Harmonic Impedance of Horizontal Grounding Electrode under Soil Ionization Effect

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Abstract: One of faults that occur in electric power system is due to the striking of lightning current pulses. The current in lightning pulse is up to some kilos of ampere and has high content of frequency. The main objective of grounding system is taking these pulses to earth. Due to high current in pulses the soil ionization effect takes place. This paper presents harmonic impedance of horizontal grounding electrode when it is hit by fast lightning current pulses. Also, this study takes into account soil ionization effect. As well as, in this paper a comparison between harmonic impedance when soil ionization effect is taken into account or not, is done. Transmission line (TL) approach is used within this study. The effect of soil electrical parameters, length of grounding electrode and type of lightning stroke are considered in this study.

Keywords: Current pluses, soil conductivity, soil ionization effect, transmission line approach, transient impedance.

1 Introduction

In last decade the demand of electricity is increased due to huge progress in technology in the world. So, a system of protection was required in the electrical systems to avoid faults that occurred in it. One of the most important protection systems is grounding system. The basic idea of grounding system is taking the current faults that occur in electrical system into earth. One of the faults that occur in the electrical system is due to the lightning current pulse [1-13]. These lightning pulses have high current and have high frequency content. So, for this reason, the performance of grounding system under lightning current pulses should be studied. Increasing the applied current wave of lightning will lead to an increase in the electric field strength around grounding system, and when the electric field exceeds a critical value of electric field the soil is punctured by the tracking and a spark over or an arc is generated [14-16]. Then the soil ionization effect occurs around grounding system. Some of scholars set empirical equation to study the critical field strength. One of empirical model to estimate the critical breakdown field strength as functions in soil resistivity is that of E.E. Oettle [17]. Another model to estimate the critical breakdown field strength as functions in electrical parameters of soil is that of Manna and Chowdhuri [18]. Scholars study the soil ionization effect and set an empirical model when study transient behaviour of grounding electrode [19]. Weck's proposed grounding resistance equation that is taken into account soil ionization effect [20] which is adopted by CIGRE [21]. This formula takes into account the equivalent geometry of the ionization zone to calculate the grounding electrode resistance. Another model proposed by Bellaschi et al. [22] for single driven electrode and multi- driven electrode. This model takes into account the geometry of soil ionization zone as new geometry of grounding electrode then studies the performance of the grounding electrode. When large current dissipates in the earth, discharge channels near to electrode will be formed when the electric field exceeds the critical and formed the enlargement of the dissipation area. This dissipation area is the new effective radius of grounding electrode; this due to the resistance of arc is considered zero [9, 23-26]. Third model proposed by Nor et al. [27] to estimate soil ionization effect in any soil that can apply by any impulses. The last model proposed by Liew and Darveniza [28] to estimate soil ionization effect based on dynamic model of soil. The lightning current pulses have high content of frequency. This frequency effects impedance of grounding electrode under studying the soil ionization effect. This paper studies the harmonic impedance of horizontal grounding electrode under soil ionization effect. Also, in this paper, the parameters affect the harmonic impedance of horizontal grounding electrode such as: length of grounding electrode, type of lightning stroke and different electrical parameters of soil, are investigated. There are many scholars studied the harmonic impedance without taking into account the soil ionization effect. These scholars used numerical method such as finite element method, method of moment and antenna theory [7, 29 and 30]. This study uses a simple method called transmission line (TL) approach [1].

2 Mathematical models

This section explains a model used to simulate lightning current wave. Also, explains empirical model of the critical breakdown field strength. Also, this section, explains the new effective radius of horizontal grounding electrode under soil ionization effect. At the end, the transmission line approach which is used to simulate the horizontal grounding electrode behavior under lightning condition has been explained.

2.1 Lightning Current Impulse Model

In this paper, two lightning current waveforms corresponding to first lightning stroke and subsequent lightning stroke are used. The Heidler's lightning current $i(t)$ function is chosen to represent the current waveform [31, 32]. Heidler equation is;

$$i(t) = \frac{I_0}{\eta} \frac{(\frac{t}{\tau_1})^n}{1+(\frac{t}{\tau_1})^n} e^{(-t/\tau_2)} \qquad (1)$$

$$\eta = e^{-(\tau_1/\tau_2)(n(\tau_2/\tau_1))^{1/n}} \qquad (2)$$

Where t is the time in second, I_0 is the amplitude of the current pulse, τ_1 is the front time constant, τ_2 is the decay time constant, n is exponent having values between 2 to 10, and η is the amplitude of the correction factor.

The first stroke waveform is reproduced by one and the subsequent stroke is reproduced by the sum of two Heidler's functions with the parameters given in Table 1 [31]. Figure 1 shows lightning current waves of first and subsequent return strokes according to equations (1) and (2).

Table 1 Parameters for lightning return stroke currents

Parameters	I_0	τ_1	τ_2	n	I_0	τ_1	τ_2	n
First stroke	28	1.8	95	2	--	--	--	--
Subsequent stroke	10.7	0.25	2.5	2	6.5	2	230	2

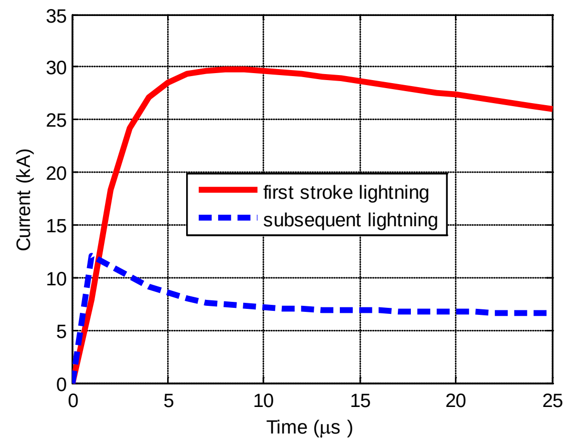


Figure 1. Typical waveforms of lightning first and subsequent return strokes (adapted from [31])

2.2 Critical Breakdown Field Strength

Many scholars have studied the soil breakdown. The critical breakdown field strength (E_c) is commonly defined as the value at which the soil breakdown happens. According to different scholars' experiments and measurements, the values of (E_c) are from tens to thousands kV/m. Manna and Chowdhuri [18] proposed the relation between the critical breakdown field strength (E_c) and electrical parameter of soil as follows:

$$E_c = 8.6083\varepsilon_g^{-0.0103}\ \sigma_g^{-0.15264} \qquad \text{(kV/cm)} \quad (3)$$

Where, σ_g is the soil conductivity (S/m) and ε_g is the permittivity of soil (F/m). From above equation it is found that the breakdown of the soil depends on electrical parameters of the soil.

2.3 Modeling of horizontal grounding electrode

In this paper, transmission line approach (TL) is used. In this method any transmission line (grounding electrode) is divided into N segment each segment consists of R_g, C_g, and L_g. The formula of R_g, C_g, and L_g are:

Resistance for horizontal electrode is [1].

$$R_g = \frac{\rho}{2\pi}\ln\left(\frac{2l}{\sqrt{2ad}} - 1\right) \qquad (\Omega) \qquad (4)$$

The grounding capacitance is [1].

$$C_g = \frac{\rho\varepsilon_g}{R_g} \qquad \text{(F)} \qquad (5)$$

The inductance of electrode is [1].

$$L_g = \frac{\mu}{2\pi}\left[\ln\frac{2l}{a} - 1\right] \quad \text{(H)} \qquad (6)$$

Where, μ is the permeability of soil (H/m), **a** is the radius of grounding electrode, ρ is the soil resistivity (Ω.m), l is the length of segment of the horizontal grounding electrode (m), ε_g is the relative permittivity of soil (F/m) and d is the depth of grounding electrode (m). After calculating R_g C_g , L_g the harmonic impedance to ground $Z(jw)$ can be computed as input impedance of an open transmission line in frequency domain [33-38] as:

$$Z(jw) = Z_o coth(\gamma l) \qquad (7)$$

$$Z_0 = \sqrt{\frac{j\omega L_g}{\left(1/R_g + j\omega C_g\right)}} \qquad (8)$$

$$\gamma = \sqrt{j\omega L_g\left(1/R_g + j\omega C_g\right)} \qquad (9)$$

From above equations, it is noticed that the harmonic impedance depends on only geometry, electromagnetic properties of the ground system and electric soil parameter.

2.4 Radius of soil ionization segment

This section explain the model of soil ionization that proposed by Bellaschi et al. [22]which assumed that when soil ionization is occurred due to lightning current pluses the radius of grounding electrode is changed then the parameters of grounding electrode is changed. The equivalent new radius of grounding electrode is [9, 23-26].

$$a_i = \frac{\rho\, I_m}{2\,\pi\, E_c\, l} \quad \text{(m)} \qquad (10)$$

Where, I_m is the maximum value of lightning current injected (A) and l is the length of segment of horizontal grounding electrode (m).

3 Results and Discussion

In this section, the performance of horizontal grounding electrodes is investigated. The grounding electrode has a length equals 1, 3 and 10 m, and a radius equals 12.5 mm. The conductivity of soil is assumed to be equal 0.01, 0.02, 0.003 and 0.005 S/m, and its permittivity equals 10 F/m. The depth of the horizontal grounding electrode is assumed to be equal 0.5 m.

Figures 2 to 4 show the harmonic impedances of horizontal grounding electrode with different lengths, which is subjected to first lightning stroke and subsequent lightning return stroke currents, and they are calculated when soil ionization effect was taken into account and wasn't taken into account at conductivity equals 0.01 S/m. From these figures, it is seen that harmonic impedance does not affect with type of lightning pulses when soil ionization effect wasn't taken into account. Also, it is seen that harmonic impedance is increasing with decreasing the length of grounding electrode when soil ionization effect is ignored. When soil ionization effect was taken into account the harmonic impedance was changing with changing type of lightning pulses and length of grounding electrode. It is seen that harmonic impedance is decreased when soil ionization effect was taken into account. Also, it is seen that grounding electrode of length equals 1 meter gives lower harmonic impedance than other lengths of horizontal grounding electrodes. At the end, it is seen that harmonic impedance of first lightning stroke is lower than harmonic impedance of subsequent lightning stroke.

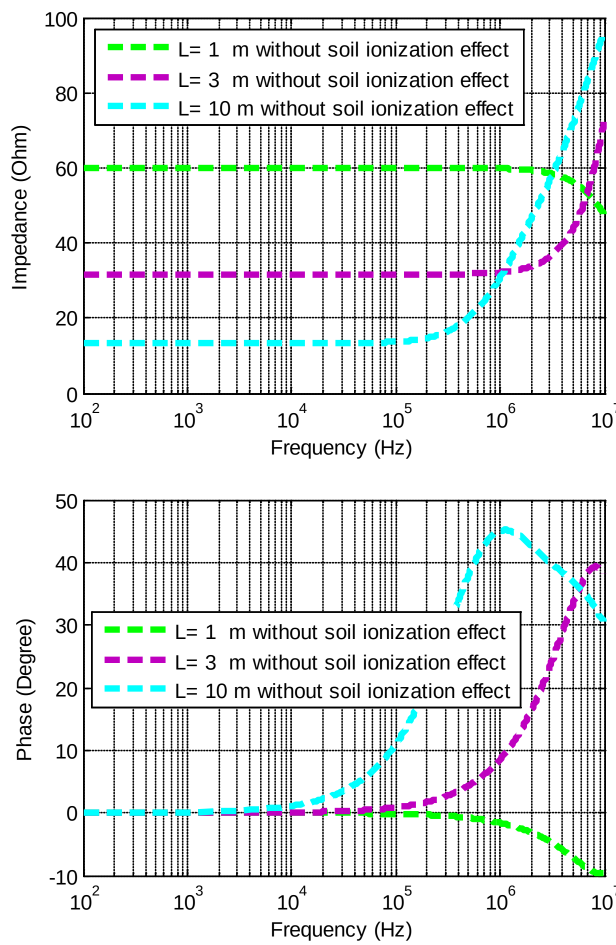


Figure 2. Harmonic impedance of horizontal grounding electrode with conductivity = 0.01 S/m at first and subsequent lightning strokes without soil ionization effect

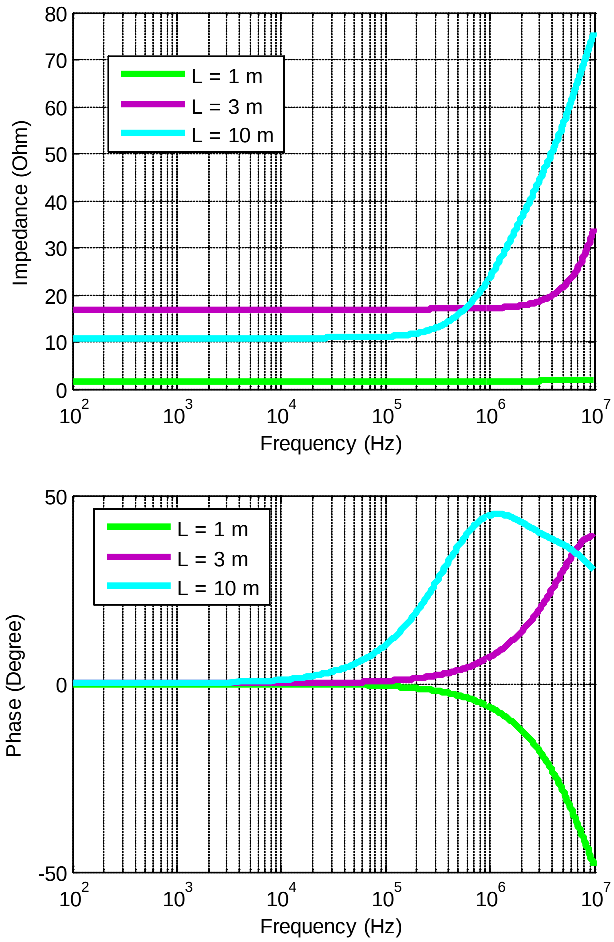


Figure 3. Harmonic impedance of horizontal grounding electrode with conductivity = 0.01 S/m at first lightning stroke with soil ionization effect

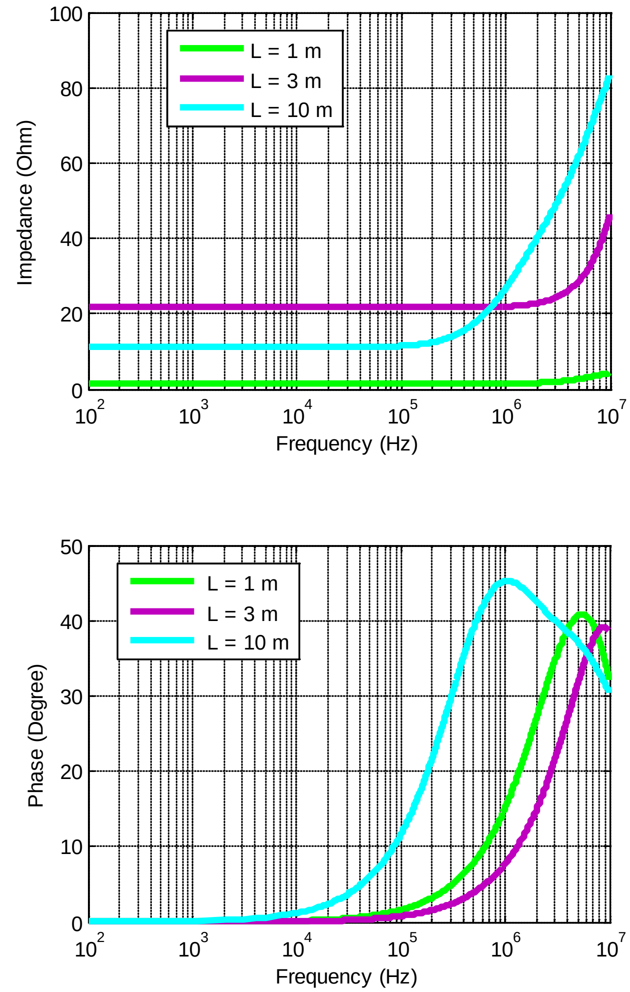
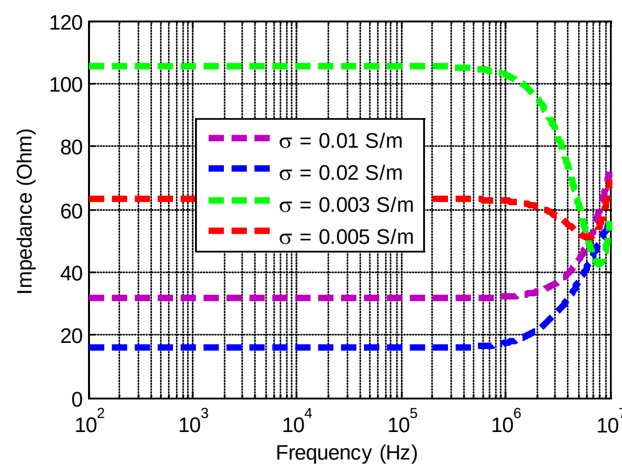
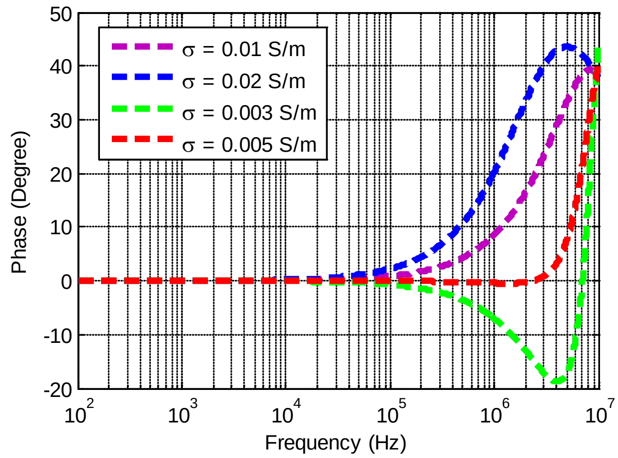


Figure 4. Harmonic impedance of horizontal grounding electrode with conductivity = 0.01 S/m at subsequent lightning stroke with soil ionization effect

Figures 5 to 7 show the harmonic impedances of horizontal grounding electrode with different conductivities, which is subjected to first lightning stroke and subsequent lightning return stroke currents, and they are calculated when soil ionization effect was taken into account and wasn’t taken into account. From these figures, it is seen that harmonic impedance is decreased when soil conductivity is increased. Also, it is seen that harmonic impedance is strongly decreased when soil ionization effect was taken into account. It seen that harmonic impedance didn't change by type of lightning pulse when soil ionization effect wasn't taken into account. At the end, it is seen that harmonic impedance of first lightning stroke is decreased more than harmonic impedance of subsequent lightning stroke in case of soil ionization effect was taken into account.





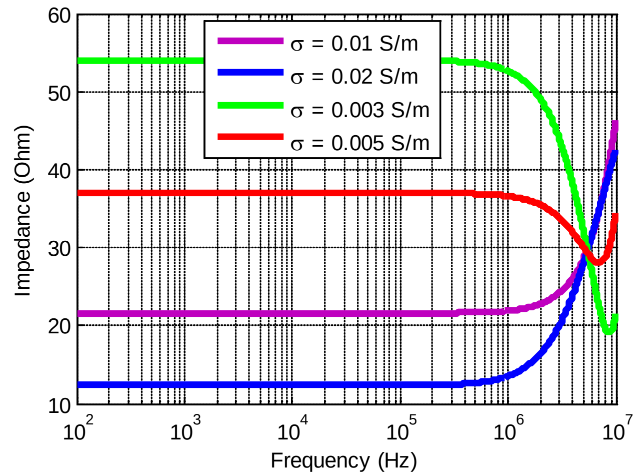
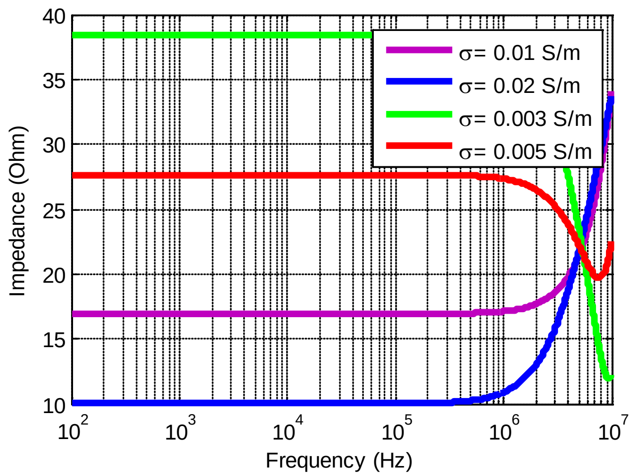


Figure 5. Harmonic impedance of horizontal grounding electrode with length = 3 at first and subsequent lightning strokes without soil ionization effect



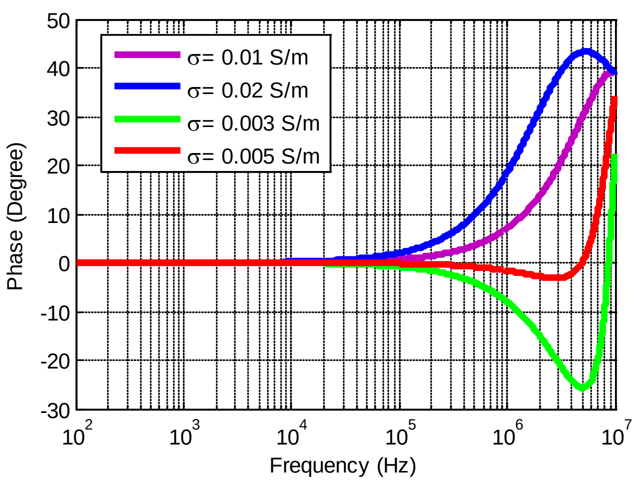


Figure 6. Harmonic impedance of horizontal grounding electrode with length = 3 m at first lightning stroke with soil ionization effect

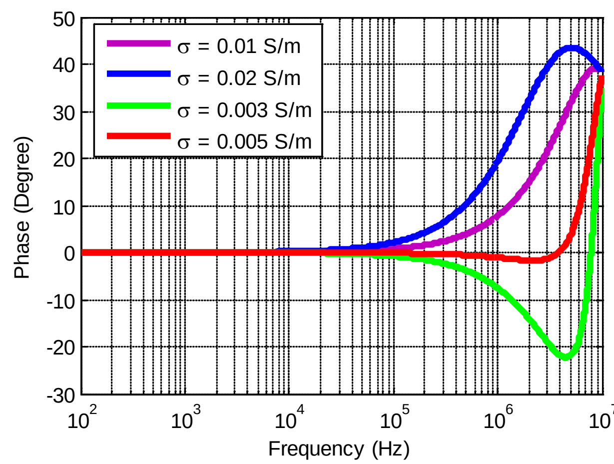


Figure 7. Harmonic impedance of horizontal grounding electrode with length = 3 m at subsequent lightning stroke with soil ionization effect

Figures 8 to 10 show the harmonic impedances of horizontal grounding electrode with different burial depth of grounding electrode, which is subjected to first lightning stroke and subsequent lightning return stroke currents, and they are calculated when soil ionization effect was taken into account and wasn't taken into account. From these figures, it is seen that harmonic impedance is decreased with increasing burial depth when soil ionization effect was not taken into account. In case of soil ionization effect was taken into account, the harmonic impedance is increased when burial depth is increased. Also, in this case the harmonic impedance is higher at first lightning stroke than harmonic impedance at subsequent. This means that harmonic impedance is affected by type of lightning pulses, burial depth and frequency content in lightning pulse.

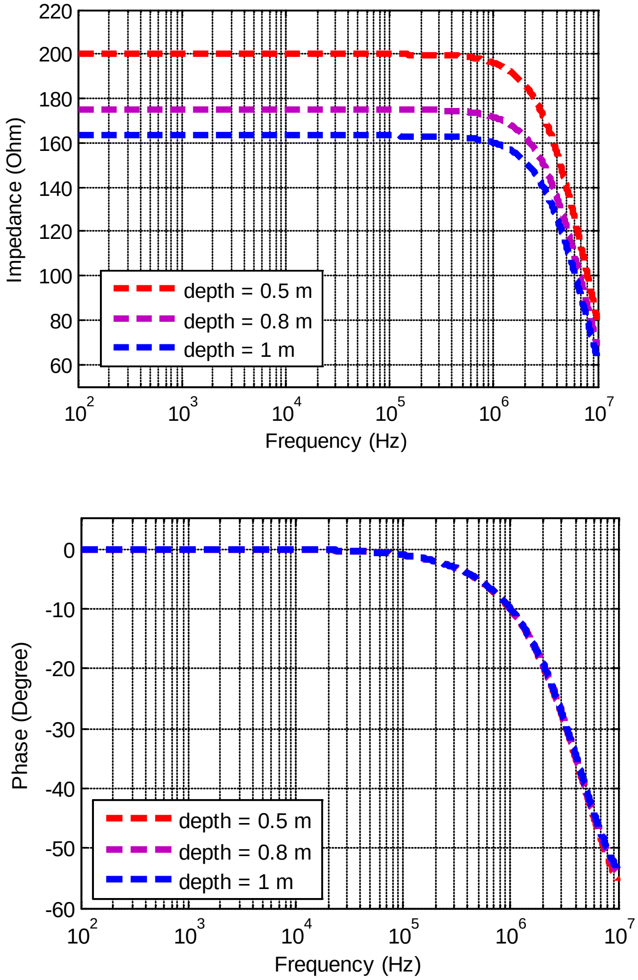
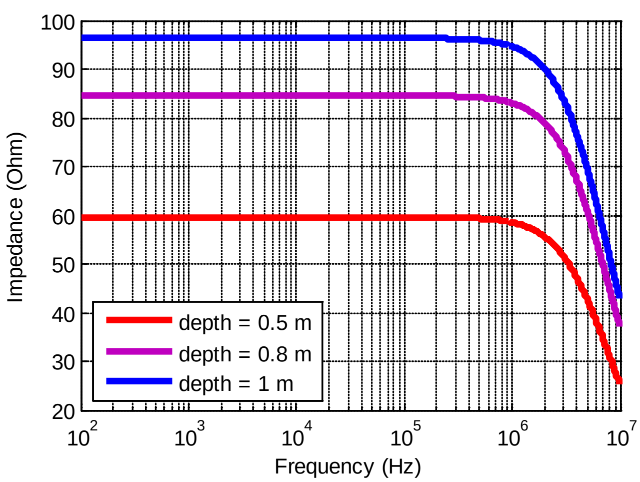


Figure 8. Harmonic impedance of horizontal grounding electrode with length = 1 m and conductivity = 0.003 S/m at first and subsequent lightning strokes without soil ionization effect



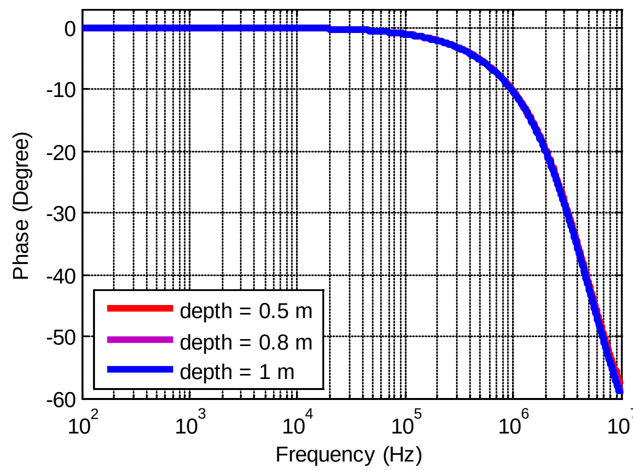


Figure 9. Harmonic impedance of horizontal grounding electrode with length = 1 m and conductivity = 0.003 S/m at first lightning stroke with soil ionization effect

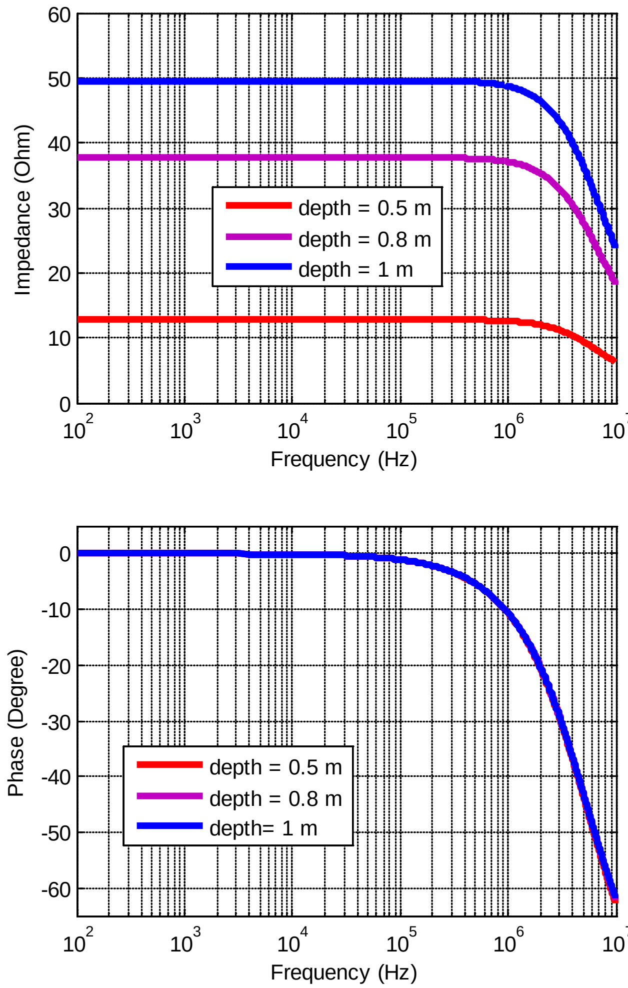
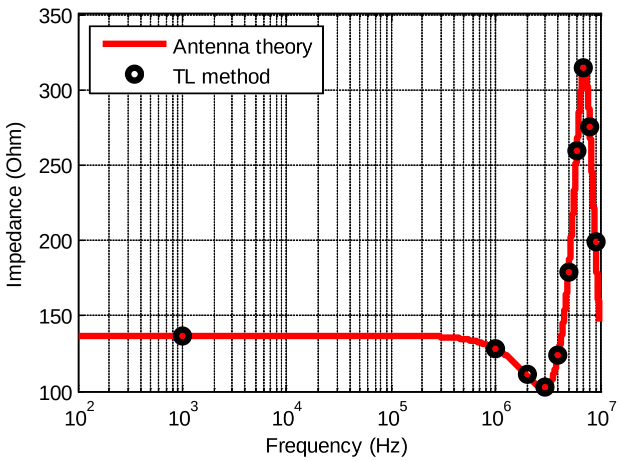


Figure 10. Harmonic impedance of horizontal grounding electrode with length = 1 m and conductivity = 0.003 S/m at subsequent lightning stroke with soil ionization effect

4 Validation of the Method

In this section, the harmonic impedance is compared to the results obtained using antenna theory method [8]. Figure 11 shows harmonic impedance of horizontal grounding electrode without taking the soil ionization effect into account. The grounding electrode has a length equals 10 m, burial depth equals 1 m, and a radius equals 5 mm. The resistivity of soil is assumed to be equal 1000 ohm.m and its relative permittivity equals 5 F/m [8]. From this figure, it is found that the results that obtained by transmission line approach give a good agreement with the results of antenna theory method [8].



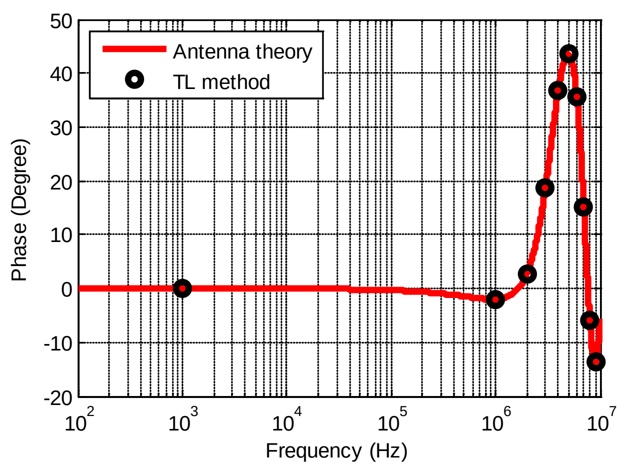


Figure 11. Harmonic impedance of horizontal grounding electrode with length = 10 m and conductivity = 0.001 S/m without soil ionization effect

5 Conclusions

This paper used the transmission line (TL) method for calculating the harmonic impedance of the horizontal grounding electrode when soil ionization effect is taken into account. It is found that the harmonic impedance of horizontal grounding electrode is decreased when soil ionization effect is taken into account. Also, it is found that harmonic impedance of first lightning stroke is lower than harmonic impedance of subsequent lightning stroke at same length of grounding electrode and same electrical parameters of soil. Also, the harmonic impedance is increased when burial depth is increased. It is concluded that harmonic impedance is affected by type of lightning pulses, burial depth of horizontal grounding electrode and frequency content in lightning pulse. At the end, the performance of horizontal grounding is improved when soil ionization effect is taken into account.

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