

On the High Frequency Response of Grounding Electrodes: Effect of Soil Dielectric Constant

ISSN 0000-0000
doi: 0000000000
www.journal.org

Bamdad Salarieh^{1*}, Jeewantha De Silva^{2*}, Behzad Kordi¹

¹ Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Manitoba, Canada

² Manitoba Hydro International, Winnipeg, Manitoba, Canada

* E-mail: salarieb@myumanitoba.ca

Abstract: Grounding electrodes have an important role in electric power transmission and distribution systems. They are used to prevent excessive hazardous voltages between metallic structures and ground in the case of system faults or lightning surges. It is important that they provide a low impedance path for the current in to the ground. 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. In order to have an accurate estimation of the developed overvoltages and the backflashover rate of the transmission lines due to a 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 paper investigates the high frequency behavior of the grounding electrodes by solving a full-wave electromagnetic problem using the Finite Element Method (FEM). The focus is on taking into account the effect of the variation of soil relative permittivity which has been neglected in the previous studies of the grounding systems. This allows an evaluation of the response of grounding systems due to seasonal changes and specifically change of the water content of the soil, 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 modeling of electrodes buried in highly resistive soil.

1 Introduction and Background

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 modeling of grounding electrodes.

In general, the problem of modeling grounding electrodes is solved using 1) theoretical, 2) numerical, and 3) experimental [4-6] methods. The theories are either based on the circuit [7-9] or transmission-line formulations [10-14]. Full-wave electromagnetic modeling, using numerical techniques are based on Finite Element Method (FEM) [15-18], Method of Moments (MOM) [19-22], Finite-Difference Time-Domain (FDTD) method [23-25], and Partial Electric Equivalent Circuit (PEEC) [26,27]. These methods can be considered as the most rigorous and accurate modeling 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 dependency of soil electrical parameters is disregarded in this paper, therefore the results give a conservative estimate of the upper bound of the grounding impedance.

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 to 20 MHz. In this paper, we develop a full-wave electromagnetic model that is solved using the Finite Element Method (FEM). Frequency-domain impedance of the grounding electrodes are calculated using the proposed model that is compared with other modeling approaches. 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 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

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

To determine $I(j\omega)$, a commercial finite-element full-wave electromagnetic solver* is employed to solve the wave equation in the frequency domain that is given by [34]

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

where

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

and $\mathbf{E}(x, y, z)$ is the electric field vector. The finite simulation space is enclosed by perfect electric conductor (PEC) boundary to allow a return path for the current. The soil region is modeled 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 modeled 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 [35, 36]. 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 [35]. 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].

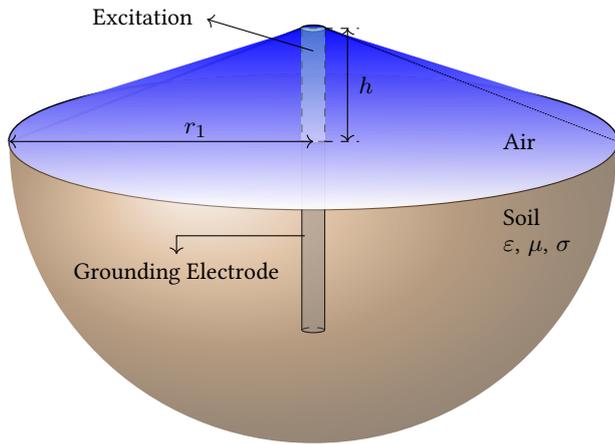
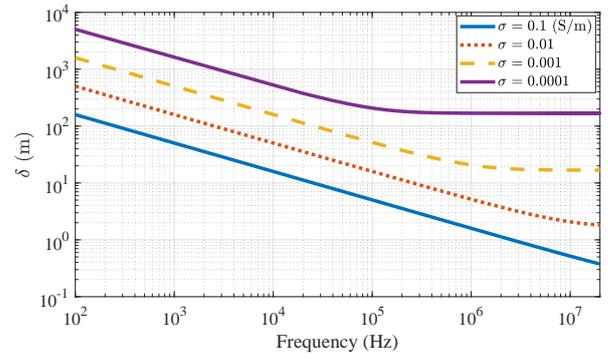
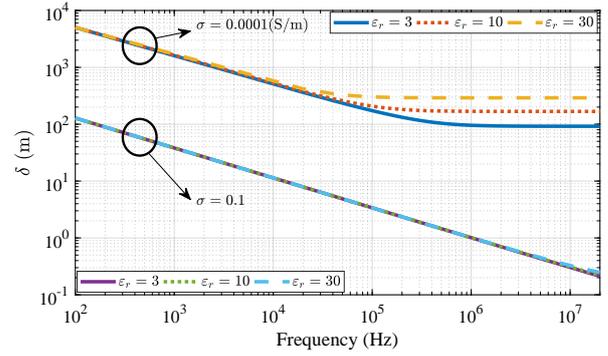


Fig. 1: Proposed FEM model for the calculation of the grounding impedance. The air region is represented by the blue cone of height h , the brown hemisphere with radius r_1 is representing the ground region, and a rectangular port is defined for the excitation.

In (2), as the frequency increases the term $\sigma/\varepsilon\omega$ decreases, that means the effect of soil conductivity on the propagation of



(a)



(b)

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

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.

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. 2a, [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. 2b. However, at high frequencies (*i.e.* > 100 kHz) and for soil of low conductivity, the skin depth is larger for soil with higher permittivities. 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 modeling 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.

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

*Ansys HFSS

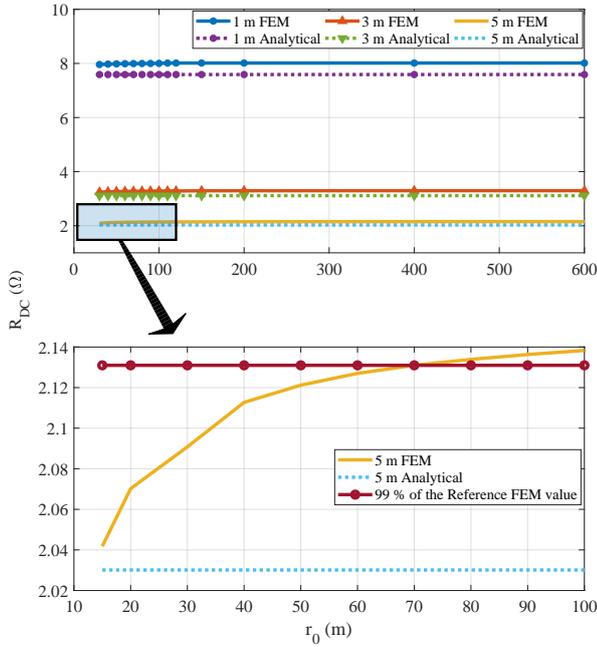


Fig. 3: Electrostatic analysis of a vertical electrode buried in a homogeneous soil with conductivity of $\sigma = 0.1$ S/m as a function of ground radius obtained with FEM, and analytical formulae [10].

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 polarize 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 [38, 39]. Measurements have shown that the variation of dielectric constant with moisture content depends on soil types [40]. 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], [38]. 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 [41]. As reported in [42], 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 [38], 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 [39]. 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) [44]. 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 normalized magnitude of the impedance, $|Z(j\omega)|/Z_{DC}$, 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 to 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") [45], [46].

The harmonic impedance of 1, and 5 m vertical grounding electrodes with $\epsilon_r = 10$ are shown in Figs. 4 and 5. The response of grounding electrodes is practically constant up to a certain frequency, which is called the characteristic or the break frequency f_c [47], above which the electrode has either an inductive or a capacitive response based on the length of the electrode and the soil conductivity. As the conductivity increases, the effect of ground displacement current becomes less important and an inductive behavior is seen in the high frequency region. This can be quantitatively described in terms of the ratio $\sigma/\omega\epsilon$. Another influencing parameter is the length of the electrode which introduces an inductive behavior as it increases. Furthermore, the resonant region starts 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 highest amount of variation is seen in the regions of resonant behavior for both of the theoretical modeling approaches, where they predict resonances of much higher peaks. Nevertheless,

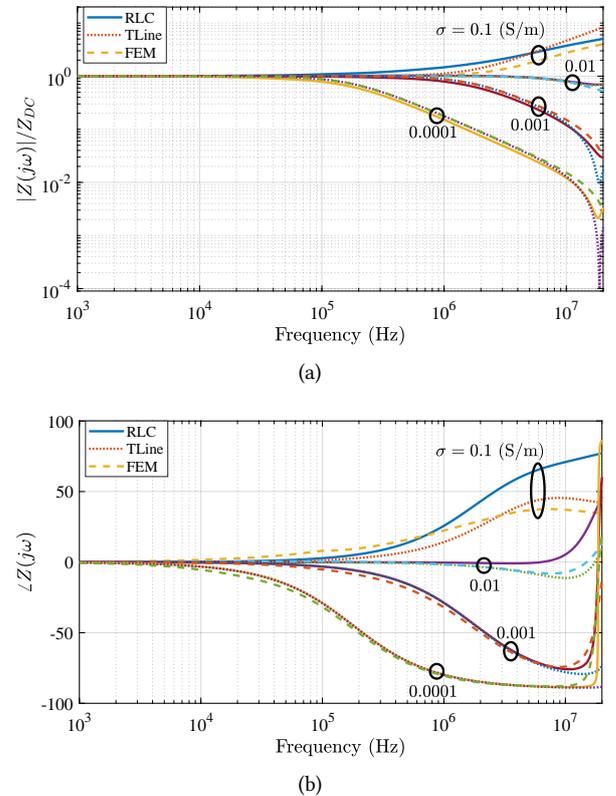
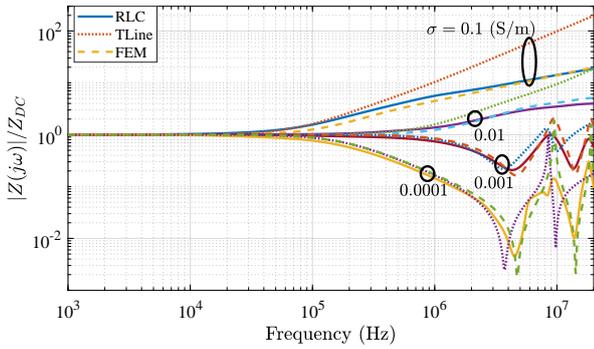
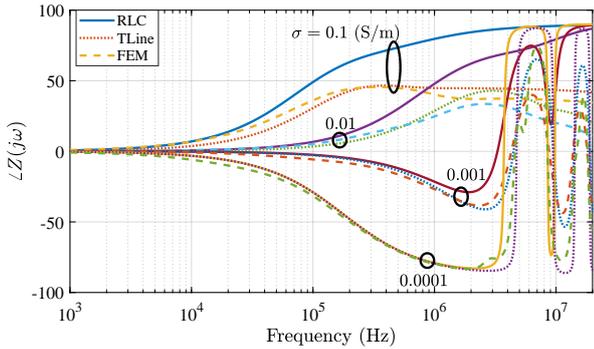


Fig. 4: Grounding impedance of 1 m vertical electrode for $\epsilon_r = 10$ (a) normalized magnitude, (b) phase angle.



(a)



(b)

Fig. 5: Grounding impedance of 5 m vertical electrode for $\epsilon_r = 10$ (a) normalized magnitude, (b) phase angle.

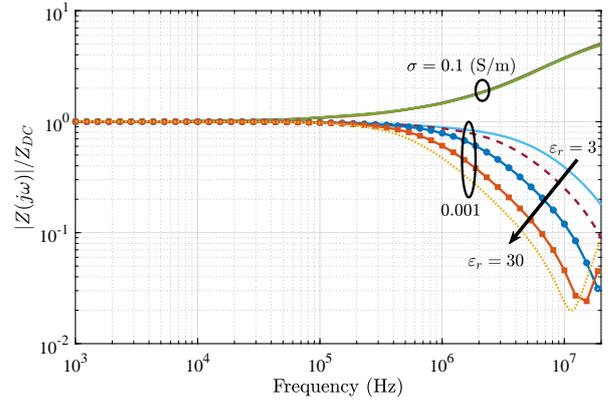
the theoretical models lead to very small errors up to the MHz frequencies, especially in the case of the highly resistive earth and shorter electrodes.

Regarding the effect of soil electrical permittivity on the harmonic impedance of the grounding electrodes, Figs. 6a and 6b show the variation of high frequency impedance of a vertical grounding electrode of length 1 m as the soil relative permittivity is changed from $\epsilon_r = 3$ 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). In a highly resistive soil (1000 and 10000 Ωm) and low frequency range, the performance of the grounding electrode doesn't 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 behavior is observed in soil of very high permittivity.

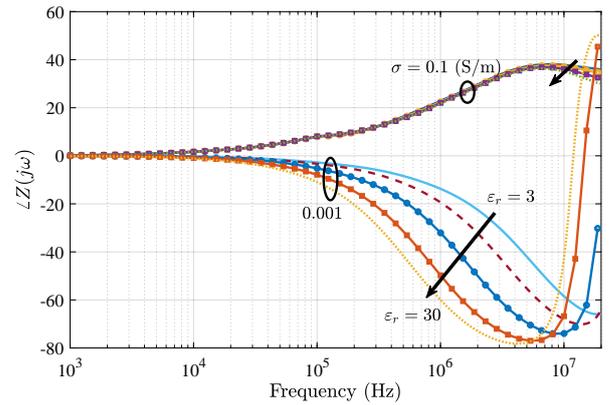
3.2 Characteristic Frequency

The frequency limit for the resistive behavior of grounding electrodes was termed as the characteristic frequency f_c by Gary [47]. In this paper, the grounding impedance is considered to be resistive if its phase angle is in the range of $\pm 5^\circ$. As demonstrated in Figs. 4 and 5, the characteristic frequency increases as the length of the electrode or the soil conductivity decreases.

Figure 6 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.*, $\sigma = 0.001$ S/m) shows a capacitive high frequency response, and increasing the soil permittivity makes its capacitive behavior more pronounced. As such, in this case, increasing the permittivity of the ground will result in a reduced characteristic frequency.



(a)



(b)

Fig. 6: Normalized magnitude (a) and phase angle (b) of harmonic impedance of a 1-m vertical grounding electrode for ground conductivity $\sigma = 0.1$ and 0.001 S/m and relative permittivity $\epsilon_r = 3, 5, 10, 20, 30$.

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. 7. 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 it is different in a lower resistive soil.

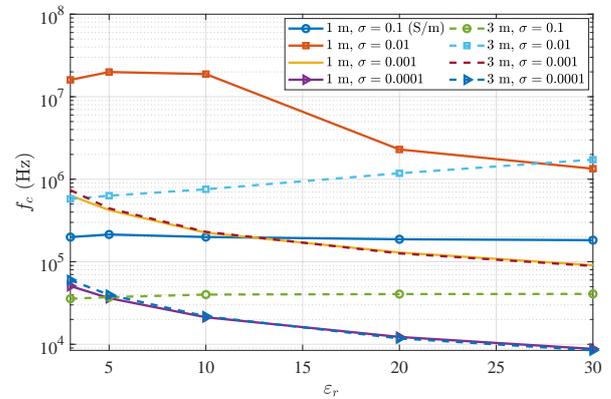


Fig. 7: Dependence of the characteristic frequency (f_c) on the dielectric constant and frequency for a vertical electrode of length 1 and 3 m.

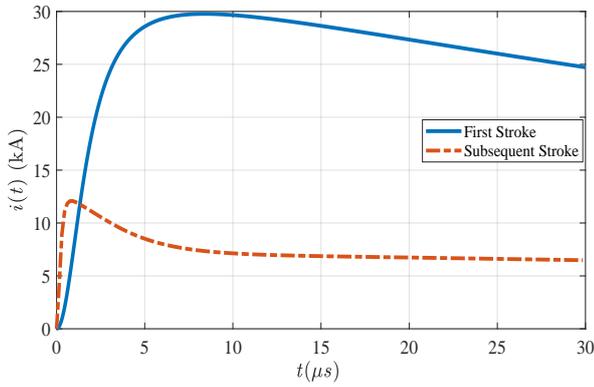


Fig. 8: First and subsequent return stroke current waveforms.

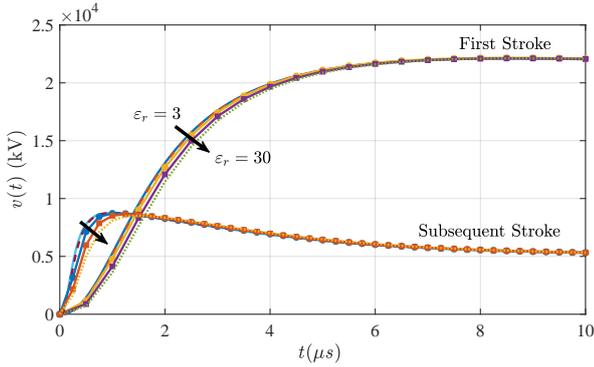


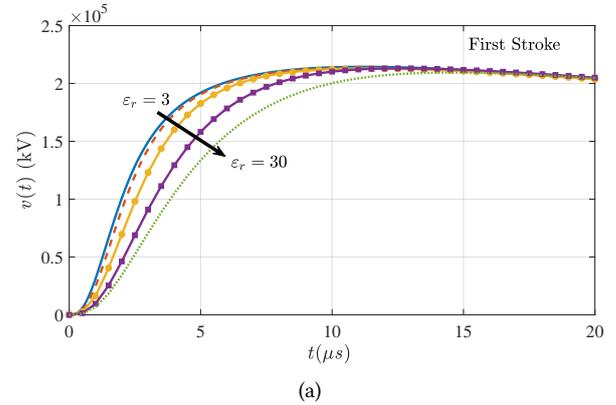
Fig. 9: Grounding electrode potential rise of a 1 m vertical electrode in a soil with a conductivity of $\sigma = 0.001$ S/m and relative permittivity of $\epsilon_r = 3, 5, 10, 20,$ and 30 due to the first and subsequent stroke currents.

4 Time Domain Analysis

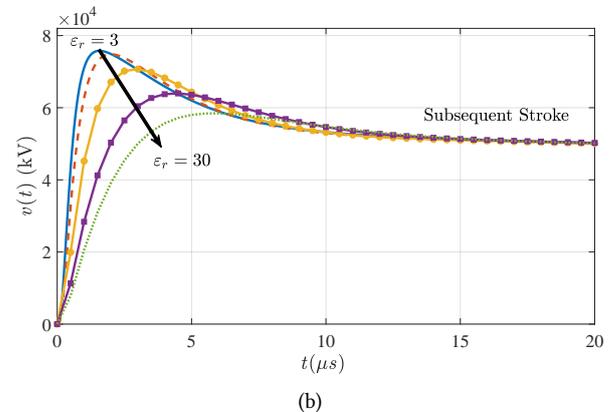
In this section, the influence of soil permittivity on the potential rise of grounding electrodes is analyzed in the time domain. A lightning surge current pulse is applied to the electrode and the potential rise with reference to remote earth is determined. The lightning current waveforms of first and subsequent strokes employed in this work are approximated by Heidler's formulation [2], [48], [49] and plotted in Fig. 8. They have a rise time of $4.61 \mu\text{s}$ and $0.49 \mu\text{s}$, respectively as defined in [51]. To determine the potential rise of grounding electrodes, $v(t)$, directly in the time domain, Vector Fitting [52] is employed to approximate the impedance of grounding electrodes with rational functions. Recursive convolution method [50] is then used to obtain the time domain potential rise of grounding electrodes, $v(t)$. In Fig. 9, 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) [50]. 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 the electrode and the lightning current. Once the peak of the voltage is passed, the stationary period is reached where the behavior 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. Figure 10 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 $\epsilon_r = 3$ to $\epsilon_r = 30$, 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. 10a) and subsequent (Fig. 10b) strokes, respectively. Similar variation for the case of $\sigma = 0.001$ S/m is 2% and 6% only. This is in agreement with Fig. 6, 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. 10a is $6.05 \mu\text{s}$ for $\epsilon_r = 3$ and $9.27 \mu\text{s}$ for $\epsilon_r = 30$. For the potential rise of grounding electrode corresponding to the subsequent stroke, the rise time varies from $0.97 \mu\text{s}$ to $4.16 \mu\text{s}$. The other parameter that has an influence on the grounding impedance is the length of the grounding electrode. As shown in Fig. 11, 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 $\epsilon_r = 3$ and $\epsilon_r = 30$ is 5.75 and $8.11 \mu\text{s}$, respectively. For the case of a subsequent stroke, the rise time varies from 0.81 to $3.93 \mu\text{s}$. 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.

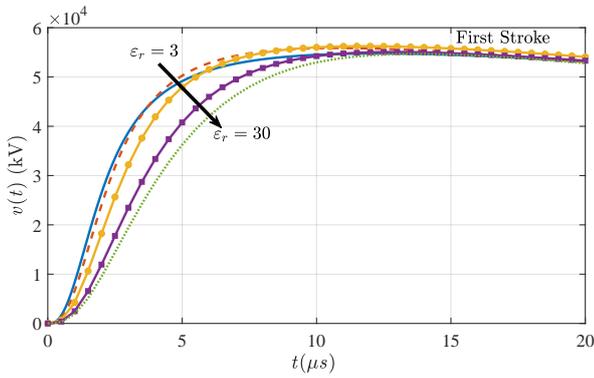


(a)

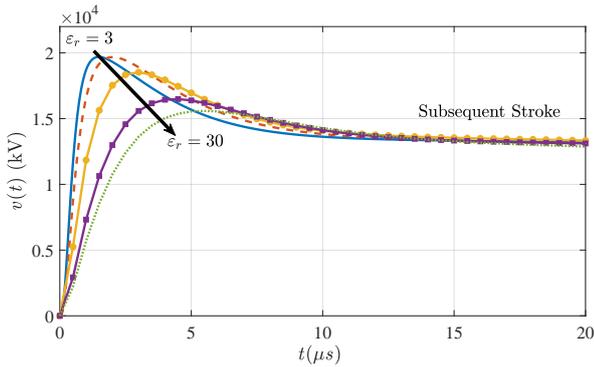


(b)

Fig. 10: 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 $\epsilon_r = 3, 5, 10, 20,$ and 30 due to a) first and b) subsequent stroke current.



(a)



(b)

Fig. 11: 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 $\epsilon_r = 3, 5, 10, 20,$ and 30 due to a) first and b) subsequent stroke current.

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. It has been known that water content of the soil is between 4 to 30% of the total weight of soil throughout most of the year. This change corresponds to values of dielectric constant of 2 to 30. 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 $\epsilon_r = 3$ 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.

6 References

- [1] Hasse, P., Wiesinger, J.: 'Handbook for lightning and grounding' (Munich: Pflaum, 1993, 4th edn.)
- [2] Heidler, F.: 'Calculation of lightning current parameters', IEEE Trans. on Power Deli., 1999, 14, (2), pp. 399–404
- [3] Grcev, L.: 'Modeling of grounding electrodes under lightning currents', IEEE Trans. on Electromagn. Compt., 2009, 51, (3), pp. 559–571
- [4] Lu, H., Feng, Z., Tong, X., et al.: 'Observation and analysis of the sparkover around grounding electrode under impulse current', IET Gener. Transm. Distrib., 2017, 11, (8), pp. 1997–2002
- [5] Sekioka, S., Sonoda, T., Ametani, A.: 'Experimental study of current-dependent grounding resistance of rod electrode', IEEE Trans. on Power Deli., 2005, 20, (2), pp. 1569–1576
- [6] Gazzana, D. S., Smorgonskiy, A., Mora, N., et al.: 'An experimental field study of the grounding system response of tall wind turbines to impulse surges', Electric Power Systems Research, Elsevier, 2018, 160, pp. 219–225
- [7] Ramamoorthy, M., Narayanan, M. M. B., Parameswaran, S., et al.: 'Transient performance of grounding grids', IEEE Trans. on Power Deli., 1989, 4, (4), pp. 2053–2059
- [8] Otero, A. F., Cidras, J., del Alamo, J. L.: 'Frequency-dependent grounding system calculation by means of a conventional nodal analysis technique', IEEE Trans. on Power Deli., 1999, 14, (3), pp. 873–878
- [9] Cidras, J., Otero, A. F., Garrido, C.: 'Nodal frequency analysis of grounding systems considering the soil ionization effect', IEEE Trans. on Power Deli., 2000, 15, (1), pp. 103–107
- [10] Sunde, E. D.: 'Earth conduction effects in transmission systems' (New York: Dover, 1968, 2nd edn.)
- [11] Liu, Y., Theethayi, N., Thottappillil, R.: 'An engineering model for transient analysis of grounding system under lightning strikes: Nonuniform transmission-line approach', IEEE Trans. on Power Deli., 2005, 20, (2), pp. 722–730
- [12] Shi, Z., Liu, L., Xiao, P., et al.: 'Applying transmission line theory to study the transmitting turn-off current in a long grounded wire', IEEE Trans. on Antennas Prop., 2017, 65, (10), pp. 5112–5122
- [13] Liu, Y., Zitnik, M., Thottappillil, R.: 'An improved transmission line model of grounding system', IEEE Trans. on Electromagn. Compt., 2001, 43, (3), pp. 348–355
- [14] Chiheb, S., Kherif, O., Tegar, M.: 'Impedance nature of long horizontal grounding electrode employing TLM', Proc. Int. Conf. on Elec. Scie. and Tech., 2018, pp. 1–4
- [15] Nekhoul, B., Guerin, C., Labie, P., et al.: 'A finite element method for calculating the electromagnetic fields generated by substation grounding systems', IEEE Trans. on Magnetics, 1995, 31, (3), pp. 2150–2153
- [16] Salarieh, B., De Silva, H. M. J., Kordi, B.: 'Wideband EMT-compatible model for grounding electrodes buried in frequency dependent soil' in Proc. IPST'19 - International Conference on Power Systems Transients, Perpignan, France, Jun. 16-20, 2019
- [17] Akbari, M., Sheshyekani, K., Alemi, M.: 'The effect of frequency dependence of soil electrical parameters on the lightning performance of grounding systems', IEEE Trans. on Electromagn. Compt., 2013, 55, (4), pp. 739–746
- [18] Arajo, A., R., J., Kurokawa, S., Seixas, C., M., et al.: 'Overvoltage analysis of transmission towers considering the influence of tower footing impedance' Int. Symp. on Ligh. Prot., 2017, pp. 6

- [19] Grcev, L., Dawalibi, F.: 'An electromagnetic model for transients in grounding systems', *IEEE Trans. on Power Deli.*, 1990, 5, (4), pp. 1773–1781
- [20] Grcev, L., Kuhar, A., Arnautovski-Toseva, V., et al.: 'Evaluation of high-frequency circuit models for horizontal and vertical grounding electrodes', *IEEE Trans. on Power Deli.*, 2018, 33, (6), pp. 3065–3074
- [21] Honarbakhsh, B., Karami, H., Sheshyekani, K.: 'Direct characterization of grounding system wide-band input impedance', *IEEE Trans. on Electromagn. Compt.*, 2018, 60, (1), pp. 292–293
- [22] Dawalibi, F., Selby, A., Olsen, R. G.: 'Electromagnetic-fields of energized conductors', *IEEE Trans. on power Del.*, 1993, 8, (3), pp. 1275–1284
- [23] Tanabe, K.: 'Novel method for analyzing the transient behavior of grounding systems based on the finite-difference time-domain method' *Proc. IEEE Power Eng. Soc. Winter Meeting*, 2001, pp. 1128–1132
- [24] Tanabe, K., Asakawa, A.: 'Computer analysis of transient performance of grounding grid element based on the finite-difference time-domain method' *Proc. IEEE Int. Symp. Elec. Comp.*, 2003, pp. 209–212
- [25] Baba, Y., Nagaoka, N., Ametani, A.: 'Modeling of thin wires in a lossy medium for FDTD simulations', *IEEE Trans. Electromagn. Compt.*, 2005, 47, (1), pp. 54–60
- [26] Chen, H., Du, Y.: 'Lightning grounding grid model considering both the frequency-dependent behavior and ionization phenomenon', *IEEE Trans. Electromagn. Compt.*, 2019, 61, (1), pp. 157–165
- [27] Yutthagowith, A., Ametani, A., Nagaoka, N., et al.: 'Application of the partial element equivalent circuit method to analysis of transient potential rises in grounding systems', *IEEE Trans. Electromagn. Compt.*, 2011, 53, (13), pp. 726–736
- [28] Smith-Rose, R. L.: 'Electrical measurements on soil with alternating currents', *Institute of Electrical Engineers, Proc. of the Wireless Section of the Institution*, 1934, 9, (27), pp. 293–309
- [29] Messier, M.: 'Another soil conductivity model', *Internal rep.*, Santa Barbara, CA, 1985
- [30] Pedrosa, A. G., Alipio, R. S., Schroeder, M. A. O., et al.: 'Simulation of behavior electrical grounding-comparative analysis for performance in frequency-domain', *Proc. Int. Workshop Appl. Model Simul.*, Rio de Janeiro, Brazil, 2010, pp. 89–92
- [31] Portela, C. M.: 'Measurement and modeling of soil electromagnetic behavior', *Proc. IEEE Int. Symp. Electromagn. Compt.*, 2, 1999, pp. 1004–1009
- [32] Visacro, S., Alipio, R.: 'Frequency dependence of soil parameters: Experimental results, predicting formula, and influence on the lightning response of grounding electrodes', *IEEE Trans. on Power Deli.*, 2012, 27, (2), pp. 927–935
- [33] Visacro, S., Alipio, R., M. H. M. Vale, et al.: 'The response of grounding electrodes to lightning currents: The effect of frequency-dependent soil resistivity and permittivity', *IEEE Trans. on Electromagn. Compt.*, 2011, 53, (2), pp. 401–406
- [34] Ramo, S., Whinnery, J. R., Duzer, T.: 'Fields and waves in communication electronics', (New York, Wiley, 1994, 3rd edn.)
- [35] Weil, C. M., Riddle, B. F., Novotny, D. R., et al.: 'Modal cutoff in coaxial transmission lines of conical and cylindrical geometries', *Radio-Frequency Technology Division, National Institute of Standards and Technology (NIST)*, 2002, pp. 1229–1232
- [36] Villiers, D. I. L.: 'Analysis and design of conical transmission line power combiners', *Ph.D. dissertation*, University of Stellenbosch, 2007
- [37] Scott, J. H.: 'Electrical and magnetic properties of rock and soil', *Theoretical notes*, Note 18, U. S. Geological Survey
- [38] Thring, L. M., Boddice, D., Metje, N., et al.: 'Factors affecting soil permittivity and proposals to obtain gravimetric water content from time domain reflectometry measurements', *NRC Research Press*, 2014, 51, pp. 1303–1317
- [39] Portela, C. M., Gertrudes, M. C., Pissolato, J.: 'Earth conductivity and permittivity data measurements: Influence in transmission line transient performance', *Electric Power System Research*, 2006, pp. 907–915
- [40] Wang, J. R., Schmutge, T. J.: 'An empirical model for the complex dielectric permittivity of soils as a function of water content', *IEEE Trans. on Geoscience and Remote Sensing*, 1980, 1, (4), pp. 288–295
- [41] Scott, J. H., Carroll, R. D., Cunningham, D. R.: 'Dielectric constant and electrical conductivity measurements of moist rock: A new laboratory method', *U. S. Geological Survey*, 1967, 72, (20), pp. 5101–5115
- [42] Smith, K. S., Longmire, C. L.: 'A universal impedance for soils', *Defence nuclear agency*, Alexandria, VA, USA, 1975
- [43] Mooney, H. M.: 'Magnetic susceptibility measurements in Minnesota', *Geophysics*, 1952, 17, (3), pp. 531–543
- [44] Nettleton, L. L.: 'Geophysical prospecting for soil', (New York, McGraw Hill Book Co., 1940, 2nd edn.)
- [45] Bourq, S., Sacepe, B., Debu, T.: 'Deep earth electrodes in highly resistive ground: Frequency behavior' *Proc. IEEE Int. Symp. Elec. Comp.*, 1995, pp. 584–589
- [46] Paul, C. R.: 'Analysis of multiconductor transmission lines', (IEEE Press, 2007, 2nd edn.)
- [47] Gary, C.: 'The impedance of horizontally buried conductors', *Proc. of the First Inter. Symp.: Lightning and Mountains*, 1994, pp. 148–151
- [48] Rachidi, F., Janischewskyj, W., Hussein, A. M., et al.: 'Current and electromagnetic field associated with lightning-return strokes to tall towers', *IEEE Trans. on Electromagn. Compt.*, 2001, 43, (3), pp. 356–367
- [49] Chowdhuri, P., Anderson, J. G., Chisholm, W. A., et al.: 'Parameters of lightning strokes: A review', *IEEE Trans. on Power Deli.*, 2005, 20, (1), pp. 346–358
- [50] Kuffel, E.: 'High voltage engineering fundamentals', (Butterworth - Heinmann, 2000)
- [51] Gustavsen, B., Semlyen, A.: 'Rational approximation of frequency domain responses by vector fitting', *IEEE Trans. on Power Deli.*, 1999, 14, (3), pp. 1052–1061
- [52] Noda, T.: 'Identification of a multiphase network equivalent for electromagnetic transient calculations using partitioned frequency response', *IEEE Power Engineering Society General Meeting*, 2005