ARTICLE IN PRESS

Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Characteristics of the horizontal electric field associated with nearby lightning return strokes

J.L. Yu [a,b], Y.D. Fan [b,*], J.G. Wang [b], R.H. Qi [b], M. Zhou [b], L. Cai [b], M.J. Cui [b], Z.J. Yuan [c]

[a] School of Electrical Engineering, Northeast Dianli University, Jilin, China
[b] School of Electrical Engineering, Wuhan University, Wuhan, China
[c] State Grid Ningbo Yinzhou Power Supply Company, Ningbo, China

ARTICLE INFO

Article history:
Received 27 February 2015
Received in revised form
3 December 2015
Accepted 18 February 2016

Keywords:
Lightning
Characteristics
Horizontal electric field
MTLL
FDTD

ABSTRACT

There exists inherent difficulty in measuring the horizontal electric field (E_r) associated with lightning return strokes due to the overshadowing effect of the vertical electric field component, not much progress in E_r measurements were observed until now. In order to study the characteristics of E_r associated with nearby lightning return strokes, the modified transmission-line model with linear current decay with height (MTLL) return stroke model and Finite Difference Time Domain (FDTD) method were used to calculate E_r for 12 observation points with different distances (20, 50 100, and 200 m) away from the lightning channel and different heights (0, 10, and 20 m) above ground. Four characteristic parameters, namely, the return-stroke speed (v), the total length of the return stroke channel (H), the ground relative permittivity (ε) and the ground conductivity (σ), were considered. Results show that the polarity of E_r changes between the ground level and the space. The influence intensity rank of the four characteristic parameters on E_r at ground level is: $\sigma > v > \varepsilon > H$. The influence of the characteristic parameters on E_r are more important for $v \le 0.6$c, $H \le 6000$ m and $\sigma \le 2.5 \times 10^{-3}$S/m.

1. Introduction

It is well known that the interference and damage to electrical and electronic equipment caused by lightning electromagnetic pulse (LEMP) is very serious (Rakov and Rachidi, 2009). Since the horizontal electric field (E_r) is much smaller than the vertical electric field in the lightning electromagnetic pulse (LEMP) (Miki et al., 2002; Yang et al., 2009), there exists inherent difficulty in measuring E_r due to the overshadowing effect of the vertical electric field component. Until now, very few attentions have been devoted to E_r and very few E_r observation data has been obtained. In fact, E_r close to the return stroke channel may reach to a very high value, which plays an essential role in many fields, such as the calculation of interaction of lightning-radiated electromagnetic fields with lightning induced over-voltage on transmission lines and telecommunication lines (Rachidi, 2012).

Several approximate formulas have been developed to calculate the lightning horizontal electric field, among which, Wave Tilt Formula, as firstly proposed by Norton, (1937), is one of the best known one that can be applied for distances farther than a few kilometers. Cooray, (1992), using an expression for the surface impedance of the finitely conducting earth, proposed a technique which is suitable for distances as short as 200 m. Rubinstein, (1996), on basis of the work in Cooray, (1992), developed the Cooray–Rubenstein (CR) formula which can solve this problem more simply and efficiently. Wait, (1997) analyzed the problem in frequency domain and derived the conditions under which the CR formula is valid. A modified version of the CR formulation was proposed by Cooray, (2002); Meredith et al. (2010), noting that, when the surface conductivity began to decrease, E_r would played an increasingly more significant role, developed a new formula with an imperfect conductive surface.

The effects of the characteristic parameters, such as the total length of return stroke channel, the return-stroke speed, the ground conductivity, and the ground relative permittivity, cannot be ignored in the theoretical calculation of LEMP. However, the above-mentioned four characteristic parameters, as well as return stroke parameters and earth electrical parameters, are presently hardly valued in proper scopes due to the limitation of inherent observation defect. Generally, they were valued in larger decentralized range because of lack in corresponding research, this situation directly affecting the accuracy of the LEMP calculation. In fact, the channel length is generally not longer than 10 km (Cooray, 2008; Shoory et al., 2009), the return stroke speed is smaller than the speed of light (Rakov, 2007; Baba and Rakov, 2009), and the ground conductivity is in the range of 10^{-4}–10^{-2} S/m (Baba and

* Corresponding author.
E-mail address: ydfan@whu.edu.cn (Y.D. Fan).

http://dx.doi.org/10.1016/j.jastp.2016.02.017
1364-6826/

Please cite this article as: Yu, J.L., et al., Characteristics of the horizontal electric field associated with nearby lightning return strokes. Journal of Atmospheric and Solar-Terrestrial Physics (2016), http://dx.doi.org/10.1016/j.jastp.2016.02.017

Rakov, 2008; Yang and Zhou, 2004). Nevertheless, very few quantitative analyses of the effects of characteristic parameters on LEMP calculation have been investigated.

In order to study the characteristics of E_r associated with nearby lightning return strokes and the influence of characteristic parameters on the horizontal electric field, four representative characteristic parameters, namely, the return-stroke speed (v), the total length of return stroke channel (H), the ground relative permittivity(ε) and the ground conductivity (σ) were taken into account. Effects of these parameters on E_r for 12 observation points with different distances (r=20, 50, 100, 200 m) away from the lightning channel and different heights (h=0, 10, 20 m) above ground are calculated and discussed.

2. Theory and numerical simulation

In this paper, the FDTD method elaborated by Yee, (1966) was used to evaluate the effect of characteristic parameters. Based on the axisymmetric characteristics, 3D physical model of lightning return stroke can be simplified into 2D Transverse Magnetic (TM) model, and the Maxwell's equations are as follows:

$$\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\mu_0 \frac{\partial H_\varphi}{\partial t} - \sigma H_\varphi \tag{1}$$

$$\frac{\partial H_\varphi}{\partial z} = -\varepsilon \frac{\partial E_r}{\partial t} - \sigma E_r \tag{2}$$

$$\frac{1}{r}\frac{\partial (rH_\varphi)}{\partial r} = \varepsilon \frac{\partial E_z}{\partial t} + \sigma E_z \tag{3}$$

The modified transmission-line model with linear current decay with height (MTLL) is adopted (Rakov and Dulzon, 1987).

Fig. 1(a) shows the ground vertical electric field observed 15 m away from lightning channel of a rocket-triggered lightning conducted on July 11, 2000 at Camp Blanding, Florida (Miki et al., 2002). Fig. 1(b) shows the ground vertical electric field calculated 15 m away from lightning channel. The current is calculated from the following analytical expression.

$$i(0,t) = I_{01}\frac{(t/\tau_1)^2}{[(t/\tau_1)^2+1]}\cdot e^{-t/\tau_2} + I_{02}(e^{-t/\tau_3} - e^{-t/\tau_4}) \tag{4}$$

The values of the parameters chosen are: I_{01}=3.25 kA, τ_1 =0.072 µs, τ_2=16.67 µs; I_{02}=8.95 kA, τ_3=100 µs, τ_4=0.5 µs. Moreover, $v=1.5\times10^8$ m/s, H=7500 m, ε=10, $\sigma=2.5\times10^{-4}$ S/m. Fig. 2 shows a comparison of the exact horizontal field at ground level 100 m away from lightning channel with the one calculated by FDTD method. In the calculation, the conditions of the simulations are identical to those adopted by Cooray, (2002). The channel-base current is expressed as (4) with a 12 kA peak. Moreover, v=1.5 × 108 m/s, H=9000 m, ε=10, and σ=0.001 S/m.

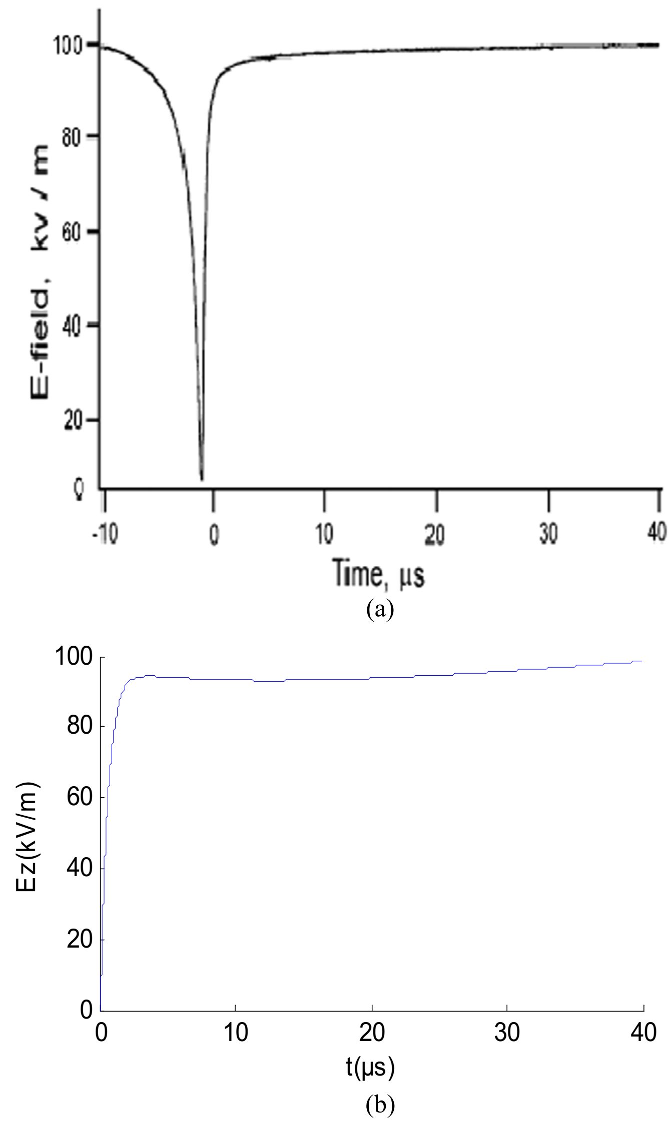

Fig. 1. Measured ground vertical electric field (a) and calculated ground vertical electric field (b) 15 m away from the lightning channel.

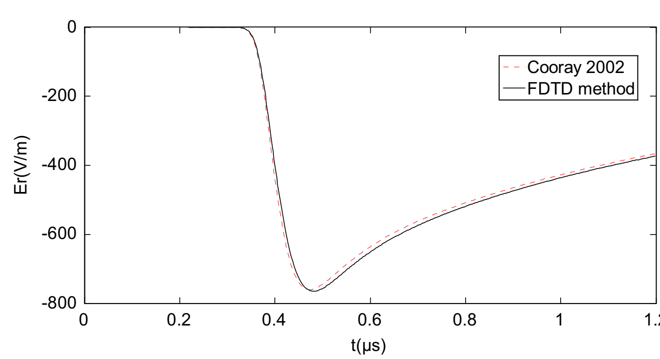

Fig. 2. Comparison of the exact horizontal field (dotted line, Cooray, 2002) at ground level with the one calculated using FDTD method (solid line). σ=0.001 S/m.

3. Results

In order to check the effect of the four parameters on calculation results, the range of the parameters were set as v: 0.2c–1.0c(c is the light speed) H: 1000–9000 m ε: 2–12 σ: 1.0×10^{-4}–6.25×10^{-2} S/m.

The channel base current is expressed as (4) with a −11.5 kA peak. The location of the 12 observation points were set as:

(1) 4 observation points at ground level
(r=20 m, h=0 m); (r=50 m, h=0 m);
(r=100 m, h=0 m); (r=200 m, h=0 m)

(2) 4 observation points at 10 m height
(r=20 m, h=10 m); (r=50 m, h=10 m);
(r=100 m, h=10 m); (r=200 m, h=10 m)

(3) 4 observation points at 20 m height
(r=20 m, h=20 m); (r=50 m, h=20 m);
(r=100 m, h=20 m); (r=200 m, h=20 m)

Please cite this article as: Yu, J.L., et al., Characteristics of the horizontal electric field associated with nearby lightning return strokes. Journal of Atmospheric and Solar-Terrestrial Physics (2016), http://dx.doi.org/10.1016/j.jastp.2016.02.017