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Lightning Electromagnetic Fields at Different Heights above the Ground

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Abstract— **This paper presents the computed results of electric and magnetic fields generated by the near by lightning. The electric and magnetic fields have been computed for different heights ranging from 10 m to 2 km above the ground and for the lateral distances varying from 20 m to 2 km from the lightning return stroke. For airborne vehicles e.g. satellite launch vehicles, missiles etc, it has become necessary to understand the behavior of these when illuminated by a strong electromagnetic fields generated by a near by lightning. The coupling of these fields with the above system could be by means of the leakage of the transient electromagnetic fields through the joints of the vehicles, leakage through the improperly shielded cables, leaks through the edges of closed doors etc. This results the generation of transient voltages and currents with the internal circuitry of such systems. The objective of this work is to compute the fields along the airborne vehicles when excited by plane electromagnetic fields. These plane electromagnetic fields consist of electric and magnetic fields, where the fields could get modified at different heights from the ground plane and for different distances from the lightning channel.**

Keywords-airborne vehicle; lightning; transient electromagnetic fields;

I. INTRODUCTION

Electromagnetic field generated by lightning on airborne vehicles can cause degradation in performance if the vehicle is sensitive to the electromagnetic field environment. The aim of this paper is to compute the electric and magnetic fields radiated by lightning along the airborne vehicles. This paper presents the study on the electric and magnetic fields generated by lightning strokes with two different maximum time derivatives of lightning current. This paper also presents the results for the electric and magnetic fields for two different velocities.

The lightning return stroke is assumed to be straight and vertical above the ground plane. The lightning return stroke has been modeled using modified transmission line (MTLE) model with exponential current decay. The components of transient electromagnetic fields are viz., vertical electric field, horizontal electric field and the magnetic fields have been computed. These fields can couple with the circuitry of the system and may induce over voltages which may results malfunction of the system. The effect of variation in the rate of rise of lightning current (di/dt) and the velocity of the return stroke current on the radiate electric and magnetic fields has been studied. The electric and magnetic fields (assuming the ground as a perfect conductor) at different heights varying from 10 m to 2000 m and for lateral distance varying from 20 m to 2000 m from the lightning channel have been computed. The significance of return stroke velocity on the electromagnetic fields generated by the lightning has been studied.

II. METHOD OF ANALYSIS

A. *Lifhtning Return Stroke Current*

Fig. 1 shows the geometry of the problem. The lightning channel is assumed to be a vertical unidimensional antenna above the ground plane. Engineering model presented in the literature gives the mathematical specification of the spatial temporal distribution of the lightning current along the discharge channel $i(z',t)$ can be expressed by [1],[2],[3]

$$I(z',t) = U(t - z'/v)\, P(z')\; i(0, t - z'/v) \qquad (1)$$

Where $i(z',t)$ is the channel current at an arbitrary height z' and an arbitrary time t. $i(0,t)$ is the channel base current, $U(t)$ is the Heaviside function, $P(z')$ is the height dependent current attenuation factor ,v is the return stroke velocity of the current. For the calculation of the lightning electromagnetic field the MTLE model is adopted. The return stroke current in the lightning channel at a height z' is expressed as [4],[5]

$$i(z',t) = \begin{cases} i(0, t - z'/v)\, e^{(-z'/\lambda)} & z' \le vt \\ 0 & z' > vt \end{cases} \qquad (2)$$

Where λ is the current decay constant, v is the velocity of return stroke. For the current at the channel base i (0,t), an analytical expression described by a sum of two functions of the Heidler's expression [6],[7],[8] has been used in the computation.

$$i(0,t) = \frac{I_0}{\eta}\left[\frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n}\right] e^{(-t/\tau_2)^n} \qquad (3)$$

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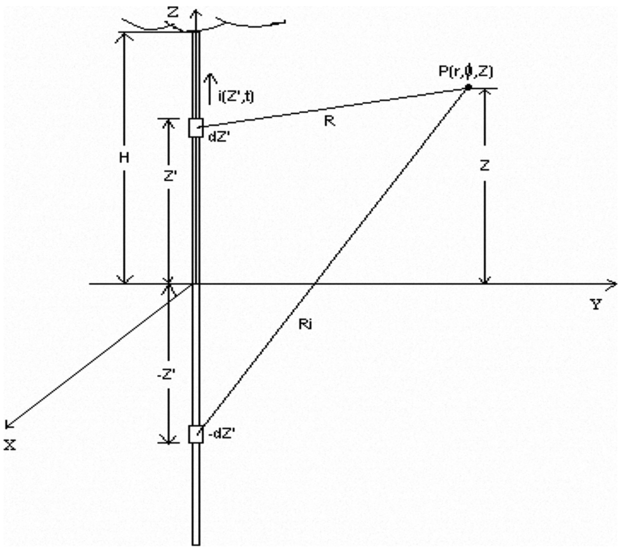


Figure 1. Geometry for lightning electromagnetic field calculation.

Where

$$\eta = e^{\left(-(\tau_1/\tau_2)(n\,\tau_2/\tau_1)^{1/n}\right)} \tag{4}$$

and I_0 is amplitude of the channel base current, τ_1 is the front time constant, τ_2 is the decay time constant, η is the amplitude correction factor and n is an exponent varies from 2 to 10. The electromagnetic fields generated by the return stroke current can be calculated once the current distribution along the channel and the return stroke speed is specified.

B. Lightning Electromagnetic Field

The electric and magnetic fields radiated from the lightning return stroke are computed from the following set of expressions (5) and (6).These are the expressions at a point P(r,Φ,z) in space [9],[10]. The equations for the vertical electric field dEz(r,z,t), horizontal electric field dEr(r,z,t) and the magnetic field strength $dH_\Phi(r,z,t)$ at a altitude z and distance r originated by a vertical dipole of infinitesimal length dz′ at a height z′ along the channel are given by

$$dEz(r,z,t)=\frac{dz'}{4\pi\varepsilon_0}\left[\begin{aligned}&\frac{2(z-z')^2-r^2}{R^5}e^{(-z'/\lambda)}\int_0^t i(0,t-z'/v-R/c)d\tau\\&+\frac{2(z-z')^2-r^2}{cR^4}e^{(-z'/\lambda)}i(0,t-z'/v-R/c)\\&-\frac{r^2}{c^2R^3}e^{(z'/\lambda)}\frac{\partial i(0,t-z'/v-R/c)}{\partial t}\end{aligned}\right] \tag{5}$$

$$dEr(r,z,t)=\frac{dz'}{4\pi\varepsilon_0}\left[\begin{aligned}&\frac{3r(z-z')}{R^5}e^{(-z'/\lambda)}\int_0^t i(0,t-z'/v-R/c)d\tau\\&+\frac{3r(z-z')}{cR^4}e^{(-z'/\lambda)}i(0,t-z'/v-R/c)\\&+\frac{r(z-z')}{c^2R^3}e^{(-z'/\lambda)}\frac{\partial i(0,t-z'/v-R/c)}{\partial t}\end{aligned}\right] \tag{6}$$

$$dH_\phi(r,z,t)=\frac{1}{4\pi}\left[\begin{aligned}&\frac{r}{R^3}e^{(-z'/\lambda)}i(0,t-z'/v-R/c)\\&+\frac{r}{cR^2}e^{(-z'/\lambda)}\frac{\partial i(0,t-z'/v-R/c)}{\partial t}\end{aligned}\right] \tag{7}$$

where

ε_o permittivity of free space,

c velocity of light,

R distance from the single dipole to the observation point $R=(r^2+(z-z')^2)^{1/2}$

The first term in (5) (6) are electro static field, the second the electric induction or intermediate field, and the third is electric radiation field. In (7) the first term is the magnetic induction and the second the radiation field. The total vertical, horizontal electric fields and magnetic fields strength are obtained by integrating (5) (6) and (7) along the channel and its image. The ground is assumed as perfect conductor. The length of the lightning channel is taken as 6 km. The current decay constant is taken as [4].

III. SIMULATION RESULTS AND DISCUSSION

For studying the influence of the rate of rise of return stroke current on the electromagnetic fields generated, the channel base current parameters have been varied to get different rate of rise of current i.e., 12 kA/µs and 120 kA/µs. The effect of the velocity of the return stroke current has been studied by using two values for the velocity v viz., 130 m/µs and 190 m/µs. The channel base currents and its derivative were computed using the expression given in equation (3) and (4) the wave forms are shown in Fig. 1 and Fig. 2. The peak amplitude of both the currents are 12 kA with maximum time derivative of 12 kA/µs and 120 kA/µs.

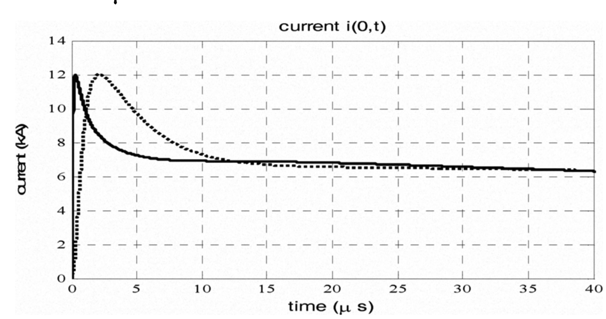


Figure 2. Channel base current for lightning return stroke, dotted line for (di/dt)max = 12 kA/µs and solid line for (di/dt)max = 120 kA/µs.

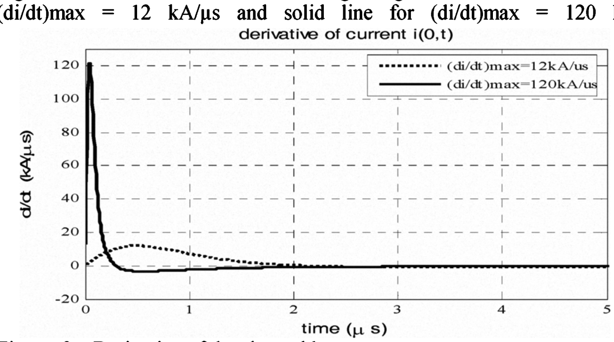


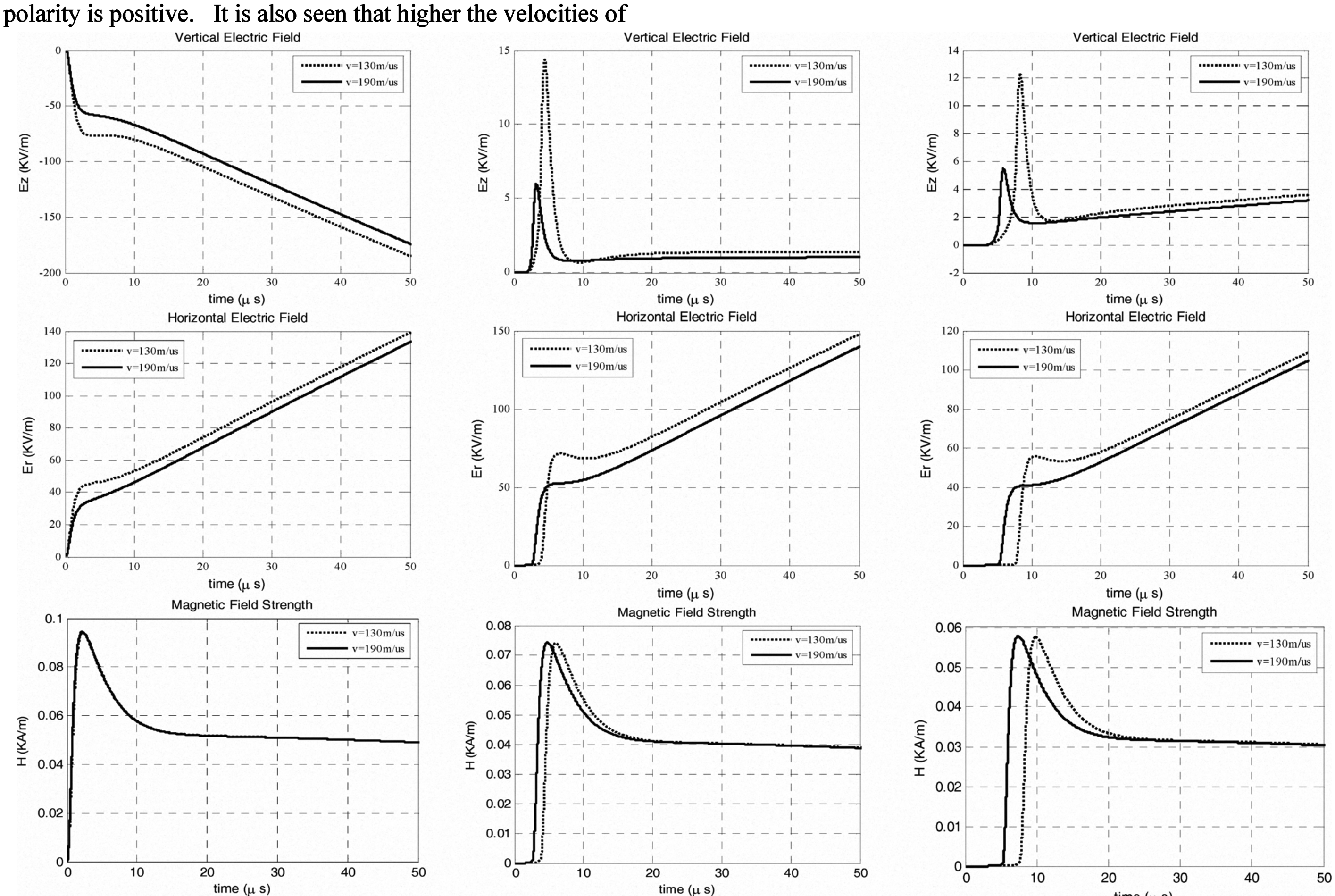
Figure 3. Derivative of the channel base currents

The electric field and magnetic field strength are computed at a distance from 20 m to 2000 m from the channel and for different heights from 10 m to 2000 m from the ground plane. Fig. 4 shows the vertical, horizontal electric fields and magnetic fields strength calculated using the expressions (5), (6) and (7) for two different velocities of return stroke i.e., v =130 m/μs and 190 m/μs. These figures show the electric and magnetic fields computed for a distance of 20 m from the channel and for different heights viz 10 m, 500 m and 1000 m from the ground. The delay in the wave forms shows the propagation delay of the current pulse along the lightning channel as well as travel decay of the electromagnetic field from the lightning channel to the observation point in free space which increases with increases of height and lateral distance to the observation point.

The variation in electromagnetic field with height as well as lateral distance from the lightning channel is shown in Fig. 4 and Fig. 5. From the Fig .4 on vertical electric field it can be observed that for distances of about 20 m from the lightning channel and about 10 m above the ground the vertical electric field is negative and for heights about 500 m and above its polarity is positive. It is also seen that higher the velocities of the return stroke lowers the magnitude of the vertical electric field.

The horizontal electric field is unipolar for all the lateral distances and heights above the ground level. The velocity of the return stroke significantly influence over horizontal electric field. The magnitude of horizontal electric field due to increasing of velocity of the return stroke is not made wide difference for a distance of about 20 m from the lightning channel and about 10 m above the ground, but for increasing of heights the magnitude of horizontal electric field has considerable difference.

The magnetic field strength at different heights above the ground at the lateral distance of 20 m from the lightning channel is also shown in Fig. 4. From these results it can be observed that for distances less then (about 500 m) the magnitude of the magnetic field strength are close to each other for two different velocities of the return stroke and the wave shape of the magnetic fields strength follows the channel base current.



(a) z = 10 m, r = 20 m (b) z = 500 m, r = 20 m (c) z = 1000 m, r = 20 m

Figure 4. Electromagnetic field variation with height z and lateral distance r. The dotted lines are for a velocity of propagation of 130 m/μs and the solid lines are for a velocity of propagation of 190 m/μs (a) z = 10 m, r = 20 m (b) z = 500 m, r = 20 m (c) z = 1000 m, r = 20 m.

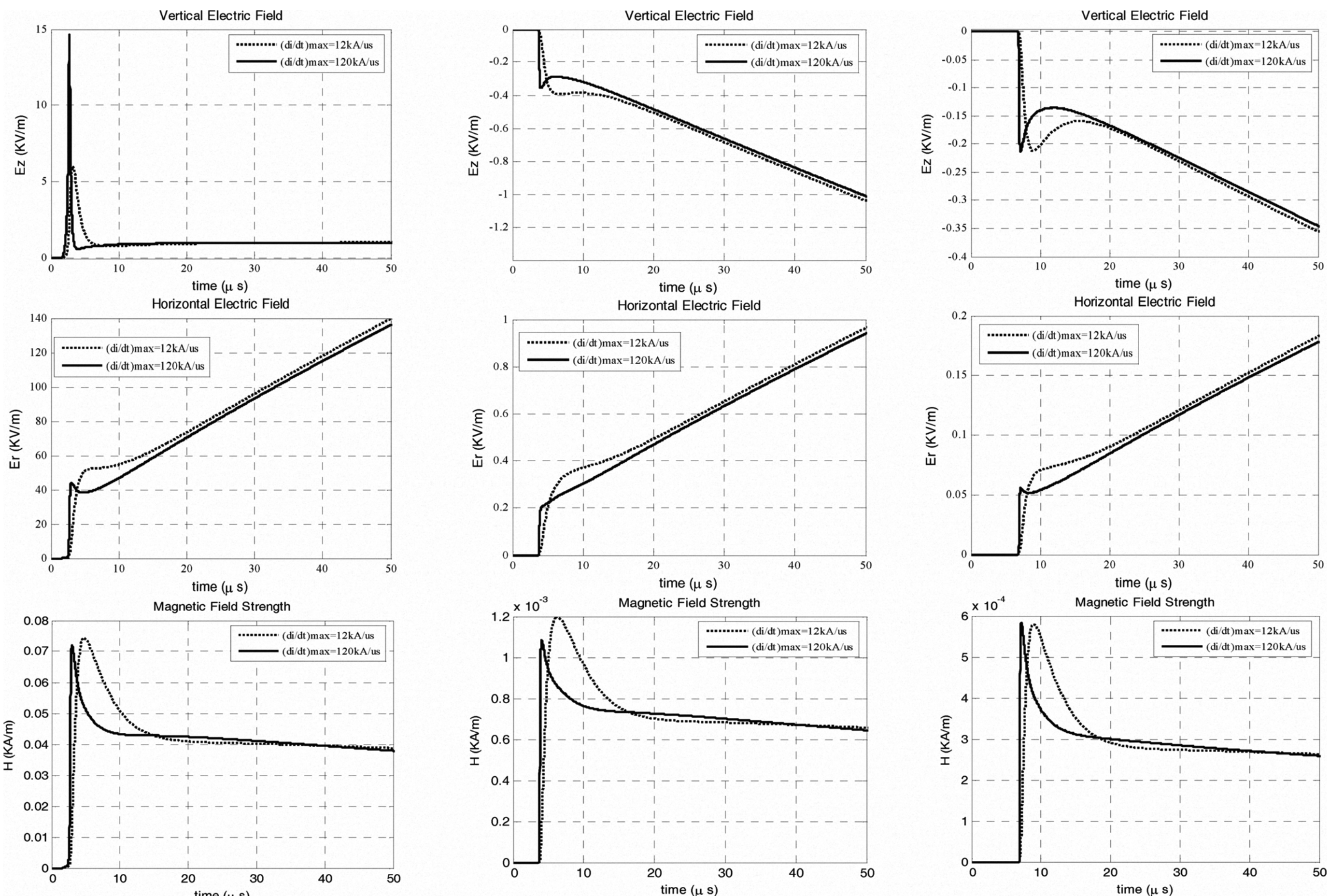
Fig. 5 presents the results for the vertical, horizontal electric fields and magnetic fields strength calculated for two different maximum time derivatives of the return stroke currents i.e., (di/dt)max =12 kA/µs and (di/dt)max = 120 kA/µs . The solid lines are the maximum time derivative of 120 kA/µs and the dotted lines are for a maximum time derivative of 12 kA/µs respectively. The velocity of the return stroke is taken as 190 m/µs. The computations were repeated for different lateral distances from the lightning channel viz., 200 m, 1000 m and 2000 m and for the observation point at a height of 500 m above from the ground plane.

From the Fig. 5 on vertical electric field, it can be observed that for height of about 500 m from the ground plane and about 20 m from the lightning channel the vertical electric field is positive, and for lateral distances about 1000 m and above its polarity is negative.

It is also seen that for distance more than 500 m the maximum time derivative of the channel base current does not influence much on the magnitude of the vertical electric field.

In Fig. 5 on horizontal electric field it can be observed that for height about 500 m from the ground plane and for lateral distance about 20 m and above the horizontal electric field is unipolar. The electric field for two different maximum time derivatives is not significant influence on horizontal electric field when ground is assumed as a perfect conductor.

Similar to the nature of vertical electric field, the nature of horizontal electric field also not influenced much by the maximum time derivative of the channel base current.



(a) r = 20 m, z = 500 m (b) r = 1000 m, z = 500 m (c) r = 2000 m, z = 500 m

Figure 5. Electromagnetic field variation with lateral distance r and height z. The dotted lines are for a maximum time derivative of 12 kA/µs and the solid lines are for a maximum time derivative of 120 kA/µs. (a) r = 20 m, z = 500 m (b) r = 1000 m, z = 500 m (c) r = 2000 m, z = 500 m.

IV. Conclusions

In this paper an analysis of the electromagnetic fields produced above the ground at various heights and for different distance from the lightning return stroke has been presented. Electromagnetic field waveforms corresponding to the return stroke speed and maximum current derivative has been analyzed by making use of the MTLE model.

It is seen that the vertical electric field is bipolar in nature and that the height at which the polarity reversal takes place increases with increases of lateral distance from the lightning channel. The horizontal electric field is always unipolar for all heights studied and for all lateral distance from the channel. The maximum time derivative of the return stroke current does not change much the magnitude as well as the wave shape of the magnetic field strength.

The velocities of the return stroke current influence on the peak magnitude of the vertical electric field. Its influence on the horizontal electric field and magnetic field strength is insignificant.

The maximum time derivative of return stroke has a significant influence on the magnitude of vertical electric field for near distances (about 20 m). The influence of the maximum time derivative of the lightning return stroke current on the vertical and horizontal electric fields is not significant on the magnitude as well as on the wave shape.

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