ANALYSIS OF THE BEHAVIOUR OF THE LIGHTNING HORIZONTAL ELECTRIC FIELD ABOVE A FINITELY CONDUCTING GROUND

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ABSTRACT

This paper discusses the characteristics of the horizontal component of the electric field produced by cloud-to-ground flashes during the return stroke phase. The analysis considers the influences of the distance between the return stroke location and the observation point (r), stroke current propagation velocity (v), and the soil type. The MTLE model is adopted for the determination of the current distribution along the return stroke channel, whereas the effect of the finite ground conductivity is taken into account by using the Cooray-Rubinstein (CR) modified approach. The paper also discusses the effect of the each horizontal electric field component (electrostatic, induction, and radiation) on the behaviour of the total horizontal electric field (E_r). The results show that, regardless of the ground conductivity (σ_g), the distance r has a great influence on the characteristics of E_r, especially on its amplitude. The results also show that the horizontal electric field is strongly influenced by the velocity v even for the case of good conductive ground and observation points close to the stroke location.

INTRODUCTION

Lightning usually causes a significant amount of outages on power distribution systems, contributing to the degradation of the power quality. A great deal of problems on overhead distribution lines is related to overvoltages induced by indirect lightning strokes. These surges depend on various parameters and their calculation requires the knowledge of the electromagnetic fields produced by the stroke current as it propagates along the return stroke channel.

While the assumption of a perfectly conducting ground is in general reasonable for the calculation of both the vertical electric and the horizontal magnetic fields, the horizontal electric field is strongly affected by the ground conductivity. This component may have an important effect on the lightning induced voltages, particularly in the case of low conductivity soils. Thus, in order to better evaluate the lightning performance of power distribution lines, design more effective protection systems, and improve the power quality indexes, it is important to understand how the E_r field is influenced by the type of soil, the distance from the stroke location, and stroke current propagation velocity.

In this paper, the characteristics of E_r field are discussed taking into account the impact of the influence of the distance between the stroke location and the observation point, the stroke current propagation velocity, and the soil types.

METHODOLOGY OF CALCULATION

Stroke Current

The current at the channel base at any time $i(0,t)$ is obtained by the sum of the two functions, and represents a typical subsequent stroke current [1]:

$$i(0,t) = \frac{I_{01}}{\eta} \cdot \frac{(t/\tau_1)^n}{(t/\tau_1)^n + 1} \cdot e^{-t/\tau_2} + I_{02}(e^{-t/\tau_3} - e^{-t/\tau_4}) \quad (1),$$

in which I_{01} = 9.9 kA, τ_1 = 0.072 µs, τ_2 = 5.0 µs, I_{02} = 7.5 kA, τ_3 = 100 µs, τ_4 = 6.0 µs [2], and

$$\eta = \exp\left[-(\tau_1/\tau_2)\cdot(n\cdot\tau_2/\tau_1)^{1/n}\right] \quad (2).$$

The $i(0,t)$ is characterized by a peak value around 11 kA and maximum rate of rise of 105 kA/µs. In order to calculate the lightning electromagnetic fields it is necessary to know the spatial-temporal distribution of the current along the stroke channel $i(z,t)$ and, for this purpose, several return stroke models have been proposed [1], [3]-[5].In the present study the modified transmission line model with exponential current decay with height (MTLE) is adopted [2], so that the current *I* at height *z* above a perfectly conducting ground plane at a certain instant *t* is given by

$$\begin{aligned} i(z,t) &= P(z)\cdot i(0,t-z/v) \quad &\text{for} \quad z \le v\cdot t \\ i(z,t) &= 0 \quad & z > v\cdot t \end{aligned} \quad (3),$$

in which $P(z) = exp\,(-z/\lambda_e)$ and λ_e are the current attenuation and decay constant factors, respectively. According Cooray *et al.* [6], the parameter λ_e should vary with the velocity *v* and the decay time constant τ_3 as follows:

$$\lambda_e = (v\cdot\tau_3)\cdot\exp(-z/\lambda_{em}) \quad (4),$$

in which λ_{em} = 4000 m.

Lightning Electromagnetic Fields

A straight vertical channel with length H of 4000 m is assumed for the calculation of the lightning electromagnetic fields. The propagation of the E_r field over a finite conducting ground plane is calculated using the CR modified approach [7]:

$$E_r(r,h,j\omega)=\lfloor E_{rg}(r,h,j\omega)\rfloor_{elet}+ \\ +\lfloor E_{rg}(r,h,j\omega)\rfloor_{ind}+\lfloor E_{rg}(r,h,j\omega)\rfloor_{rad} \quad (5),$$

in which

$$\lfloor E_{rg}(r,h,j\omega)\rfloor_{elet}=E_{rp_{elet}}(r,h,j\omega) \quad (6),$$

$$\left[E_{rg}(r,h,jw)\right]_{ind}=\begin{pmatrix}-H_{\phi pind}(r,0,j\omega)\cdot\dfrac{c\cdot\mu_0}{\sqrt{\varepsilon_{rg}+\sigma_g/j\omega\varepsilon_0}}+\\+E_{rpind}(r,h,j\omega)\end{pmatrix} \quad (7),$$

$$\left[E_{rg}(r,h,jw)\right]_{rad}=\begin{pmatrix}-H_{\phi prad}(r,0,j\omega)\cdot\dfrac{c\cdot\mu_0}{\sqrt{\varepsilon_{rg}+\sigma_g/j\omega\varepsilon_0}}+\\+\left(0.4\cdot E_{rprad}(r,h,j\omega)\right)\end{pmatrix} \quad (8).$$

The equations (6), (7) and (8) are referred to as electrostatic, induction and radiation components, respectively.

The geometrical parameters and equations used for the calculation of both magnetic ($H_{\phi p}$) and horizontal electric fields (E_{rp}) over a perfectly conducting ground are shown in [8].

RESULTS AND DISCUSSION

Unless otherwise specified, in the simulations the stroke current propagation velocity v is assumed constant with height and equal to $1.5\text{x}10^8$ m/s, whereas the height of the observation point (h) is 10 m.

Distance to the Lightning Strike Point

In order to evaluate the influence of the distance r on the characteristics of the horizontal electric field E_r, the electrostatic, induction and radiation components were calculated separately, at distances of 50 m, and 500 m from the stroke location.

The calculations presented in Fig. 1 refer to the case of $\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$. At very short distances (r = 50 m, Fig. 1a) the electrostatic component dominates, while the radiation component is negligible. A slight contribution to the field peak and rise time of the E_r field is given by the induction component. On the other hand, for distances of some hundred meters from the stroke channel (r = 500 m, Fig. 1b), the first peak is determined by the radiation component. Afterwards, the contribution of the induction component increases and eventually it predominates, leading to a continuous increase of E_r up to 10 µs.

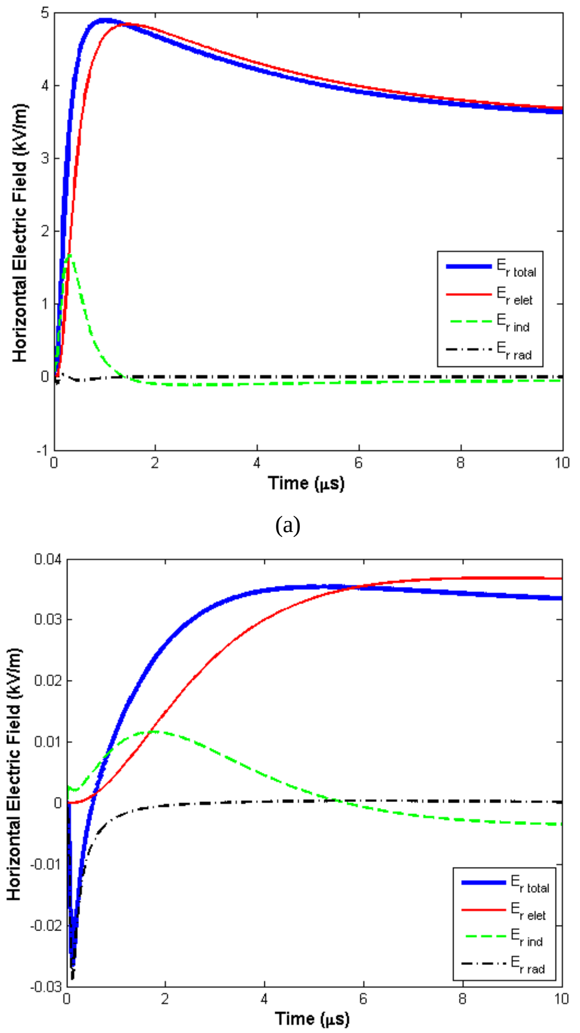
As discussed by Romero and Piantini in [8], for short distances from the stroke location (up to about 100 m) the influence of the finite ground conductivity is very small, illustrating that the assumption of the ground as a perfectly conducting plane is valid provided that the conductivity is not too low. Eq. (5) shows that, contrasting with the E_r induction and radiation components, the electrostatic one is not affected by the finite ground conductivity, regardless of the distance r. The radiation component is the first to reach its maximum and after that its absolute value decreases abruptly. At short distances from the lightning channel it has positive polarity but the contribution of its magnitude on the E_r field is negligible. However, its polarity changes to negative and its absolute value increases with the distance in such a way that for intermediate distances from the stroke location (r = 500 m, Fig. 1b) it dominates at the very beginning, causing a first negative peak on E_r. As it falls sharply after the peak, the static component, which is positive, soon predominates and as a consequence E_r presents a bipolar waveshape.

After some time (about 6 µs in the situation illustrated in Fig. 1b) the induction component changes its polarity from positive to negative and so the total horizontal field E_r presents a slightly faster decay than the static component.

Stroke Current Propagation Velocity

The influence of the stroke current propagation velocity was investigated by the calculation of the E_r field at the distance of 50 m from the stroke location and h = 10 m above ground level. The ground parameters were assumed as $\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$ and two values were considered for v: $0.6\text{x}10^8$ m/s and $2.4\text{x}10^8$ m/s. As indicated in Fig. 2, even for good conductive ground ($\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$) the velocity v has an important influence on the characteristics of the E_r field, especially on its amplitude, which decrease with the increase of v. At very short distances and good conductive ground (r = 50 m, Fig. 2), also the rise time is strongly affected by the stroke current propagation velocity.

Fig. 3 presents the electrostatic, induction, and radiation components of the E_r field at h = 10 m, r = 50 m, ground parameters $\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$, and $v = 0.6\text{x}10^8$ m/s (Fig. 3a) and $v = 2.4\text{x}10^8$ m/s (Fig. 3b). As expected, for short distances from the stroke location and good conductive ground, the static component dominates, whereas the radiation component is negligible. A slight contribution to the field peak is given by the induction component. An increase in the velocity v results in a decrease of both the rise time and peak value of the static component and, consequently, in a decrease of the amplitude of the total horizontal field E_r.



(a)

(b)

Figure 1: Horizontal electric field components at different distances from the stroke location. $\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$, h = 10 m, $v = 1.5\text{x}10^8$ m/s. (a) r = 50 m; (b) r = 500 m.

Soil Type

The ground conductivity for the same soil type varies as function of its temperature, moisture content and other parameters. In order to evaluate the influence of the soil parameters on the horizontal electric field, two soil types, taken from [9], were considered, as indicated in Table 1. For each soil type, simulations were performed considering the limits of the ground relative permittivity (ε_{rg}) given in Table 1. For good conductive ground, the variations of the E_r field were found to be negligible within the ranges indicated. On the other hand, for the case of very poorly conductive ground, the difference between the first peak (negative) corresponding to the cases of $\varepsilon_{rg} = 1$ and $\varepsilon_{rg} = 3$ was about 20% for r = 50 m and v = $1.5\text{x}10^8$ m/s.Thus, for very poorly conductive ground ε_{rg} was assumed equal to 2.

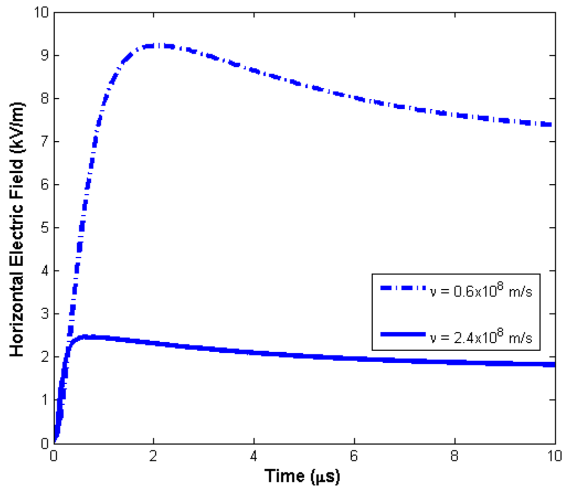


Figure 2: Horizontal electric fields for two stroke current propagation velocities. $\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$, h = 10 m, r = 50 m.

Table 1: Soil types considered in the simulations.

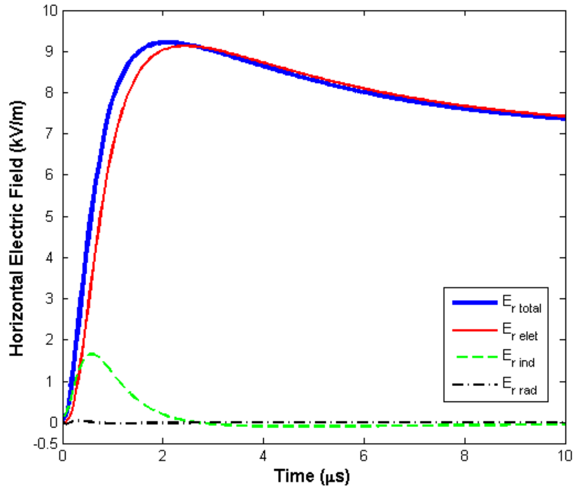
SOIL	σ_g (S/m)	ε_{rg}
Good conductive ground	0.02	4 - 30
Very poorly conductive ground	0.0002	1 - 3

Fig. 4 shows the results corresponding to field calculations at distance of 50 m from the lightning strike point for the two soil types considered. For short distances to the stroke location, the waveform of the field associated with the good conductive ground is relatively close to the field corresponding to the poorly conductive ground. The latter, however, presents a negative peak in the very beginning due to the predominance of the influence of the radiation component. The amplitude of this negative peak increases as the ground conductivity diminishes (and as the distance *r* increases).

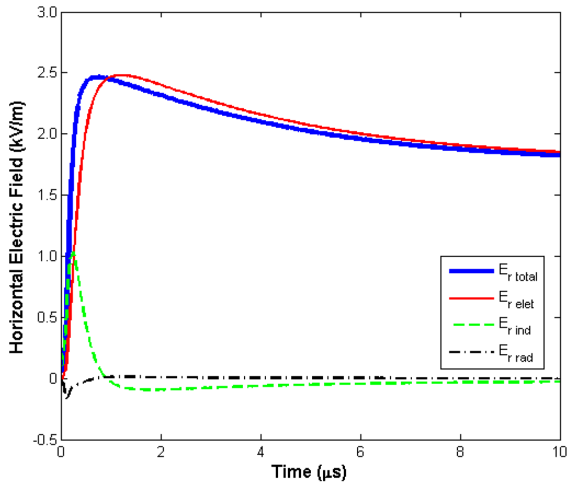
CONCLUSIONS

The behaviour of the horizontal electric field over a finitely conducting ground have been evaluated with respect to the influence of the distance to the lightning strike point, stroke current propagation velocity, and soil types. The results of the simulations have shown, regardless of the soil type, the great effect of *v* upon E_r field.

With reference to the distance from the lightning strike point, it has an important influence on the characteristics of the E_r field, especially on its amplitude, regardless of the ground conductivity. For short distances to the lightning channel, the field amplitude tends to decrease with the ground conductivity, while for distances of a few hundred meters the absolute value of E_r field magnitude tends to increase as the ground conductivity diminishes.



(a)



(b)

Figure 3: Horizontal electric field components at different stroke current propagation velocities. $\sigma_g = 0.02$ S/m and $\varepsilon_{rg} = 30$, h = 10 m; r = 50 m, (a) $v = 0.6\text{x}10^8$ m/s, (b) $v = 2.4\text{x}10^8$ m/s.

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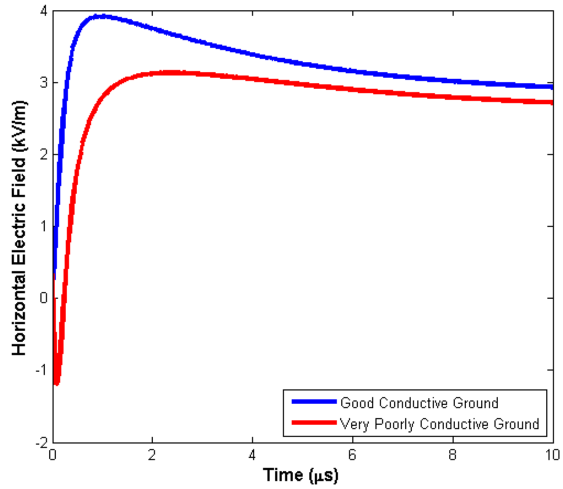

Figure 4: Horizontal electric fields for two soil types. $v = 1.5\text{x}10^8$ m/s, h = 10 m, and r = 50 m.

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