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RESEARCH ARTICLE

Performance of Grounding Electrodes Under Lightning Strokes in Uniform and Two-Layer Soils Considering Soil Ionization

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ABSTRACT This article presented the characteristics of the grounding electrodes in uniform and two layer soils when subjected to lightning including the impacts of soil ionization with frequency, soil resistivity, and permittivity variations. The critical breakdown field strength of two layer soils with different values of the reflection factors was presented. The transient probabilistic grounding potential rise and the transient impedances of the horizontal and vertical electrodes were investigated in uniform and two layer soils including the effect of soil ionization with frequency. Finally, the influences of resistivity and permittivity variations which have substantial impacts on the electric field at the occurrence of the soil ionization were considered. Moreover, transmission line approach (TL) with the aid of ATP has been used to compute the transient grounding voltages. The results indicated that the reflection factor has a significant impact on the equivalent radius of the grounding electrode. It is also observed that the peak values of the lightning induced voltages decreases sharply when the soil ionization phenomenon considering the variations in soil resistivity and permittivity with the stroke frequency changes. Furthermore, the impedances of the burial electrodes that have negative reflection factors were lower than that in case of positive reflection factors.

INDEX TERMS ATP, grounding electrodes, lightning strokes, soil ionization, soil resistivity, transmission line approach (TL), two-layer soil, uniform soil.

I. INTRODUCTION

The purpose of the grounding system is to protect the electrical networks, devices and people from any fault occurring in the electrical power system [1], [2]. The behavior of grounding electrodes against high-frequency lightning is completely different from that of the steady state or power frequency faults. The lightning current stroke causes the most severe fault in the electrical power networks. Usually this type of strokes has large amount of current that changes the electrical performance and achievement of the grounding electrodes surrounding by the soil and causes the soil ionization. A typical grounding system contains vertical or horizontal electrodes. On the other hand, in medium and high voltages substations can be designed as a grounding grid that was buried in the soil. When high transient current discharges into the earth through the grounding system the soil breakdown phenomenon occurs [2]. It has been found in the literatures [3]–[8] that the injection of high impulse current in the soil determines the degree of soil resistance non-linearity and reduction done by soil ionization and consequently the transient ground potential rise of the ground surface decreases. Therefore, it is noticed that the soil breakdown improves the efficiency of the grounding systems.

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There are two main processes that have been advanced to explain the increase of soil conduction during high impulse current discharges. The first one is the thermal heating and the second is the soil ionization process. In the thermal heating process, the discharge current increases the temperature of the existing water filling among the soil grains. Therefore, the resistivity of the heated water decreases, which in turn reduces the resistivity of the bulk soil and consequently the grounding electrode resistance [2]. In the soil ionization process, the performance of the soil electrical parameters such as the conductivity and permittivity cause the change in grounding system performance due to lightning current with high frequency content [3]–[12]. In the opinion of the present article authors, there is another factor affecting the soil ionization process, which is the variation in the solubility and ionisability of the electrolytes contained in the site natural soil. This suggested factor has to be investigated by the authors in the future. Cavka *et al.* [12], [13], Djamel *et al.* [14], Grcev [15], Grcev *et al.* [16], Alipio *et al.* [17], Pedrosa *et al.* [18], and Visacro [4] studied the performance of the grounding electrodes in uniform soil when lightning current took place in the network. They considered the frequency impact on the surrounding soil in their researches. Many methods based on different theories in the frequency domain with an appropriate fast Fourier Transform have been developed. Such methods are circuit theory [19], [20], transmission line model [21]–[23], electromagnetic field theory [24]–[26], hybrid methods [27] and the generalized modified mesh current method [28]–[30]. CIGRE grounding electrode resistance model is widely used to determine the minimum grounding electrode resistance obtained at current peak [31].

In the current work, the critical electric field intensity as a function of the soil electrical conductivity, soil permittivity and the frequency content of lightning impulse were studied. The effective radius of the soil ionization when lightning impulse frequency content and soil resistivity variations were considered. The reflection factor effect on the transient grounding potential rise (TGPR), transient earth surface potential (TESP) and transient impedance of the grounding electrode (TIGE) have been investigated and the soil permittivity and conductivity variations with time were included. It can be concluded that the reflection factor has significant impact on the equivalent radius of the electrode. It was observed that the transient voltage peak value decreases sharply when the soil ionization phenomenon is considered and the value of impulse impedance of the soil that has negative reflection factor is lower than that in case of positive reflection factor.

II. SOIL IONIZATION MODELING UNDER LIGHTNING STROKE

In the soil ionization process, the electric field enhancement in air voids enclosure among the soil grains, causing the soil breakdown occurrence [2]. Since the resistance of the ionized air is much smaller than the resistance of the soil grains, the equivalent soil resistance decreases. Hence, it is concluded that the soil ionization is mostly accepted as the main factor in the soil breakdown phenomenon. The performance of grounding system when soil ionization phenomenon occurs in uniform soil is investigated by references [2]–[13], and in non-uniform soil in [30]. CIGRE Working Group proposed an empirical model to calculate the grounding resistance as a function of high impulse current when the soil ionization influence is considered. This Group suggested equation to compute the grounding electrode resistance with soil ionization consideration as the following [31].

$$\boldsymbol{R_i} = \frac{\boldsymbol{R}}{\sqrt{1 + {\boldsymbol{i(t)}}/{\boldsymbol{I_g}}}} \tag{1}$$

where R is the low current grounding electrode resistance in Ω, $i(t)$ is the peak transient current in [kA] and I_g is the limit current in [kA] at which the soil ionization occurs and it is given as :

$$\boldsymbol{I_g} = \frac{\boldsymbol{E_c \rho}}{\boldsymbol{2\pi R^2}} \tag{2}$$

where ρ is the soil resistivity in Ω.m] and E_c is the soil critical electric field intensity in [kV/m], which is recommended by CIGRE to be 400 kV/m [31].

Bellaschi [2] proposed a model taking into account the geometry of the ionized zone as the new geometry of the grounding electrode. This is happened because the arc resistance is considered to be zero due to the dissipation of large current through the earth. Discharge channels near to the electrode will be formed when the electric field exceeds its critical value and formed the enlargement of the dissipation area.

III. SOIL CHARACTERISTICS UNDER LIGHTNING STROKE

A. APPARENT RESISTIVITY OF TWO SOIL HORIZONTAL LAYERS

In two soil horizontal layers, the apparent soil resistivity ρ_a can be calculated according to reference [32] by the following formulas;

$$\rho_a = \frac{\rho_1}{\left[1 + \left[(\frac{\rho_1}{\rho_2}) - 1\right][1 - e^{\frac{1}{k(z+2h)}}]\right]} \text{ For } \rho_2 < \rho_1 \tag{3}$$

$$\rho_a = \rho_2[1 + \left[(\frac{\rho_2}{\rho_1}) - 1\right][1 - e^{\frac{-1}{k(z+2h)}}]] \text{ For } \rho_2 > \rho_1 \tag{4}$$

where h is the burial depth of grounding grid, k is the reflection factor, which can be defined as, $k = [(\rho_2 - \rho_1) / (\rho_1 + \rho_2)]$, z is the top layer thickness, ρ_1 is the upper soil resistivity and ρ_2 is the lower soil resistivity [33], [34].

B. CRITICAL BREAKDOWN FIELD STRENGTH IN UNIFORM AND TWO SOIL HORIZONTAL LAYERS

The critical breakdown field strength (E_c) is commonly defined as the value at which soil breakdown happens. Many authors investigated the soil breakdown phenomena when subjected to high-frequency lightning [30], [35]. According to Scholar' [31], [36] experiments and measurements the (E_c) values are considered to be from tens to thousands kV/m depending on the soil composition. The critical breakdown field strength (E_c) as constant value is recommended by CIGRE [31] or calculated by E.E. Oettle equation [36], which proposed the relation between the critical breakdown field strength (E_c) and the soil resistivity as follows

$$E_c = 241\rho^{0.215} \tag{5}$$

The critical electric field intensity as a function of the soil resistivity is considered by [12], [13], while the influence of the frequency variation on the soil ionization phenomenon is ignored by some investigators [14].

Recently, some researchers included the effect of frequency content on the performance of the grounding system when soil ionization phenomenon occurs in uniform and non-uniform soils [30]. Manna and Chowdhuri [37] proposed a relation between the critical breakdown field strength (E_c) and the soil dielectric constant and its conductivity as given in equation (6).

$$E_c = 8.6083\varepsilon_g^{-0.0103}\sigma_g^{-0.15264} \tag{6}$$

where σ_g is the soil conductivity (in mS/cm), and ε_g is the soil relative permittivity.

Moisture content in a soil is a major factor in the change of the soil relative permittivity. The water has permittivity value close to 80, as compared to the dry soil permittivity, which ranges from 3 to 15.The measurement of the soil permittivity is highly dependent on its moisture content, which varies from place to place and from time to time [38].

Fig. 1 presents the critical breakdown field strength using Scott expression, Messier expression and Visacro and Portela expression. In this figure the following values are considered, $\rho_1/\rho_2 = 300/100$ when k = −1/2, $\rho_1/\rho_2 = 500/100$ when k = −2/3, $\rho_1/\rho_2 = 100/300$ when k = 1/2, $\rho_1/\rho_2 = 100/500$ when k = 2/3 and finally when k = 0 the soil is uniform and its resistivity is considered as 100 Ω.m. Fig. 1(a) shows the critical breakdown field strength of two layers soil with different values of the reflection factor, when the grounding electrode is subjected to 30 kA lightning high frequency content. The critical breakdown field strength is calculated also by applying expression of Scott *et al.,* in which the soil dielectric constant ε_r and the soil conductivity σ are functions in the lightning strokes frequency [39] as follows:

$$\varepsilon_r(f) = 10^D \tag{7}$$

where

$$\begin{aligned} D = {} & 5.491 + 0.946log_{10}(\sigma_{100Hz}) - 1.097log_{10}(f) \\ & + 0.069log_{10}^2(\sigma_{100Hz}) \\ & - 0.1141.097log_{10}(f)\,log_{10}(\sigma_{100Hz}) \\ & + 0.067log_{10}^2(f) \end{aligned} \tag{8}$$

$$\sigma(f) = 10^n \text{ [MS/m]} \tag{9}$$

where

$$\begin{aligned} n = {} & 0.028 + 1.098log_{10}(\sigma_{100Hz}) - 0.068log_{10}(f) \\ & + 0.036log_{10}^2(\sigma_{100Hz}) - 0.046log_{10}(f)\,log_{10}(\sigma_{100Hz}) \\ & + 0.0180.067log_{10}^2(f) \end{aligned} \tag{10}$$

where f is the supply frequency in [Hz], and σ_{100Hz} is the soil conductivity at 100 Hz in [M S/m]

$$\varepsilon_r(f) = \frac{\varepsilon_\infty}{\varepsilon_0}(1 + \sqrt{\frac{\sigma_{DC}}{\pi f \varepsilon_\infty}}) \tag{11}$$

$$\sigma(f) = \sigma_{DC}(1 + \sqrt{\frac{4\pi f \varepsilon_\infty}{\sigma_{DC}}}) \text{ [S/m]} \tag{12}$$

Fig. 1(b) shows the critical breakdown field strength of two layer soil with different values of the reflection factor using Messier formula [40], [41] for calculating the soil dielectric constant and its conductivity and Manna and Chowdhuri model for the calculations of the critical breakdown field strength.

Based on Laboratory measurements of tests done on many soil samples using supply frequency ranges from 40 Hz to 2 MHz Visacor and Portela developed empirical equations for the soil permittivity and conductivity calculations as a function of supply frequency [41] as the following.

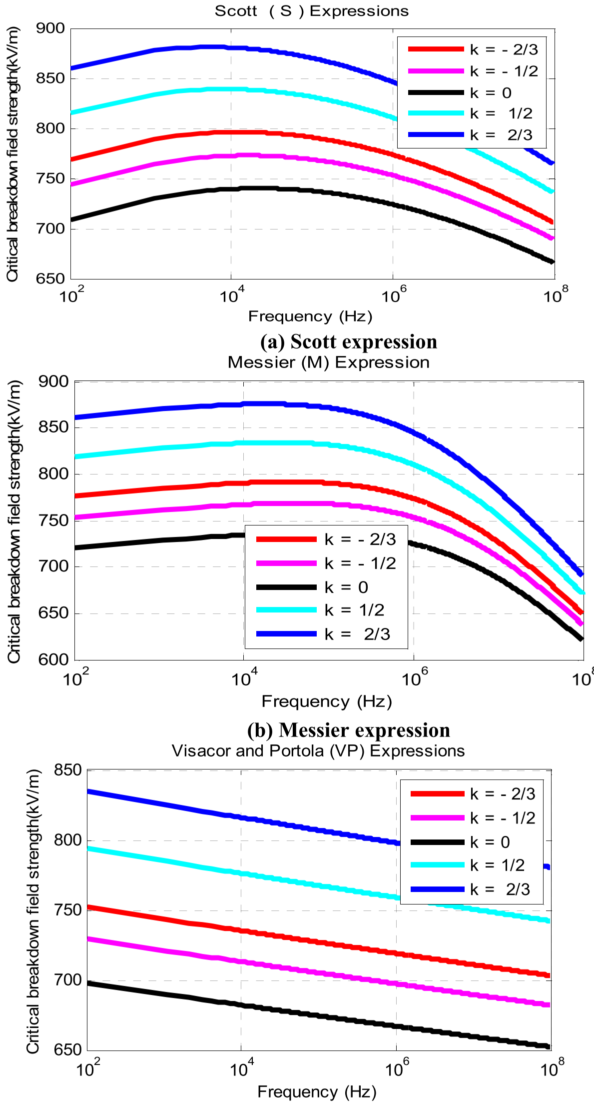
$$\varepsilon_r(f) = 2.34 \times 10^6(\frac{1}{\sigma_{100Hz}})^{-0.535} \cdot f^{-0.597} \tag{13}$$

$$\sigma(f) = \sigma_{100Hz}(\frac{f}{100})^{0.072} \tag{14}$$

The calculations of the critical breakdown field strength of two layer soil with different values of the reflection factor as given in Fig. 1(c) are done by using Visacor *et al* formulas [42] for calculating the soil dielectric constant and the soil conductivity and Manna and Chowdhuri model for the calculations of the critical breakdown field strength.

Fig. 1 proved that regardless of the lightning high frequency content, the value of the critical breakdown field of the homogeneous soil having 100 Ω.m is less than its value in the two-layer soil, whether the reflection coefficient is positive or negative. By comparing the critical breakdown field strength results in Fig 1. (a) and Fig 1. (b), there are marked differences in the critical breakdown field values at low frequencies. At high frequencies less noticeable changes are observed with the reflection factor variation.

In Fig. 1 (c) using Visacor *et al.* formula [43] for the calculations of both the dielectric constant and the conductivity of the soil and Manna and Chowdhuri for the calculations of the critical breakdown field strength, a sharp decrease in the critical breakdown field strength value with the increase of the lightning frequency is observed. This is probably due to the dependence of Scott's and Messier formulas on the dc conductivity σ_{DC} to calculate the soil dielectric constant and its conductivity while on the other hand Visacor *et al.* formula considered the change in the soil dielectric constant and its conductivity as a function of



(a) Scott expression

(b) Messier expression

(c) Visacro and Portela expression

FIGURE 1. Critical breakdown field strength using (a) Scott expression, (b) Messier expression and (c) Visacro and Portela expression.

conductivity σ_{100Hz} at 100Hz. The values of σ_{DC} and σ_{100Hz} are considered in the calculations as 0.01 S/m and 0.098 S/m respectively [44]. Finally the results given in Fig. 1 reflect that homogeneous soil up to100 Ω.m has critical breakdown field strength less than heterogeneous soil and consequently better characteristic in grounding system. Finally it is observed that the obtained results by the use of Scott and Messier expressions are close to each other, while results of Visacro and Portela expression are not compatible with them. This may be due to what was illustrated in the previous lines of the article

C. LIGHTNING CURRENT IMPULSE MODEL

In the current work, two lightning current waveforms corresponding to first and subsequent lightning strokes are used. The Heidler's lightning current function (HF) is chosen to represent the current waveform [44], [45].

$$i(t) = \frac{I_0}{\eta}\frac{(\frac{t}{\tau_1})^n}{1+\frac{t}{\tau_1}^n} e^{(-t/\tau_2)} \tag{15}$$

$$\eta = e^{-(\tau_1/\tau_2)(n(\tau_2/\tau_1))^{1/n}} \tag{16}$$

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 correction factor [44].

D. EFFECTIVE ELECTRODE RADIUS INCLUDING SOIL IONIZATION EFFECT

Due to lightning current, the soil ionization occurs when the leakege current in the earth exceeds its critical value as given in Equation (2). The occurrence of the soil ionization by lightning current pulses leads to an increase of the grounding electrode radius subsequently, decrease in the ground resistance, transient voltages, and transient impedances are happened. The new effective radius of grounding electrode $\boldsymbol{r_i}$ in meter is proposed by equation (17), which is a general equation for both vertical and horizontal rods [46], [47]. In this equation $\boldsymbol{\rho}$ is the soil resistivity in Ω.m, $\boldsymbol{I_m}$ is the maximum value of the stroke current in kA, $\boldsymbol{E_c}$ is the electric critical field in kV/m and $\boldsymbol{l}$ is the electrode length in m.

$$\boldsymbol{r_i} = \frac{\boldsymbol{\rho I_m}}{\boldsymbol{2\pi E_c l}} \tag{17}$$

Figure 2 shows the effective radius of the soil ionization around the electrode with different reflection factors, calculated by various soil models when subjected to first and subsequent return current stroke. According to National Electric Code (NEC), 250.52(A) (5) in 2017 [48] and the field experience, the electrode length is considered to be 3 m and the laying depth of horizontal grounding electrode is 0.5 m. The actual electrode diameter was 0.014 m. Table 1 gives the effective electrode radius including soil ionization influence at first and second lightning strokes versus the reflection factor. The variation of the soil resistivity as a result of the soil ionization around a vertical and horizontal rods due to the impact of the first stoke, at instance when the impulse current reached its peak value is given in Figs 2-c and 2- d by using FEM and COMSOL multiphasic program. The FEM [49] can be used to simulate the case under study. It is based on the following governing equations:

$$\nabla \cdot J = 0 \tag{18}$$

$$J = \sigma E + \frac{\partial D}{\partial t} + J_e \tag{19}$$

$$E = -\nabla V \tag{20}$$

where, J is the vector of the current density, (A/m^3); σ is conductivity, (S/m); E is the electric field strength, (V/m); and J_e is the current density, (A/m^3); V is electrical potential, (V).The proposed model consists of an electrode buried in uniform or two layer soils, the upper boundary condition

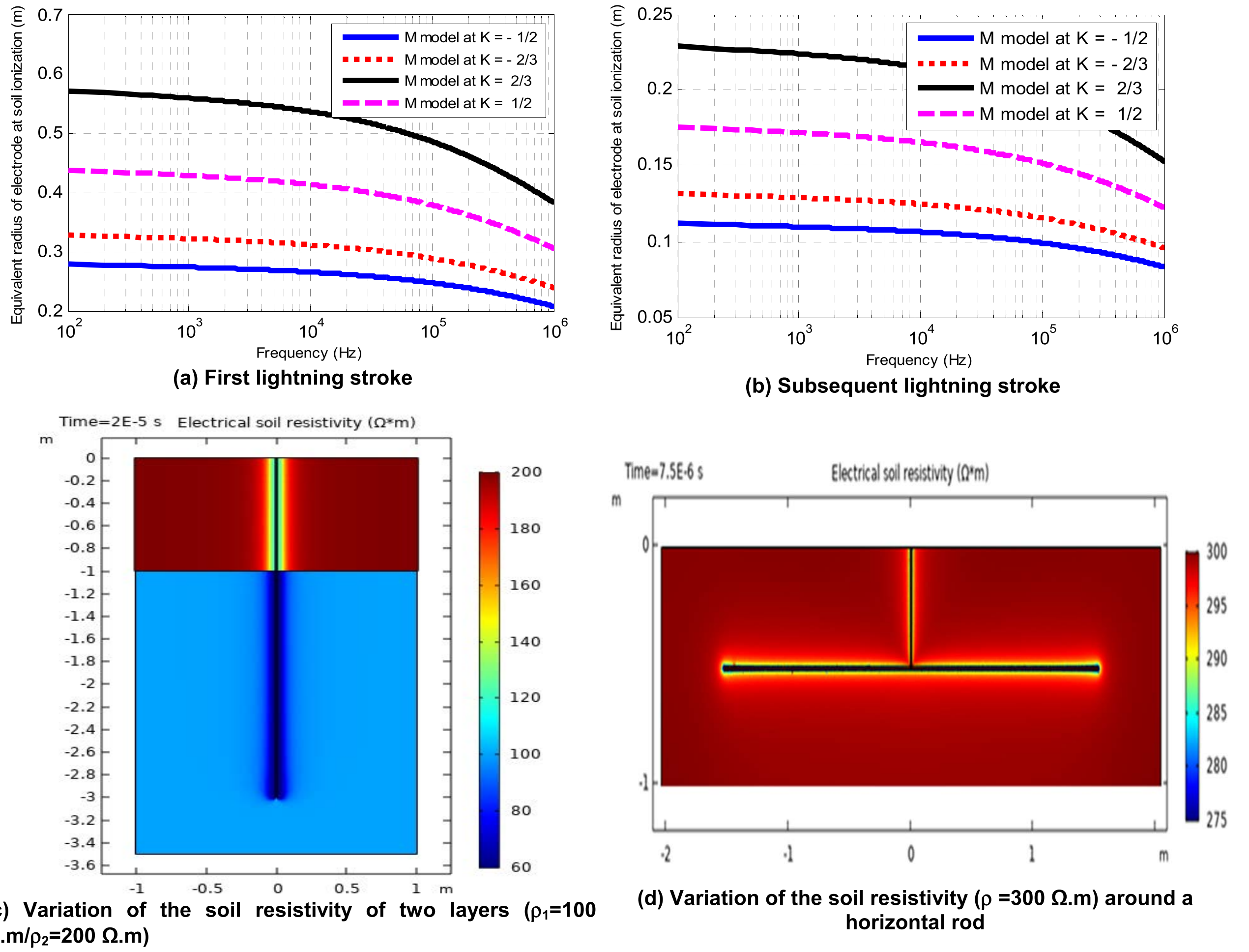


FIGURE 2. Equivalent radius of horizontal and vertical electrodes at soil ionization phenomena, the electrode has 3 m length and 7 mm radius with different reflection factors using Messier model (a) at first lightning stroke, (b) at subsequent lightning stroke, (c) Variation of the soil resistivity of two layers (ρ_1 = 100 Ω.mρ_2 = 200 Ω.m) around a vertical rod and (d) Variation of the soil resistivity (ρ = 300 Ω.m) around a horizontal rod.

is considered as an electrical insulation boundary, which is characterized by:

$$n \cdot J = 0 \tag{21}$$

where, n is the outward normal direction to the surface of that boundary side.

The other three boundary conditions are considered as floating potential. In this simulation, when the local electric field E within a certain point in the soil exceeds the critical value E_c, the ionisation begins at this point and the soil becomes ionised by the following manner [50]

$$\rho = \rho_0 e^{(-t/\tau)} \tag{22}$$

where ρ_0 is the steady-state resistivity, t is the time defined so that $t = 0$ at the instant of $E = E_c$ and τ is the ionisation time constant. The decreasing resistivity with time represents soil ionization process. During the de-ionisation process, the variable resistivity law is expressed as follows [50].

$$\rho = \rho_i + (\rho_0 - \rho_i)(1 - e^{-t/\tau_1})(1 - E/E_c)^2 \tag{23}$$

where ρ_i is the minimal values reached by soil resistivity during the ionisation process, τ_1 is the de-ionisation time constant and E is the actual amplitude of the electric field. The increasing resistivity with time from ρ_i to ρ_0 represents de-ionisation process of soil.

The soil critical electric field E_c is set to be 110 kV/m [50]–[52], furthermore, the time constants are chosen the same values as those reported by Liew and Darveniza [52], ($\tau = 2\ \mu$, τ_1= 3μs).

From Figures 2-c and 2- d, it is noticed that the resistivity of the soil layers are decreased within the area around the rod. The reduction in the soil resistivity reached to about 38 % of its steady state value and it is uniformly distributed around both the vertical and the horizontal rods.

From Table 1 and Fig. 2 a and b, it can be concluded that the reflection factor has a significant impact on the equivalent radius of the electrode. Increasing the reflection factor leads to influenced impact in the equivalent radius increase. Conversely, the increase in the lightning stroke frequency leads to a decrease in the equivalent radius of electrode.

TABLE 1. Effective electrode radius including soil ionization impact at first and second lightning strokes verses reflection factor, the electrode has 3 m length with electrode diameter 0.014 m.

Lightning stroke	K (Reflection factor)	r_i without considering the frequency impact, m	r_i including the soil ionization effect using Messier expression, m	r_i including the soil ionization effect using Scott expression, m	r_i including the soil ionization effect using Visacor et al expression, m
First stroke	2/3	0.5396	0.2935	0.3107	0.3908
	1/2	0.4123	0.3971	0.3980	0.2992
	0	0.2063	0.2038	0.2070	0.1504
	-2/3	0.3084	0.3005	0.3033	0.2242
	-1/2	0.2618	0.2566	0.2598	0.1905
Subsequent stroke	2/3	0.2183	0.1780	0.1718	0.1354
	1/2	0.1668	0.1402	0.1355	0.1037
	0	0.0834	0.0747	0.0727	0.0521
	-2/3	0.1247	0.1079	0.1046	0.0777
	-1/2	0.1059	0.0930	0.0903	0.0660

Again it is observed that the results of Scott expression and Messier expression are close to each other, while results of Visacro and Portela expression are somewhat far from their results

IV. MODELING OF GROUNDING ELECTRODE UNDER LIGHTNING

In this section, the performance of grounding electrodes (horizontal or vertical) in two-layer soil including the effect of the soil ionization with frequency and soil resistivity variations is investigated. The grounding electrode has 3 m length and 7 mm radius, the laying depth of the horizontal grounding electrode is considered as 0.5 m, and the thickness of first layer is assumed to be 1m. The soil relative permittivity is considered to be 10 for first layer and 8 for the second layer considering the moisture content [53]. Finally, the reflection factors are taken as −1/2, −2/3, 1/2, 2/3, and k = 0 with uniform soil resistivity 100 Ω.m.

In this paper transmission line model (TLM) in ATP is used to simulate the grounding electrodes. In (TLM) method any grounding electrode can be divided into N segments each one contains grounding resistance, capacitance and inductance elements as given in Fig. 3 in case of horizontal grounding electrode. The formulas of R_g, C_g and L_g are given in references [3], [8]. The grounding resistance, capacitance and electrode inductance of the vertical electrode are calculated by using equations 24, 25, and 26, respectively [3], [8].

$$R_g = \frac{\rho}{2\pi} \ln(\frac{4l}{\text{a}} - 1) \tag{24}$$

$$C_g = \frac{\rho\varepsilon}{R_g} \tag{25}$$

$$L_g = \frac{\mu}{2\pi} [\ln \frac{2l}{\text{a}} - 1] \tag{26}$$

where, μ is the soil permeability (H/m), a is the radius of grounding electrode, which is replaced by $\boldsymbol{r_i}$ when the ionization process is started, ρ is the soil resistivity and l is the length of grounding electrode. The resistance, inductance and capacitance of the horizontal electrode can be calculated by using the relations given in Equations 27, 28 and 29 [8], where R_i is the resistance of the i^{th} segment with a length of l_i, ρ is the soil resistivity and h is the burial depth of the grounding electrode and a is the radius of grounding electrode.

$$R_i = \frac{\rho}{2\pi l_i} \left[\frac{2h+a}{l_i} + ln\frac{l_i + \sqrt{l_i^2 + a^2}}{a} - \sqrt{1 + \left(\frac{a}{l_i}\right)^2} + ln\frac{l_i + \sqrt{l_i^2 + 4h^2}}{2h} - \sqrt{1 + \left(\frac{2h}{l_i}\right)^2} \right] \tag{27}$$

In single horizontal rod the inner self-inductance of a grounding conductor under high frequency can be ignored comparing with its external self-inductance because of the strong skin effect, so the self- inductance Li of the i^{th} segment can be calculated by [8].

$$L_i \approx \frac{\mu_o l_i}{2\pi} \left(ln\frac{2l_i}{a} - 1 \right) \tag{28}$$

where l_i is the length of the i^{th} segment of grounding electrode and μ_o is the permeability of free space.

The shunt capacitance C_i of the i^{th} segment with a length of l_i and an ionization zone radius of a_i in an infinite medium is [8].

$$C_i(a_i) = \frac{2\pi\varepsilon l_i}{\frac{a_i}{l_i} + ln\frac{l_i + \sqrt{l_i^2 + a_i^2}}{a_i} - \sqrt{1 + \left(\frac{a}{l_i}\right)^2}} \tag{29}$$

where ε is the soil permittivity. The transient behavior of the grounding electrode is investigated by using ATP-EMTP [54] and the electrode parameters. The number of the segments required for an accurate simulation is dependent on the highest frequency of the injected transient wave, the higher the frequency, the larger the number of sections is required. However, the difficulty of incorporating the frequency dependent soil properties limits the application of the approach in transient analysis, since the lightning current has frequency components.

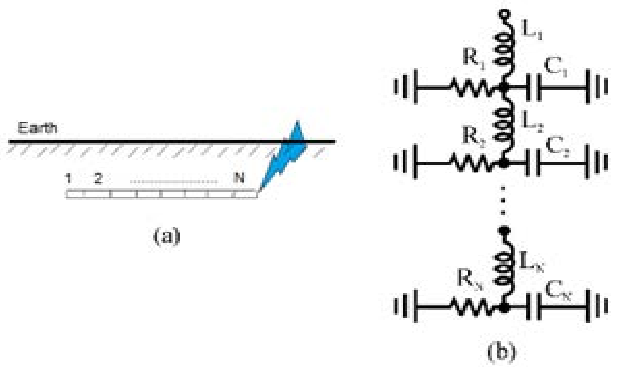


FIGURE 3. Simulation of buried horizontal electrode subjected to lightning stroke, (a) transmission line model (TLM) of horizontal electrode and (b) the passive element circuit represents horizontal electrode.

V. TRANSIENT GROUNDING VOLTGES IN TWO LAYER SOILS

A. TRANSIENT GROUND POTENTIAL RISE (TGPR)

Figure 4 shows the transient ground potential rise when the horizontal and vertical rods are subjected to 30 kA first lightning strokes with ignoring the soil ionization impact and when it is considered using Messier expression, Scott expression and Visacor and Portela formula at constant $\rho_1/\rho_2 = 300/100$ as given in Fig. 4(a). The rod length is considered to be 3 m with 0.014 m diameter. Figure 4a. showed that the peak value of the transient voltage decreases sharply when the soil ionization phenomenon is considered regardless of the used model in the calculations. This is due to the increase in the effective radius of grounding electrode. Figs 4 (b), (c) and (d) illustrate the transient ground potential rise using Messier expression and Scott *et al.* expression for including the frequency and soil resistivity variations impacts on the soil ionization electric field. Fig. 4 (b) contains the calculations done by using Messier expression at different reflection factors for horizontal electrode. In Fig.4 (c), calculations are carried out using Messier expression at different reflection factors for vertical electrode and in Fig.4 (d), the calculations are achieved using Scott expression at different reflection factors for horizontal electrode. It is noticed that Scott *et al.* and Messier [41] expressions calculations are very close in magnitudes and shapes. Marked difference is noticed when Visacor *et al. formula* [43] is used as given in Fig. 4(a). It is noticed also that the reflection factor has an influence impacts on the grounding potential rise; the minimum value is obtained in case of 100 Ω.m uniform soil resistivity. Finally, it is observed that horizontal electrodes gave lower peak values comparing with the vertical electrodes.

To investigate the effect of lightning current's front time T_f, on the soil resistivity and permittivity, the equivalent frequency f_{eq} of the lightning current is determined as in [55]

$$f_{eq} = \frac{1}{4T_f} \tag{30}$$

f_{eq} is used in frequency dependent soil properties and T_f is the lightning current's front time.

TABLE 2. Front time effect on TGPR and Transient impedance.

front time T_f µs	Frequency (kHz)	(TGPR) (kV)	Transient Impedance (Ω)
80	31.25	666.7	22.22
0.8	312.5	321.3	26.7

The equivalent frequencies for the first and the subsequent return stroke currents are considered to be 31.25 kHz and 312.5 kHz, respectively. Table 2 shows the effect of front time on the performance of horizontal grounding electrode in two layer soil for reflection factor = -2/3 at 30 kA lightning stroke. From table 2 it is noticed that the front time has noticeable effect on the (TGPR) and transient impedance. As the front time is decreased from 80 μs to 0.8 μs, the TGPR and transient impedance are dropped by 51.8% and 20.1% respectively.

Figure 5 gives similar relations between TGPR and the soil reflection factors in case of subsequent lightning strokes strike with the use of horizontal and vertical grounding electrodes. The results indicate that the peak values of the transient grounding potential rise are reduced comparing with the TGPR of first lightning stroke due to the decrease in the effective radius of grounding electrode. As given in Fig. 5 increasing the reflection factor increases the transient grounding potential rise TGPR. The time interval of subsequent lightning stroke TGPR and the time required to reach to the stroke peak value are shorter compared with the first lightning stroke grounding potential rise.

B. TRANSIENT EARTH SURFACE POTENTIAL (TESP)

The earth surface potentials of horizontal and vertical grounding electrodes including the effect of soil ionization for 3 m electrode length, 7 mm radius and different values of reflection factors are given in Fig. 6 for first lightning stroke. The grounding electrode is simulated by ATP-EMTP [54]. Messier expression and Scott expression are used to include the effect of frequency and soil resistivity variations on the soil ionization process. Fig. 6(a) gives the TESP in case of horizontal electrode using Messier expression, Fig. 6(b) gives the TESP in case of vertical electrode using Messier expression, Fig. 6(c) gives the TESP in case of horizontal electrode using Scott expression and, Fig. 6(d) shows the TESP in case of vertical electrode using Scott expression. From this figure it is noticed that the TESP is higher for two-layer soil (different values of reflection factors) than TEPS in case of 100 Ω.m uniform soil. It is observed also that, the peak value of TESP in case of horizontal electrode is much lower than that in case of vertical electrode. According to the results of TESP curves, it is noticed that the touch voltages of horizontal electrode are lower than its value of vertical electrode. Similar calculations are done in case of subsequent lightning stroke as given in Fig. 7. Remarkable reduction in TESP is noticed

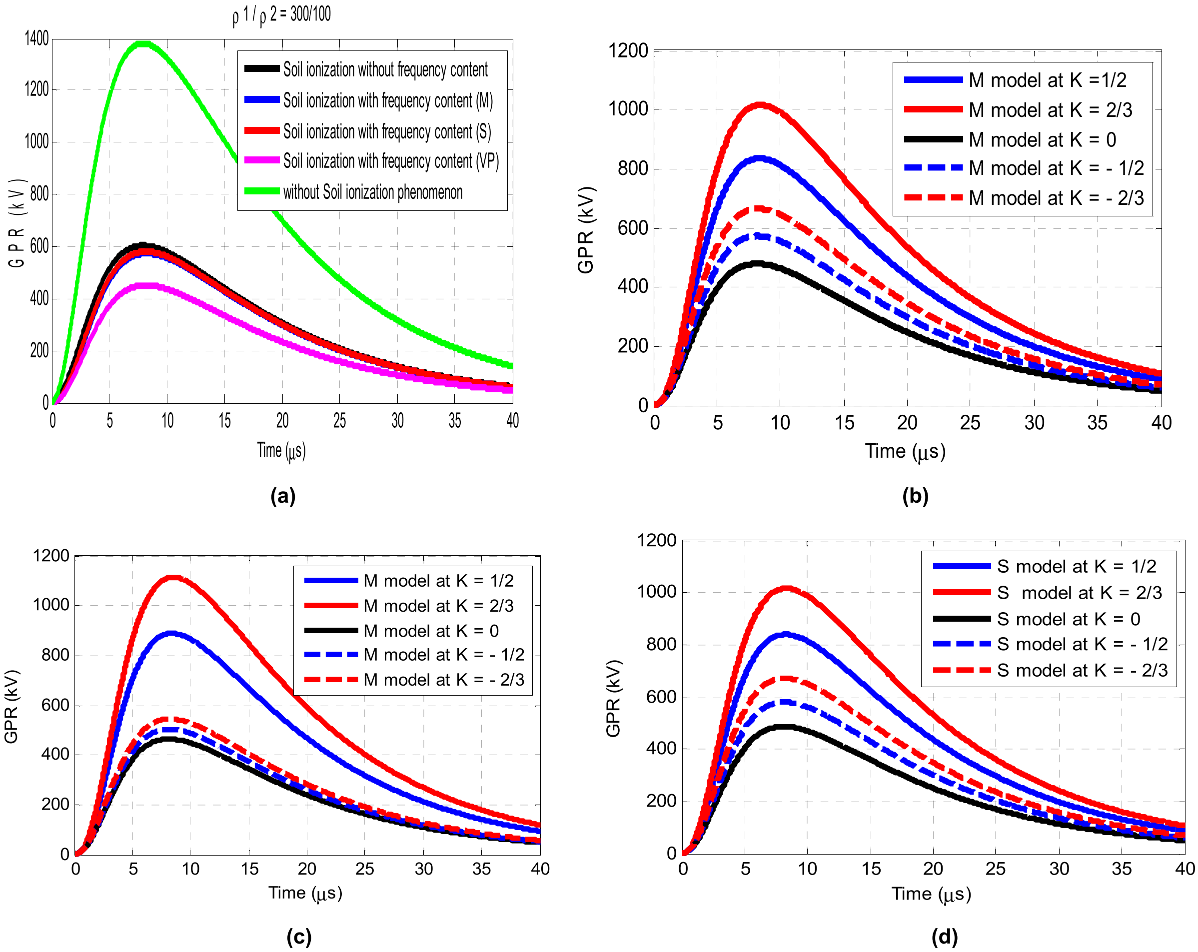


FIGURE 4. First lightning stroke TGPR of horizontal and vertical electrodes (a) at k = −1/2, horizontal electrode using Messier expression (M), Scott expression (S) and Visacor and Portela (P) formulas with soil ionization phenomena, (b) using Messier expression at different reflection factors for horizontal electrode, (c) using Messier expression at different reflection factors for vertical electrode and (d), using Scott expression at different reflection factors for horizontal electrode.

comparing with its values obtained in first lightning stroke given in Fig. 6.

C. TRANSIENT IMPEDANCE OF THE GROUNDING ELECTRODE

The transient impedance can be expressed as the ratio of voltage and current at the feeding point [55].

$$Z(t) = \frac{v(t)}{i(t)} \; (\Omega) \tag{31}$$

where $v(t)$ is transient potential of grounding electrodeat the feed point and $i(t)$ is the lightning current waveform.

Figure 8 shows the transient impedance of horizontal and vertical grounding electrodes including the soil ionization phenomenon and frequency content impacts. In this figure the electrode is subjected to 30 kA first and subsequent lightning stroke at different values of reflection factors and also at 100 Ω.m uniform soil resistivity. In Fig. 8, Messier and Scott expressions are used to investigate the influences of the frequency and soil resistivity variations on the soil ionization in the calculations of the transient impedance. From this figure, it is noticed that the transient impedance of the two-layer soil that has negative reflection factor is lower than the transient impedance in case of positive reflection factor. Also, it is seen that the computed transient impedance is low for all reflection factors than transient impedance of the grounding system in 100 Ω.m uniform soil. It is observed also that after some micro seconds the transient impedance returns to its resistance value at power frequency. It is noticed also that the reflection factor has no effect on the transient impedance of grounding electrode until reaching to about 0.5 μs in case of both horizontal and vertical rods according to Messier and Scott expressions.

Figs. 9 (a) and (b) illustrate the transien impedances of horizontal and vertical grounding electrodes respectively with different lengths at different reflection factors using Messier model for first lightning stroke. Fig.9 (c) shows the impulse impedance for the subsequent lightning stroke in horizontal rod and Fig. 9(d) shows the simulation and experimental results of transient impedance under soil ionization

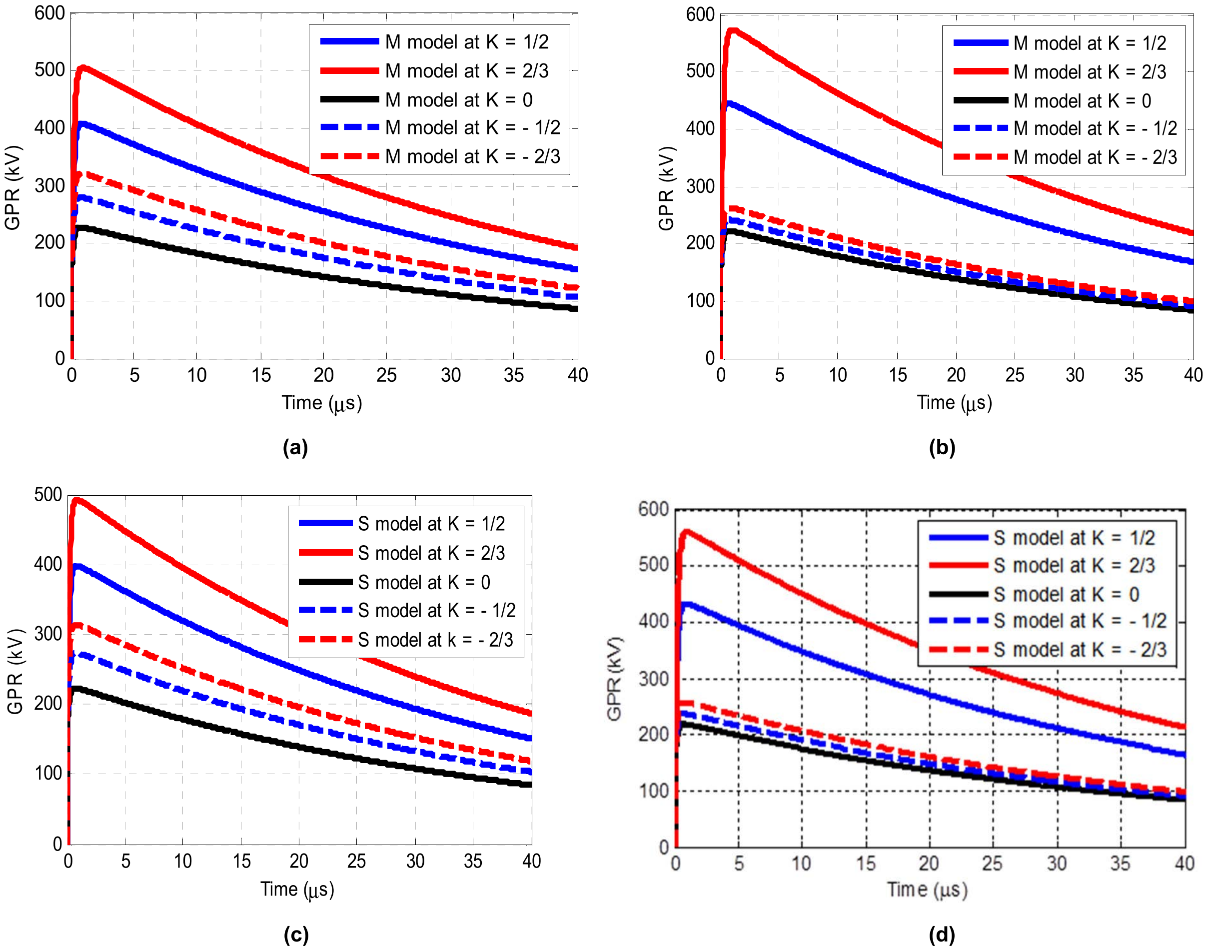


FIGURE 5. **Subsequent lightning stroke GPR of (a) horizontal using Messier expression with soil ionization phenomena, (b) vertical using Messier expression with soil ionization phenomena (c) horizontal electrode using Scott expression with soil ionization phenomena and (d) vertical electrode using Scott expression with soil ionization phenomena.**

models according to similarity approach given in [56], [57], Nixon *et al.* [35] and CIGRE [31] for a single rod and by using transmission line method. Fig. 9 (a) shows the relation between the horizontal grounding electrode length and the impulse impedance for different reflection factors including the effect of soil ionization with frequency and soil resistivity variations. From this figure it is noticed that increasing the horizontal electrode length reduces the grounding impedance when subjected to first lightning stroke until reaching to 20 m as given in the figure. After that length, a slight increase in the grounding impedance is noticed may be due to the increase in the electrode inductance. As shown in the same figure it is noticed that the reflection factor has remarkable decrease of the grounding transient impedance with the increase of the electrode length until reaching to constant value. The electrode length at this value is called the effective length of grounding electrode. Also, it is observed that in the first lightning stroke case the impulse impedance reaches to effective length before subsequent lightning stroke.

Similar calculations are done using vertical grounding electrode and there is no noticeable difference with previous characteristics as given in Fig. 9 (b). Fig. 9 (c) shows the subsequent lightning stroke impedance in horizontal rod.

For the purpose of the verifications, the calculated values of impedances are compared with that obtained by similarity approach [56]–[58], experimental measurements done by Nixon *et al.* [35], and also compared with CIGRE model calculations [31]. The data used in this case are: $\rho_1/\rho_2 = 4.48$, the upper layer thickness is taken as 1.9 m; and the lower layer thickness is considered 2.4 m until reaching to the water table (water table is defined as the upper level of the underground surface in which the soil is permanently saturated with water). The vertical electrode length is taken as 3 m. The lightning wave shapes in laboratory tests done by Nixon [35] and calculations are done by the use of two lightning current waveforms 5 kA and 30 kA with front/tail times 4/35 μ. In the case under study the critical breakdown field strength is considered to be 300 kV/m. As it seen in Fig. 9 (d) the calculated values done by using the present method are close to the experimental measurements more than that obtained by W.A. Chisholm, W. Janischewskyj [58]

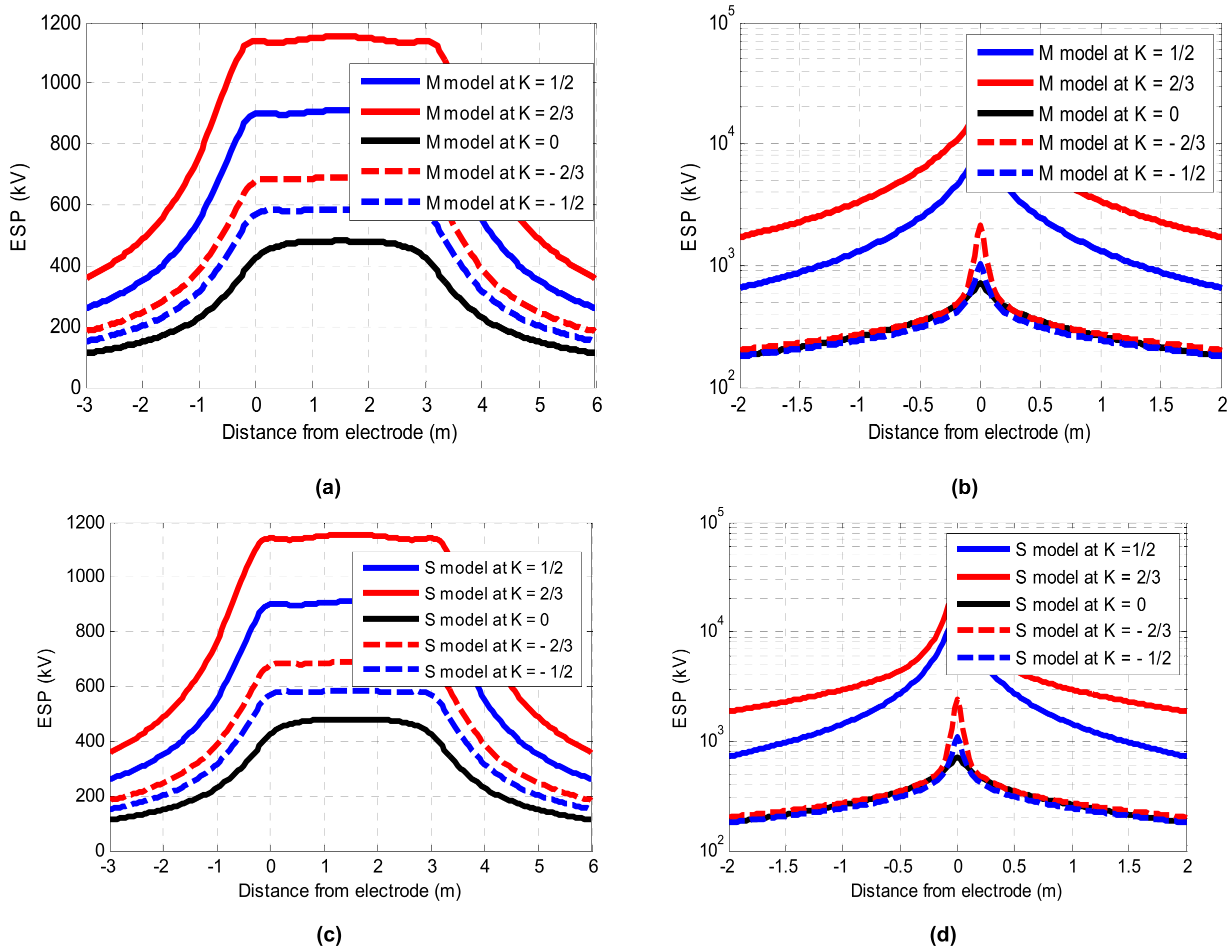


FIGURE 6. Earth surface potential (ESP) at first lightning stroke soil respecting ionization phenomena at time 5 μs (a) horizontal using Messier expression with soil ionization phenomena, (b) vertical using Messier expression with soil ionization phenomena (c) horizontal electrode using Scott expression with soil ionization phenomena and (d) vertical electrode using Scott expression with soil ionization phenomena.

and CIGRE model [31]. This may be because the current method takes into account the effect of soil ionization with the variations in soil conductivity and permittivity with the stroke frequency variations.

The authors believe that the little difference between the measured and calculated values may be due to the change in solubility and ionisability of the soil electrolytes under the stroke electric field, which is not considered in the calculations. For further confirmation of the results obtained in this article, the TGPR calculated results are compared with the experimental and results obtained by references [35], [59] as given in Table 3. From the tabulated results it can be noticed that the difference is within +1.7% to −5.7%, which proves the high credibility of the used method in this article .

VI. INFLUENCE OF THE UPPER SOIL LAYER THICKNESS ON THE GROUND ELECTRODE PERFORMANCE

It is very interesting to investigate the effect of the upper layer thickness on the ground electrode performance. Table 4 gives

TABLE 3. Comparison between experimental measurement of TGPR by Nixon *et al.* [35], by Liu, Y.Q [46] and calculated by the present paper.

Calculated Max (TGPR) by the present model using the data given in Ref. [35]	483.2 (kV)
Measured Max TGPR by Nixon et al. [35]	492 (kV)
Calculated Max (TGPR) by the present model using the data given in Ref. [46]	185 (kV)
Measured Max (TGPR) by Liu, Y.Q [46]	175 (kV)

the influence of thickness of the upper layer soil on maximum TESP, TGPR and transient impedance for horizontal grounding electrode in non-uniform soil for different reflection factors at 30 kA first lightning stroke at time = 5μs. From this table it is noticed that with the increase of upper layer thickness the maximum values of the TGPR, TESP and transient impedance decrease when the reflection factor is positive, i.e. $\rho_2 > \rho_1$). The opposite is happened when the reflection factor was negative, i.e. $\rho_1 > \rho_2$). This can be understood in both cases as a result of changing the value

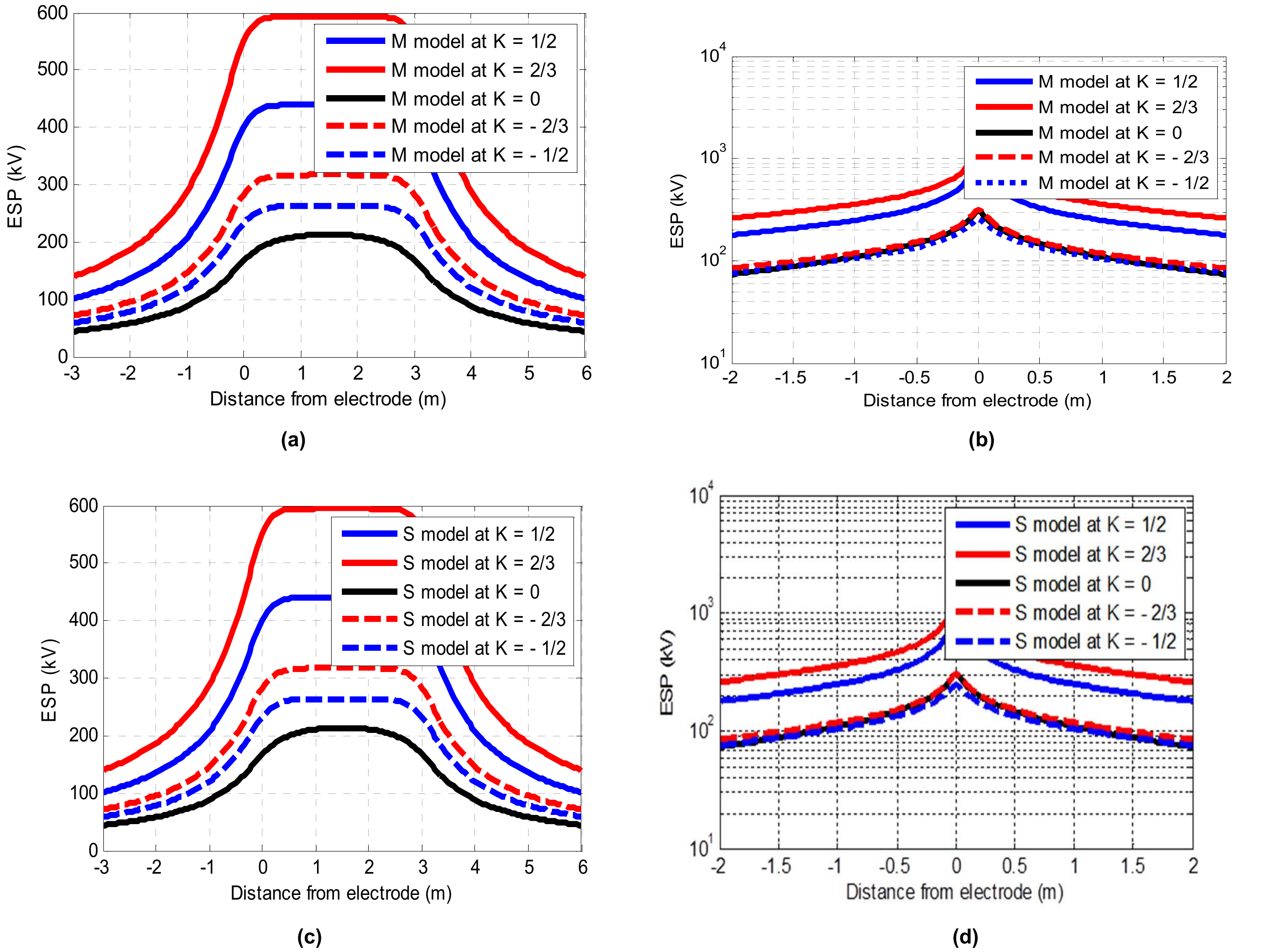


FIGURE 7. Earth surface potential (ESP) at subsequent lightning stroke respecting ionization phenomena at time 5 μs (a) horizontal using Messier expression with soil ionization phenomena, (b) vertical using Messier expression with soil ionization phenomena (c) horizontal electrode using Scott expression with soil ionization phenomena and (d) vertical electrode using Scott expression with soil ionization phenomena.

TABLE 4. Maximum TESP, TGPR and Transient Impedance verses the upper layer thickness.

Reflection factor (k)	Thickness of upper layer soil (m)	Max. (TESP) (kV)	Max. (TGPR) (kV)	Max. Transient Impedance (Ω)
2/3	0.8 (m)	1224	1045	34.833
	1 (m)	1154	1016	33.86
	1.5 (m)	1085	954.49	31.816
-2/3	0.8 (m)	680	645.73	21.52
	1 (m)	690	666.7	22.22
	1.5 (m)	774	714.62	23.82

of the upper layer soil resistivity. Table 5 gives the influence of laying depth of the horizontal grounding electrode on the TGPR and the Transient Impedance.

From Table 5 it is noticed that increasing the burial depth of the electrode reduces TGPR and the transient impedance regardless of whether the reflection factor is positive or negative

TABLE 5. Effect of burial depth of horizontal grounding electrode in non-uniform soil.

Reflection Factor (k)	Burial depth of grounding electrode (m)	(TGPR) (kV)	Transient Impedance (Ω)
-2/3	0.5 (m)	666.7	22.22
	0.8 (m)	596.8	19.89
2/3	0.5 (m)	1016.03	33.86
	0.8 (m)	754.87	25.16

VII. DISCUSSION OF THE OBTAINED RESULTS

In this article the grounding electrodes performance under lightning strokes in uniform and two-layer soil including the influence of soil ionization with frequency and soil resistivity variations was investigated. Constant values of electric field for all soil types are proposed to be used as medium of grounding system by Oettle [59], Musa [60] and CIGRE [31]. These values are 1000, 300, and 400 kV/m respectively. They considered that E_c is independent of the soil properties.

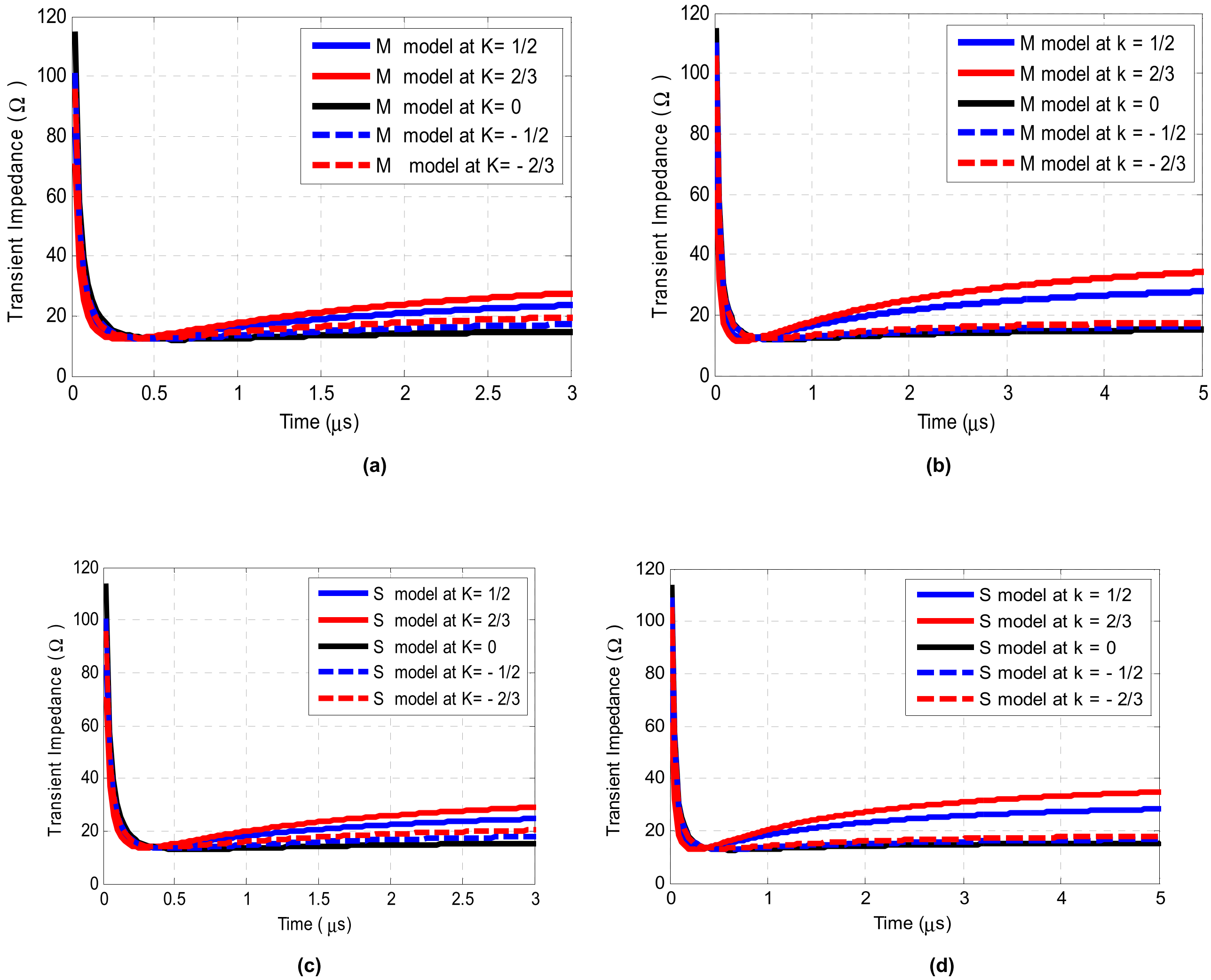


FIGURE 8. Transient impedance at first lightning stroke respecting ionization phenomena (a) horizontal using Messier expression with soil ionization phenomena, (b) vertical using Messier expression with soil ionization phenomena (c) horizontal electrode using Scott expression with soil ionization phenomena and (d) vertical electrode using Scott expression with soil ionization phenomena.

E. E. Oettle equation [36] proposed a relation to calculate the E_c value as a function of the soil resistivity. In this study the formula given in equation 6 suggested by Manna and Chowdhuri [37] to correlate the soil resistivity and soil permittivity with the critical electric field value E_c [59], [37] was used. Based on extensive frequency variations used in this work to calculate the soil critical electric field values (in kV/cm), it is noticed that the obtained results by the use of Scott and Messier expressions are close to each other, while results of Visacro and Portela expression are not compatible with them. This is also reflected in the calculations of transient ground potential rise, transient earth surface potential and transient impedance of the grounding electrode. By comparing the critical breakdown field strength results in Fig 1. (a) and Fig 1. (b), it is noticed that marked difference in the critical breakdown field values at low frequency is noticed, while at high frequency less noticeable changes are observed with the reflection factor variation. Sharp decrease in the critical breakdown field strength value with the increase of the lightning high frequency is observed as given in Fig. 1(c).

The ionization radius around the electrode varies dynamically with the changes of the soil parameters, reflection factor and the grounding electrode system such as the electrode length, burial depth, soil resistivity, soil permittivity, critical electric field and the maximum value of the stroke current and its frequency. From Table 1 and Fig. 2 it can be concluded that the reflection factor has significant impact on the equivalent radius of electrode. As it is illustrated in Table 1, increasing the reflection factor leads to influenced effect in the equivalent radius increase.

The changes in magnitudes of transient grounding voltages and transient impedances of the horizontal and vertical rods when subjected to the first and subsequent lightning strokes in two layer soil have been occur because of the distribution of the electric field around the electrode changes by the

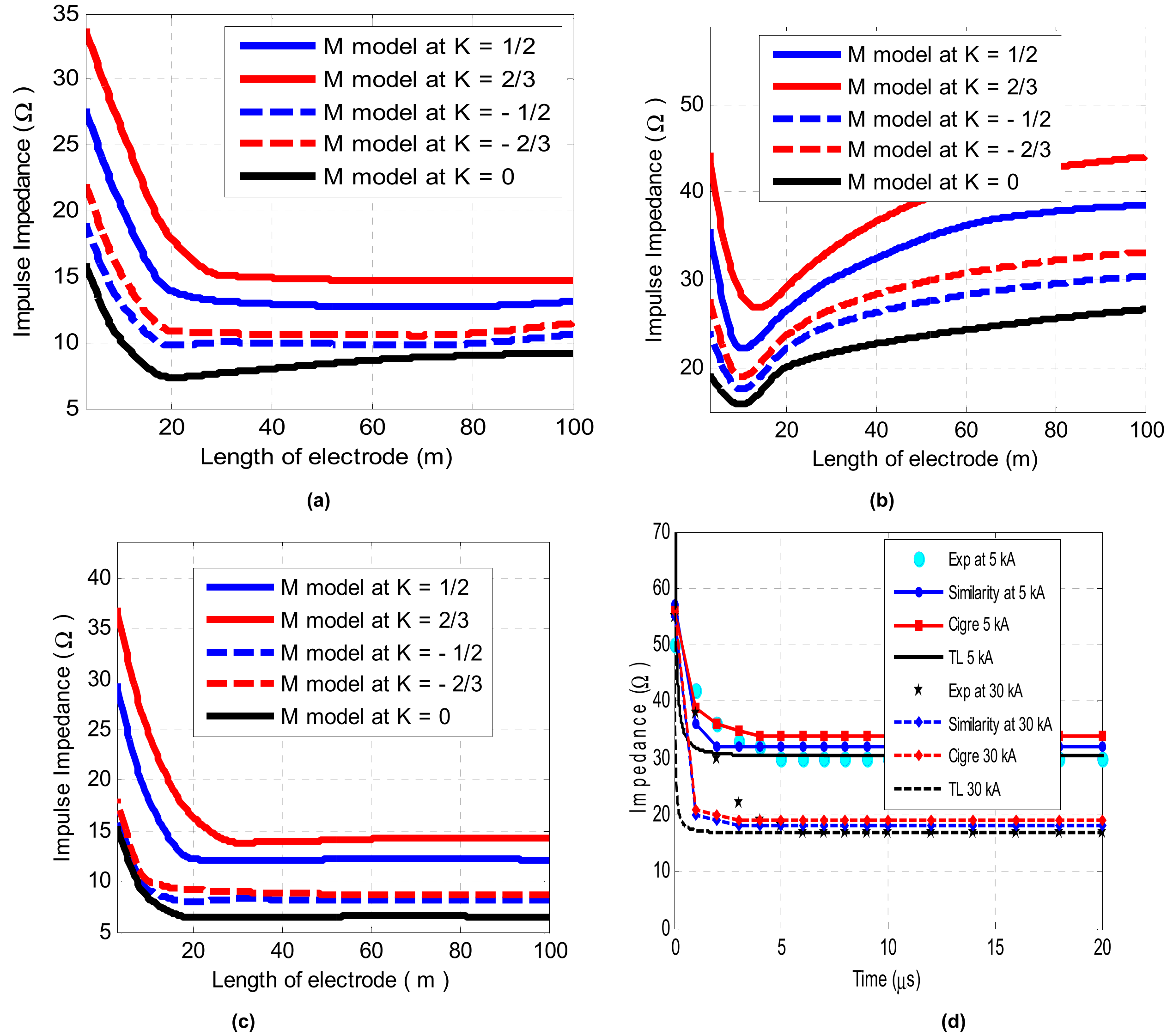


FIGURE 9. Transient impedances with different electrode lengths at different reflection factors using Messier model (a) transient impedances of horizontal grounding electrodes, (b) transient impedances of vertical grounding electrodes, (c) for the subsequent lightning stroke in horizontal rod and (d) Simulation and experimental results of transient impedance under soil ionization models according to similarity approach [50], Nixon *et al.* [35] and CIGRE [31] for a single rod by using transmission line technique.

variations in the current distribution along the electrode and the variation in the soil surrounding the electrode resistivity done by ionization process.

VIII. CONCLUSION

This article is characterized by providing a model for calculating the impact of the soil ionization phenomenon on the transient probabilistic ground potential rise, the transient impedances and transient earth surface potential considering the variations in soil conductivity and permittivity with the stroke frequency, such this model was not covered in previous articles.

The critical breakdown field strength of two layer soil with different reflection factors is presented. The transient probabilistic ground potential rise (TGPR) in uniform and in two layer soils is studied. The transient impedances of horizontal and vertical electrodes are calculated considering the effect of soil ionization including the influence of soil ionization with frequency and soil resistivity variations. It is concluded that the reflection factor has significant impact on the equivalent radius of the electrode. It is observed that the transient voltage peak value decreases sharply when the soil ionization phenomenon is considered and the impulse impedance of the soil that has negative reflection factor is lower than that in case of positive reflection factor. For the verifications of the present study the calculated transient impedances and TGPR are compared with experimental results obtained by Nixon *et al.* and Liu, Y.Q, where a good agreement is noticed. Also, it is noticed that with the increase of upper layer thickness the maximum values of the transient ground potential rise, transient earth surface potential and transient impedance decrease when the reflection factor is positive, i.e. $\rho_2 > \rho_1$). The opposite is happened when the reflection factor was negative, i.e. $\rho_1 > \rho_2$).

The calculations done by the use of Scott and Messier expressions are close to each other, while results of Visacro and Portela expression are not compatible with them. So Scott and Messier expressions may be more accurate in the calculations. Finally, the paper pointed out to that the change in solubility and ionisability of the soil electrolytes under the stroke electric field, which is not considered in the calculations and may need more investigation in the future. This may justify the difference between the measured and calculated .

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