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A finite-difference time-domain approach for the evaluation of electromagnetic fields radiated by lightning strikes to tall structures

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ABSTRACT

We present an analysis of the electromagnetic fields at very close range from a tower struck by lightning. The electromagnetic fields are evaluated for observation points above, on the surface and below the ground plane characterized by a finite conductivity. The computations are obtained using the Finite-Difference Time-Domain (FDTD) technique, in which the so-called engineering models are incorporated to represent the spatial–temporal distribution of the current along the channel and along the strike object. The approach is tested using a set of simultaneously recorded data published in the literature consisting of the current measured at the top of the Peissenberg tower and the associated electric and magnetic fields and very good agreement has been found. Simulation results are performed for an observation point located 50 m from the base of the channel (or tower, when present) and for three cases, namely (i) a lightning strike to ground, and (ii) a lightning strike to a 168-m tall tower, and (iii) a lightning strike to a 553-m tall tower. The effect of the presence of the tower and the effect of finite ground conductivity on the generated above-ground and underground electromagnetic fields are illustrated and discussed. It is shown that the underground electric fields are markedly affected by the ground conductivity. The underground electric field is predominantly horizontal with a negative polarity. The vertical electric field component is characterized by a bipolar wave-shape. The ground conductivity affects in a lesser degree the magnetic field penetrating into the ground. Above the ground and on the ground surface, the vertical electric field and the azimuthal magnetic field generated by a lightning return stroke initiated at ground level are nearly insensitive to the height of the observation point above ground. For the considered distance range (50 m), they can be computed assuming the ground as a perfectly conducting plane. The magnetic field above ground at such close distance is virtually not affected by the ground conductivity. The presence of a tower results in a significant decrease of the vertical electric field in the immediate vicinity of the tower. Unlike the case of a ground-initiated return stroke, the above-ground vertical electric field associated with a return stroke to tall tower is very much affected by the ground conductivity. Depending on the value of this latter, this component could exhibit an inversion of polarity.

1. Introduction

The interaction of lightning with tall strike objects has recently attracted considerable attention among lightning researchers (e.g. [1]), mainly because lightning current data are often collected by means of instrumented towers.

The data obtained by Berger and co-workers (e.g. [2]) in the 1970s represent still today the most complete statistical characterization of lightning current parameters. More recently, experimental observations on both current and electromagnetic fields have been obtained on tall telecommunication towers (e.g. CN Tower in Canada [3], Peissenberg Tower in Germany [4], Gaisberg Tower in Austria [5]).

The obtained experimental data on towers, as well as theoretical analyses (e.g. [6–12]), have provided evidence that the presence of a tall strike object can affect the measured lightning return stroke current, as well as the associated return stroke electromagnetic fields. As a result, some of the return stroke models, namely the engineering models and the electromagnetic or Antenna Theory (AT) models, initially developed for the case of return strokes initiated at ground level, have been extended to take into account the

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presence of a vertically extended strike object (e.g. [6,13,14]). In the engineering return stroke models, the spatial and temporal distribution of the channel current is specified in terms of directly observable parameters such as the channel base current and the return stroke speed. The presence of an elevated strike object in such models has been considered by assuming the object as a uniform, lossless transmission line (e.g. [13]). In Antenna Theory models (e.g. [15–18]), the strike objects and the lightning channel are generally represented using thin wires. The Maxwell's equations are numerically solved using the method of moments (e.g. [19]) to find the current distribution along the lightning channel and the strike object, from which the radiated electromagnetic fields can be computed.

In this paper, we present an analysis of the electromagnetic fields at very close range from a tower struck by lightning. The components of the electromagnetic fields are evaluated for observation points above and below the ground surface, characterized by a finite conductivity. The computations are obtained using a Finite-Difference Time-Domain (FDTD) method, in which the return stroke channel and the elevated strike object are appropriately included and represented using engineering models [6,13]. The approach is tested using a set of simultaneously recorded data published in the literature consisting of the current measured at the top of the Peissenberg tower and the associated electric and magnetic fields [20]. Simulation results are performed for lightning strikes to ground, and for lightning strike to a tall tower. Two different tower heights are considered. The effect of the presence of the tower and effect of finite ground conductivity on the generated above-ground and underground electromagnetic fields are analyzed and discussed.

2. Proposed method

2.1. Electromagnetic fields calculation

The electromagnetic fields generated by lightning are computed using the Finite-Difference Time-Domain (FDTD) method [21]. This technique solves Maxwell's time-dependent curl equations directly in the time-domain by converting them into finite-difference equations that are then solved in a time matching sequence by alternately calculating the electric and magnetic fields in an interlaced spatial grid. For lightning engineering models, the two-dimensional (2-D) cylindrical coordinates can be adopted [22–24].

When time-domain electromagnetic field equations are solved using finite-difference techniques in unbounded space, there must be a method limiting the domain in which the field is computed. This is achieved by truncating the mesh and using absorbing boundary conditions (ABC) at its artificial boundaries to simulate the unbounded surroundings. In our calculations, we have adopted the first-order Mur absorbing conditions [25].

2.2. Distribution of current along the tall strike object and along the lightning channel

2.2.1. Rachidi et al. model

The engineering models, initially proposed for ground-initiated lightning return strokes, have been recently extended to tower-initiated return strokes [13]. In Ref. [13], adopting a distributed-source representation of the channel, general equations for the spatial–temporal distribution of the current along the lightning channel ($z' \geq h$) and along the strike object ($0 \leq z' \leq h$) have been derived [13]:

Table 1
$P(z')$ and v^* for different return stroke models (adapted from Ref. [26])

Model	$P(z')$	v^*
BG	1	∞
TCS	1	$-c$
TL	1	v
MTLL	$1-z'/H$	v
MTLE	$\mathrm{Exp}(-z'/\lambda)$	v

$$\begin{aligned} i(z',t) = {} & (1-\rho_t)\sum_{n=0}^{\infty}\Big[\rho_t^n\rho_g^n i_0\Big(h, t-\frac{h-z'}{c}-\frac{2nh}{c}\Big) \\ & + \rho_t^n\rho_g^{n+1} i_0\Big(h, t-\frac{h+z'}{c}-\frac{2nh}{c}\Big)\Big] \\ & \times u\Big(t-\frac{h+z'}{c}-\frac{2nh}{c}\Big) \quad \text{for } 0 \leq z' \leq h \end{aligned} \tag{1}$$

$$\begin{aligned} i(z',t) = {} & \Big[P(z'-h) i_0\Big(h, t-\frac{z'-h}{v^*}\Big) - \rho_t i_0\Big(h, t-\frac{z'-h}{c}\Big) \\ & + (1-\rho_t)(1+\rho_t)\sum_{n=0}^{\infty}\rho_g^{n+1}\rho_t^n i_0\Big(h, t-\frac{h+z'}{c}-\frac{2nh}{c}\Big)\Big] \\ & \times u\Big(t-\frac{z'-h}{v}\Big) \quad \text{for } z' \geq h \end{aligned} \tag{2}$$

Eqs. (1) and (2) are based on the concept of 'undisturbed current' $i_0(t)$, which represents the idealized current that would be measured at the tower top if the current reflection coefficients at its both extremities were equal to zero.

In Eqs. (1) and (2), h is the height of the tower, ρ_t and ρ_g are the top and bottom current reflection coefficients for upward and downward propagation waves, respectively, c is the speed of light (wave propagation speed along the strike object), v is the return stroke front speed, v^* is the current-wave speed, $P(z')$ is a model-dependent attenuation function, $u(t)$ is the Heaviside unit-step function and n is an index representing the successive multiple reflections occurring at the two ends of the strike object.

Expressions for $P(z')$ and v^* for some of the most commonly used return stroke models are summarized in Table 1, in which λ is the attenuation height for the MTLE model and H is the total height of the lightning channel.

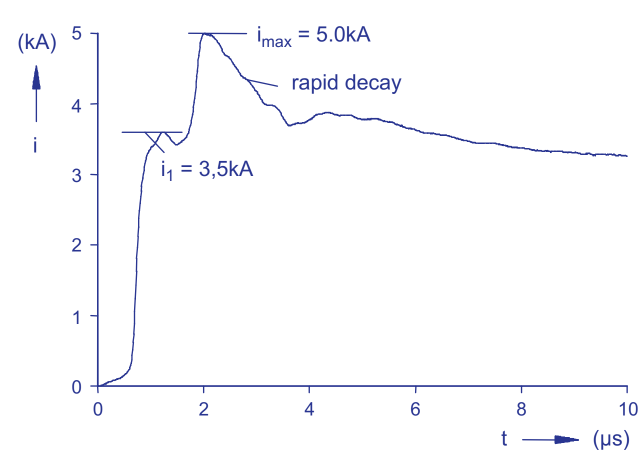

Fig. 1. Current measured at the top of the 168-m tower (adapted from Ref. [20]).