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A new approach to calculate electric fields and charge density distribution when lightning strikes a tall object

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ABSTRACT

We derive electric field expressions, associated with lightning strikes to a tall object, using the monopole (Continuity Equation) technique which is distinctly different from the traditional dipole (Lorentz Condition) technique. Expressions to calculate the charge density along the tall object and lightning channel based on the assumptions of the transmission line model of the lightning strikes to a tall object and a series point current source placed at the object top, are also derived. These expressions are used to calculate the very close-range electric fields in the monopole (Continuity Equation) technique in terms of the retarded current and charge density along the tower and lightning channel and their results are compared with those calculated from the traditional dipole (Lorentz Condition) technique in terms of the retarded current along the tower and lightning channel. Alternative explanations are provided to the inversion of polarity of the vertical electric field at very close range based on distribution of charge density along the tower and lightning channel.

1. Introduction

Lightning interaction with tall objects has gained great interest during the last years [1–6]. The so-called engineering models which were originally applied to return stroke process have been extended to take into account tall grounded structures. One is the distributed parallel current source model proposed by Rachidi et al. [7], where different currents are injected at the top of the tall object and along the lightning channel. Another one is the lumped series voltage source model proposed by Baba and Rakov [8], where the same currents are launched into the tall object and lightning channel by a series voltage source connected between the tall object and the channel. Recently, Thottappillil and Nelson [9,10] modeled the lightning strike to a tall tower as a series point current source injecting the same current pulse at the top of the tower into the tower structure and the lightning channel. Here we adopt the series point current source model [9,10] for deriving the charge density distribution along the tall object and along the lightning channel.

The paper is organized as follows. In Section 2, the series point current source model and continuity equation are used to derive charge density expressions along the tall object and the lightning channel. Section 3 presents the validation of above charge density expressions, by employing the monopole (Continuity Equation) technique in terms of the retarded current and charge density and the traditional dipole (Lorentz Condition) technique in terms of the retarded current [11,12]. Section 4 shows the charge density distribution versus height along the tower and the lightning channel, and alternative explanations are given for the inversion of polarity of the vertical electric field at very close distance from the tower base when the tower is struck by lightning. Section 5 concludes the results and discusses the inference from the charge density distribution on the tall object and the lightning channel associated with lightning strikes to a tall object.

This paper is the extended and improved version of [13] in terms of more elaborated derivations of electric field and charge density expressions.

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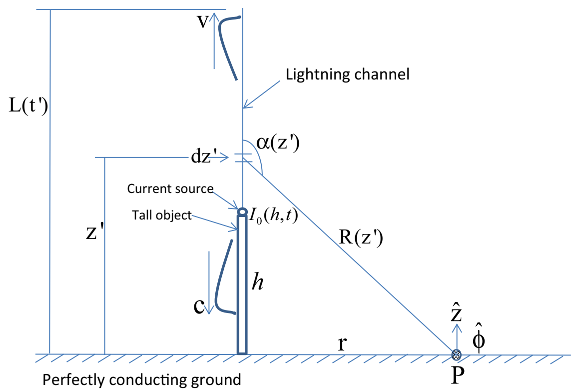

Fig. 1. Geometry of the problem in calculating vertical electric fields at ground level.

2. Derivation of charge density distribution along the tall object and the lightning channel

Both, the tall object and the lightning channel, are treated as ideal transmission lines. See Fig. 1 for the geometry of the problem and the meaning of the symbols. $I_0(h, t)$ is the series point source representing lightning current at the attachment at the tall object top. The distribution of current at any height z' along the tall object is expressed as [9,10]

$$i(z', t) = \sum_{n=0}^{\infty}\left[\gamma_t^n\gamma_g^n I_0\left(h, t - \frac{h-z'}{c} - \frac{2nh}{c}\right) + \gamma_t^n\gamma_g^{n+1} I_0\left(h, t - \frac{h+z'}{c} - \frac{2nh}{c}\right)\right] \tag{1}$$

for $0 \le z' \le h$ (along the strike object)

And the distribution of current at any height z' along the lightning channel is expressed as [9,10]

$$i(z', t) = I_0\left(h, t - \frac{z'-h}{v}\right) + (1+\gamma_t)\sum_{n=0}^{\infty}\gamma_t^n\gamma_g^{n+1} I_0\left(h, t - \frac{z'-h}{v} - \frac{2(n+1)h}{c}\right) \tag{2}$$

for $z' \ge h$ (along the lightning channel)

where h is the height of tower, c is the speed of light for current waves propagating along the tall object, and v is the speed of upward waves propagating in the lightning channel. γ_t and γ_g are the current reflection coefficients at the tall object top and object base for upward and downward propagating current waves, and their definitions are given in Eqs. (3) and (4), respectively.

$$\gamma_t = \frac{Z_t - Z_{ch}}{Z_t + Z_{ch}} \tag{3}$$

$$\gamma_g = \frac{Z_t - Z_g}{Z_t + Z_g} \tag{4}$$

Z_{ch} and Z_t are characteristic impedances of lightning channel and strike object, respectively. Z_g is equivalent grounding impedance.

The point current source $I_0(h, t)$ is assumed to inject initially the lightning current pulse into the tower and lightning channel at the top of the tall object. We can derive the charge density distribution from Eqs. (1) and (2) for the current distribution along the tall object and the lightning channel, and the following continuity equation (5), adapted from Thottappillil and Rakov [11],

$$\frac{\partial \rho^*(z', t - R(z')/c)}{\partial t} = -\frac{\partial i(z', t - R(z')/c)}{\partial z'}\,\Big|\, t - R(z')/c = const \tag{5}$$

where $R(z')$ is the distance between the source and observation point. As shown in Appendix A, by dropping $R(z')/c$, we get the distribution of charge density at any height z' along the tall object as

$$\rho^*(z', t) = -\sum_{n=0}^{\infty}\gamma_t^n\gamma_g^n\frac{I_0(h, t - ((h-z')/c) - (2nh/c))}{c} - \sum_{n=0}^{\infty}\gamma_t^n\gamma_g^{n+1}\left(-\frac{I_0(h, t - ((h+z')/c) - (2nh/c))}{c}\right) \tag{6}$$

for $0 \le z' \le h$ (along the strike object)

Similarly, the distribution of charge density at any height z' in the lightning channel can be obtained as:

$$\rho^*(z', t) = \frac{I_0(h, t - (z'-h)/v)}{v} + (1+\gamma_t)\sum_{n=0}^{\infty}\gamma_t^n\gamma_g^{n+1}\frac{I_0(h, t - ((z'-h)/v) - (2(n+1)h/c))}{v} \tag{7}$$

for $z' \ge h$ (along the lightning channel). The speed of the current wave in the lightning channel is v.