INFLUENCE OF THE PRESENCE OF A TALL STRIKE OBJECT ON LIGHTNING ELECTROMAGNETIC FIELDS

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ABSTRACT

In this paper, we have analyzed and compared distance dependences of electric and magnetic fields due to a lightning strike to a tall object of height h and due to the same strike to flat ground. In both cases, lightning was represented by a transmission line energized by a lumped voltage source connected at the channel attachment point, with the voltage magnitude $V_0(h,t)$ being expressed by $Z_{ch}I_{sc}(h,t)$, where Z_{ch} is the equivalent impedance of the lightning channel and $I_{sc}(h,t)$ is the lightning short-circuit current. The strike object was represented by a transmission line as well. Current distributions, $I(z',t)$, along the tall object ($0 \le z' \le h$) and along the lightning channel ($z' \ge h$), for this model are given by

$$I(z',t) = \frac{1-\rho_{top}}{2}\sum_{n=0}^{\infty}\left[\rho_{bot}{}^{n}\rho_{top}{}^{n} I_{sc}\left(h, t-\frac{h-z'}{c}-\frac{2nh}{c}\right)+\rho_{bot}{}^{n+1}\rho_{top}{}^{n} I_{sc}\left(h, t-\frac{h+z'}{c}-\frac{2nh}{c}\right)\right] \quad \text{for } 0 \le z' \le h \qquad (1a)$$

$$I(z',t) = \frac{1-\rho_{top}}{2}\left[I_{sc}\left(h, t-\frac{z'-h}{v}\right)+\sum_{n=1}^{\infty}\rho_{bot}{}^{n}\rho_{top}{}^{n-1}\left(1+\rho_{top}\right) I_{sc}\left(h, t-\frac{z'-h}{v}-\frac{2nh}{c}\right)\right] \quad \text{for } z' \ge h \qquad (1b)$$

where ρ_{top} is the current reflection coefficient at the top of the strike object for upward-propagating waves, ρ_{bot} is the current reflection coefficient at the bottom of the object, v is the return stroke propagation speed, and n is an index representing the successive multiple reflections occurring at the two ends of the strike object. The current distribution, $I(z',t)$, along the lightning channel for the case of strike to flat ground, is given by

$$I(z',t) = \frac{1+\rho_{gr}}{2} I_{sc}\left(0, t-\frac{z'}{v}\right) \qquad (2)$$

where $I_{sc}(0,t)$ is the lightning short-circuit current (same as $I_{sc}(h,t)$ in (1a) and (1b) but injected at z'=0 instead of $z'=h$), and ρ_{gr} is the current reflection coefficient at the channel base (ground). It is important to note that the resultant total charge transfer to ground was the same regardless of the presence of strike object.

For h=100 m, in a realistic situation when ρ_{top}=-0.5 (Z_{ch}=3Z_{ob}, Z_{ob} is the characteristic impedance of the object), ρ_{bot}=1 (Z_{gr}=0), ρ_{gr}=1 (Z_{gr}=0), and v=0.5c, and when the current waveform thought to be typical for lightning subsequent strokes (whose 10-to-90% risetime is RT=0.15 µs) is used, the vertical electric field for the tall-object case E_{z_tall} is reduced relative to the flat-ground case E_{z_flat} at distances ranging from 30 m to 2 km from the object and enhanced at distances greater than 2 km. The azimuthal magnetic field for the tall-object case H_{φ_tall} is larger than that for the flat-ground case H_{φ_flat} at any distance. Ratios E_{z_tall}/E_{z_flat} and $H_{\varphi\_tall}/H_{\varphi\_flat}$ increase with increasing distance d and decreasing the risetime of I_{sc}. At d=100 m, E_{z_tall}/E_{z_flat} increases with decreasing the height of the object h, while $H_{\varphi\_tall}/H_{\varphi\_flat}$ increases with increasing h. Beyond some distance, which depends on RT and v, E_{z_tall}/E_{z_flat} becomes insensitive to d and equal to $H_{\varphi\_tall}/H_{\varphi\_flat}$. When RT is shorter than h/c, the ratio at larger distances is analytically given by $(1-\rho_{top})(c/v+1)/(1+\rho_{gr})$. For realistic values of ρ_{top} =-0.5, ρ_{gr}=1, and v=0.5c, this ratio (far field enhancement factor) is equal to 2.25.

INTRODUCTION

It is important to know the lightning electromagnetic environment in the vicinity of a tall strike object for studying lightning return-stroke processes at early times and for optimizing lightning protection means of nearby telecommunication and power distribution lines. In this paper, we compare the vertical electric field and azimuthal magnetic field at ground level due to a lightning strike to a tall object with their counterparts due to the same strike to flat ground. Further, we will investigate influences on the fields of lightning return stroke propagation speed, return stroke current risetime, and the strike object height.

DISTRIBUTION OF CURRENT ALONG THE TALL STRIKE OBJECT AND ALONG THE LIGHTNING CHANNEL

Fig. 1 (a) shows a transmission line representation of lightning strike to a tall grounded object, comprising two lossless uniform transmission lines representing the lightning channel (whose characteristic impedance is Z_{ch}) and the tall strike object of height h (whose characteristic impedance is Z_{ob}), a lumped grounding impedance (Z_{gr}), and a lumped voltage source that generates a voltage waveform $V_0(h,t)=Z_{ch}I_{sc}(h,t)$, where $I_{sc}(h,t)$ is the lightning short-circuit current. The lightning short-circuit current, $I_{sc}(h,t)$, is defined as the lightning current that would be measured at an ideally grounded object ($Z_{gr}=0$ or $Z_{gr}<<Z_{ch}$) of negligible height ($h\approx 0$). The current propagation speed along the strike object is assumed to be equal to the speed of light c and that along the lightning channel to be equal to v, the return stroke wavefront speed. The current reflection coefficient at the bottom of the tall object (ρ_{bot}) and the current reflection coefficient at the top of the object for upward-propagating waves (ρ_{top}) are given by $\rho_{bot}=(Z_{ob}-Z_{gr})/(Z_{ob}+Z_{gr})$ and $\rho_{top}=(Z_{ob}-Z_{ch})/(Z_{ob}+Z_{ch})$.
Current distributions, $I(z',t)$, along the tall object ($0 \le z' \le h$) and along the lightning channel ($z' \ge h$), for the configuration shown in Fig. 1 (a), are given by [1]

$$I(z',t)=\frac{1-\rho_{top}}{2}\sum_{n=0}^{\infty}\left[\rho_{bot}^{\ n}\rho_{top}^{\ n}I_{sc}\left(h,t-\frac{h-z'}{c}-\frac{2nh}{c}\right)+\rho_{bot}^{\ n+1}\rho_{top}^{\ n}I_{sc}\left(h,t-\frac{h+z'}{c}-\frac{2nh}{c}\right)\right] \quad \text{for } 0\le z'\le h \qquad (1a)$$

$$I(z',t)=\frac{1-\rho_{top}}{2}\left[I_{sc}\left(h,t-\frac{z'-h}{v}\right)+\sum_{n=1}^{\infty}\rho_{bot}^{\ n}\rho_{top}^{\ n-1}\left(1+\rho_{top}\right)I_{sc}\left(h,t-\frac{z'-h}{v}-\frac{2nh}{c}\right)\right] \quad \text{for } z'\ge h \qquad (1b)$$

where n is an index representing the successive multiple reflections occurring at the two ends of the strike object. Equations (1a) and (1b) show that two current waves of the same magnitude, $(1-\rho_{top})I_{sc}(h,t)/2$, are initially injected downward, into the tall object, and upward, into the channel.
The current distribution, $I(z',t)$, along the lightning channel for the case of strike to flat ground (see Fig. 1 (b)), is given by [1]

$$I(z',t)=\frac{1+\rho_{gr}}{2}I_{sc}\left(0,t-\frac{z'}{v}\right) \qquad (2)$$

where $I_{sc}(0,t)$ is the lightning short-circuit current (same as $I_{sc}(h,t)$ in (1a) and (1b) but injected at $z'=0$ instead of $z'=h$), and ρ_{gr} is the current reflection coefficient at the channel base (ground), which is given by $\rho_{gr}=(Z_{ch}-Z_{gr})/(Z_{ch}+Z_{gr})$.
Note that (1b) reduces to (2) and (1a) reduces to (2) with $z'=0$ when h approaches zero [1]. The total charge transfer to ground, calculated integrating current given by (1a) at $z'=0$, is the same as that calculated integrating current given by (2) at $z'=0$ [2]. Therefore, current distributions for the case of strikes to a tall object, (1a) and (1b), and for the case of strikes to flat ground, (2), correspond to the same lightning discharge.

ANALYSIS AND RESULTS

In the case of lightning strike to a tall object, we assume that ρ_{top}=-0.5 (Z_{ch}=3Z_{ob}) and ρ_{bot}=1 (Z_{gr}=0). In the case of lightning strike to flat ground, we assume that ρ_{gr}=1 (Z_{gr}=0). In the following, we will consider ratios of electric and magnetic fields for the tall-object and flat-ground cases computed for different return-stroke speeds, current risetimes, and object heights.

Influence of Lightning Return Stroke Propagation Speed

In this section, we used the current waveform proposed in [3]. It is characterized by 10-to-90% risetime of 0.15 μs and thought to be typical for subsequent strokes. Fig. 2 shows ratios of vertical electric field on perfectly conducting ground for a lightning strike to a 100-m high object (E_{z_tall}) at horizontal distances *d* ranging from 30 m to 100 km and that for the same strike to flat ground (E_{z_flat}), for two values of return-stroke speed, v=0.5c and v=c. Corresponding ratios for the azimuthal magnetic field (H_{φ_tall}/ H_{φ_flat}) are also shown in Fig. 2.

Ratios E_{z_tall}/ E_{z_flat} and H_{φ_tall}/ H_{φ_flat} increase with increasing *d*. For v=0.5c and v=c, E_{z_tall} is smaller than E_{z_flat} at *d* ranging from 30 to 200 m and from 30 m to 100 m, respectively (vertical electric field is attenuated due to the presence of the 100-m high object). E_{z_tall}/ E_{z_flat} for v=0.5c is smaller than that for v=c at *d* ranging from 30 m to 2 km and larger at *d* greater than 2 km. H_{φ_tall}/ H_{φ_flat} for v=0.5c is always larger than that for v=c. The abrupt increase in E_{z_tall}/ E_{z_flat} between 2 and 3 km (see Fig. 2) is due to the fact that for d≤2 km both E_{z_tall} and E_{z_flat} rise to their peaks in several microseconds or more while for *d* >2 km the fields rise to their peaks in less than 1 μs (because total electric field peak is determined by the radiation field component at larger distances, as opposed to being determined by the electrostatic field component at smaller distances). Beyond d=3 km, both E_{z_tall}/ E_{z_flat} and H_{φ_tall}/ H_{φ_flat} attain values of 2.25 and 1.5 for v=0.5c and v=c, respectively. These are equal to the corresponding values of far field enhancement factor, k_{tall}, given in [2] and reproduced below,

$$k_{tall} = \left(1-\rho_{top}\right)\left(c / v+1\right) / \left(1+\rho_{gr}\right) \tag{3}$$

Note that (3) is valid only when the risetime of injected lightning current is shorter than the propagation time from the top of the strike object to its bottom, h/c (=0.33 μs for h=100 m).

Influence of Lightning Return Stroke Current Risetime

Fig. 3 shows ratios E_{z_tall}/ E_{z_flat} and H_{φ_tall}/ H_{φ_flat} for two values of the 10-to-90% risetime of the lightning return stroke current, 0.15 μs (in this case the overall current waveform is identical to that used in [3]) and 1.4 μs. The value of v was set at 0.5c. The ratios increase with decreasing the risetime of the lightning current. They approach 2.25 beyond 3 km and 1.13 beyond 10 km for risetimes equal to 0.15 and 1.4 μs, respectively. The former value (2.25) is equal to the far field enhancement factor given by (3). Note that (3) is not applicable to the case of 1.4 μs, since this current risetime is larger than h/c=0.33 μs.

Influence of Lightning Strike Object Height

Fig. 4 shows ratios E_{z_tall}/ E_{z_flat} and H_{φ_tall}/ H_{φ_flat} at d=100 m for h ranging from 0 to 300 m and two values of lightning return stroke current risetime, 0.15 and 1.4 μs. The value of v was set at 0.5c. H_{φ_tall}/ H_{φ_flat} increases with increasing h, while E_{z_tall}/ E_{z_flat} decreases with increasing h. Both ratios decrease with increasing the risetime of the lightning return stroke current, the decrease for magnetic field being more pronounced than for electric field.

SUMMARY

For a strike object of height h=100 m, in a realistic situation when ρ_{top}=-0.5, ρ_{bot}=1, ρ_{gr}=1, and v=0.5c, and when the current waveform whose 10-to-90% risetime is RT=0.15 μs is used, the vertical electric field for the tall-object case E_{z_tall} is reduced relative to the flat-ground case E_{z_flat} at distances d ranging from 30 m to 2 km from the object and enhanced at d greater than 2 km. The azimuthal magnetic field for the tall-object case H_{φ_tall} is larger than that for the flat-ground case H_{φ_flat} at any distance. Ratios E_{z_tall}/ E_{z_flat} and $H_{\varphi\_tall}/ H_{\varphi\_flat}$ increase with increasing distance d, and decreasing RT. At d=100 m, E_{z_tall}/ E_{z_flat} increases with decreasing h, while $H_{\varphi\_tall}/ H_{\varphi\_flat}$ increases with increasing h. Beyond some distance, which depends on RT and v, E_{z_tall}/ E_{z_flat} becomes insensitive to d and equal to $H_{\varphi\_tall}/ H_{\varphi\_flat}$.

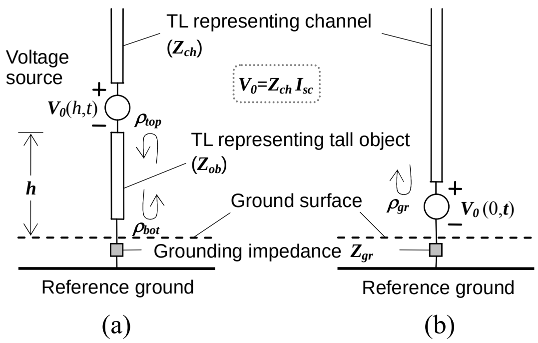

Fig. 1. Lightning strikes (a) to a tall grounded object of height h and (b) to flat ground, represented by lossless transmission lines connected in series with a lumped voltage source generating an arbitrary voltage waveform, $V_0(h,t)=Z_{ch}I_{sc}(h,t)$ or $V_0(0,t)=Z_{ch}I_{sc}(0,t)$, and a lumped grounding impedance (Z_{gr}).

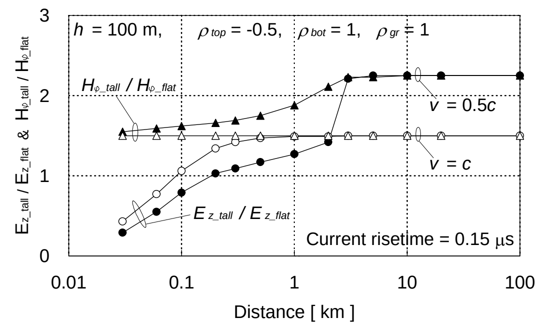

Fig. 2. Ratios E_{z_tall}/ E_{z_flat} and $H_{\varphi\_tall}/ H_{\varphi\_flat}$ as a function of horizontal distance d from the lightning channel for two different lightning return stroke speeds, v=0.5c (solid circles and triangles) and v=c (hollow circles and triangles).

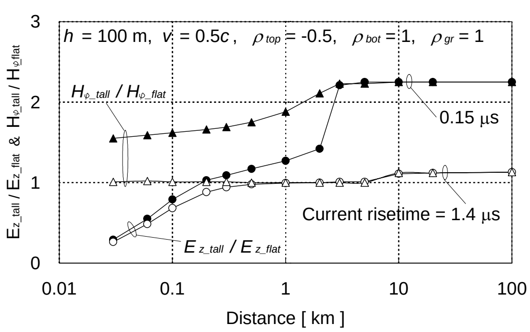

Fig. 3. Ratios E_{z_tall}/ E_{z_flat} and $H_{\varphi\_tall}/ H_{\varphi\_flat}$ as a function of horizontal distance d from the lightning channel for two different risetimes of lightning return stroke current, 0.15 μs (solid circles and triangles) and 1.4 μs (hollow circles and triangles).

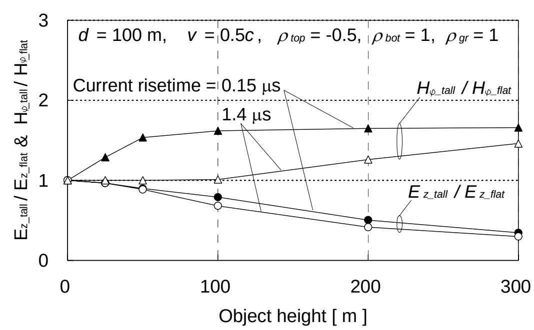

Fig. 4. Ratios E_{z_tall}/ E_{z_flat} and $H_{\varphi\_tall}/ H_{\varphi\_flat}$ at d=100 m as a function of strike object height h for two different risetimes of lightning return stroke current, 0.15 μs (solid circles and triangles) and 1.4 μs (hollow circles and triangles).

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