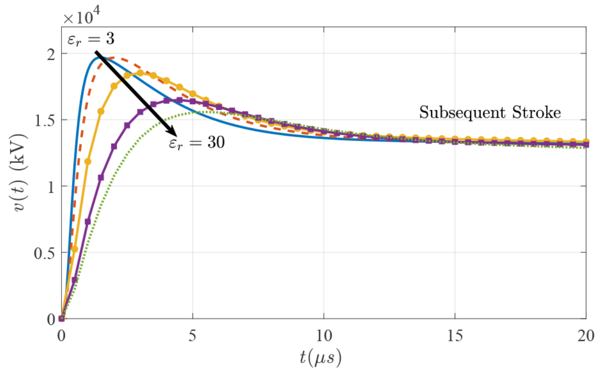

b

Fig. 12 *Grounding electrode potential rise of a* 5 m *vertical electrode in a soil with a conductivity of* $\sigma = 0.0001$ S/m *and relative permittivity of* $\varepsilon_r = 3$, *5, 10, 20, and 30 due to*
(a) First stroke current, ***(b)*** Subsequent stroke current

This is in agreement with Fig. 7, where it was shown that the effect of soil permittivity is more pronounced at higher frequencies and more resistive soil. The second important characteristic of the potential rise of grounding electrode is the rise time. As the permittivity is increased, the rise time becomes longer, which is again more affected in the case of a subsequent stroke. The rise time of the voltage in Fig. 11*a* is 6.05 μs for $\varepsilon_r = 3$ and 9.27 μs for $\varepsilon_r = 30$. For the potential rise of grounding electrode corresponding to the subsequent stroke, the rise time varies from 0.97 to 4.16 μs. The other parameter that has an influence on the grounding impedance is the length of the grounding electrode. As shown in Fig. 12, increasing the length of the electrode to 5 m results in a considerable decrease of the voltage peak. Furthermore, increasing the length of electrode results in a bigger rise time. For a 5 *m* electrode, the variation of the peak of potential rise of the grounding electrode due to the first and subsequent stroke currents, when ε varies from 3 to 30, is 2 and 16.86%, respectively. For the case of the first stroke, the rise time of the grounding electrode potential in a soil of $\varepsilon_r = 3$ and $\varepsilon_r = 30$ is 5.75 and 8.11 μs, respectively. For the case of a subsequent stroke, the rise time varies from 0.81 to 3.93 μs. It can be concluded that as the length of the electrode increases, the effect of soil permittivity is less, but it is still significant, especially for the subsequent lightning strokes. This can be due to the fact that increasing the length of the electrode makes the inductive behaviour more pronounced and the variation of soil permittivity and capacitance of the electrode less important.

5 Conclusions

This paper presented a full-wave electromagnetic simulation model to determine the potential rise of grounding electrodes due to lightning return stroke and study the influence of ground conductivity and permittivity on the peak and rise time of the grounding electrode potential. Along with the length of the electrode and the soil resistivity, the value of the soil dielectric constant was shown to highly affect the grounding impedance of rods. This effect is more pronounced as the frequency or the soil resistivity are increased, where the changes in the grounding impedance can be as high as 95% reduction for a soil of resistivity $\sigma = 0.0001$ S/m and frequencies beyond 5 MHz when the relative permittivity of the soil is changed from $\varepsilon_r = 3$ to 30. The changing trend of the characteristic frequency (the frequency above which the impedance of a grounding electrode is not resistive anymore) with the increase of the dielectric constant depends on the soil resistivity. It was shown that the characteristic frequency reduces for highly resistive soils. In the time-domain calculations, two major effects were observed as the electrical permittivity of the soil was varied. First, the peak of the grounding electrode potential decreases by up to 25% for highly resistive soil as the permittivity is changed from 3 to 30. Secondly, the rise time of the grounding electrode potential was increased by a factor of up to 4 for a vertical electrode of length 1 m. Both effects were more noticeable for subsequent lightning strokes. Although increasing the electrode length reduced the dependability of the developed overvoltages on the variation of the soil permittivity, it was still highly affecting the peak and rise time of the grounding electrode voltage. The proposed simulation model in this paper can be applied to the analysis of other type of grounding electrodes and its accuracy can be compared to field measurements in future studies. The high cost and complexity of performing field measurements highlights the importance of numerical simulation models, such as the one developed in this paper.

6 Acknowledgments

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