

Electromagnetic Fields Produced by Inclined Return Stroke Channel

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Abstract the electromagnetic fields associated with inclined lightning channel are usually characterized by pronounced fine structure, this paper investigates and quantifies the effects of channel inclination on the return stroke electromagnetic field shapes in the close, medium and far lightning environment. Using Antenna Theory (AT) model, which is extended to take into account the channel inclination, the electromagnetic fields expressions for vertical dipole are completed, and an inclined channel is properly modeled, vertical electric and azimuthal magnetic fields are computed. The field computations show that amplitudes and wave forms of the electromagnetic fields are affected more markedly by the channel inclination at close distances, and the induced voltage produced by inclined channel differs significantly from that associated with a straight channel.

Keywords Inclined Lightning Channel, Electromagnetic Field, Return Stroke, AT Model, Induced Voltage

1. Introduction

Electrical power system apparatus can be adversely affected by the cloud-to-ground (CG) lightning return stroke.

The mis-operation failure of such apparatus may not only be due to a direct contact with the lightning discharge, but it indirect coupling with the lightning channel was possible, when the lightning return stroke produced near distribution networks[1].

As a result dangerously over voltage exceeds the system basic insulation level (BIL) specified in such a voltage level. In addition, electric equipments are at risk through electromagnetic field radiated.

The issue of lightning returns stroke channel modeling has been often discussed and studied in literature[2, 3]. One of basic assumptions in most of models is that the channel is vertical, while the channel inclination effects have shown to be of great importance when calculating the lightning-induced effects on overhead lines.

LeVine and Meneghini[4] investigated an arbitrary current filament located above a perfectly conducting ground plane driven by a traveling wave. In their theoretical analysis, they were able to develop exact and approximated solutions for the resulting fields. Their exact solution predicted both radiation and near fields regardless of the distance between the observation point and filament. Whereas, their approximated solution utilized far field approximation, and

as a result, only yields electric field radiation constituents which occupy the Fraunhofer region of the filament. However, upon comparing the two solutions, they found the approximate solution failed the lower frequencies which are of particular importance in lightning studies. Lupo et al[5], in their study analysis, treated each tortuous path as a single line radiator with an arbitrary slope and height. They were able to develop closed-form solution for the electromagnetic fields by omitting any mathematical approximations.

The channel inclination effect on lightning-induced voltages was first investigated by Sakakibara[6] who modified the Rusk's model by adding appropriate additional terms in the field-to-transmission line coupling equations. He assumed that the charge density distribution along the leader channel is uniform and the current waveform is triangular. His method has been later extended to a channel with arbitrary configuration by Wu and Hsiao[7].

In this paper, Antenna Theory model for the lightning return stroke channel is applied to investigate the effect of channel inclination. AT model characteristics for the vertical return stroke channel have already been presented[8]. The channel is represented as a lossy monopole antenna fed at its base.

The return stroke current waveform predicted by the model exhibits dispersion and attenuation while travelling up along the channel, in accordance with available optical observations.

In the first part of the paper, the theoretical basis of the Antenna Theory model for the lightning return stroke model is discussed, and then the expressions for electromagnetic field originated by a vertical dipole are extended to take into account an arbitrary dipole inclination. Finally the model is

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applied to investigate effect of channel inclination on electromagnetic fields at various distances, and the induced voltages on nearby overhead lines.

2. Theory and Adapted Model

Inclined return stroke channel, which is modeled by a straight and vertical monopole antenna above a perfectly conducting ground, is shown in figure 1.

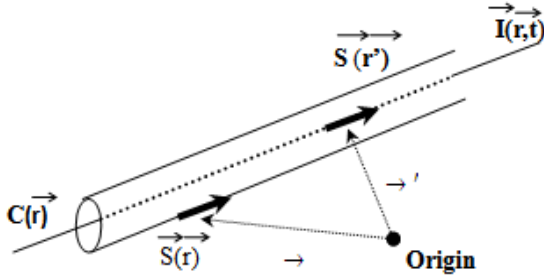


Figure 1. Wire structure

Lot of studies for determining the transient response of antennas and scatterers has grown steadily in recent years[9]. Transients may be dealt with both in time or frequency domain, a direct time-domain treatment of electromagnetic problems related to the lightning discharge is used. An integral equation developed for determining the time-dependent current distribution on wire structure excited an arbitrary time-varying electric field is reported in the literature, and will be briefly discussed. The electric field integral equation (EFIE) in time domain can be solved using the method of moments (MoM)[10].

Computer code for time-domain solutions has been developed for thin wires in the free space by F. Barbosa and J. O. S. Paulino,[11]. Time dependent Maxwell's equations provide starting point of our derivation. Desired integral equation derivation may proceed by Green's vector identity, which leads to an integral equation relating \mathbf{J} (surface current density) and \mathbf{E} (electric field) on conductor's surface under consideration. Assuming that surface consists in a small circular cross section in comparison with wavelength, current density surface integral can be replaced by a line integral along structure periphery (thin wire approximation). This approach leads to the same result as obtained by adopting assumption inherent in thin wire approximation at beginning. Latter approach is more direct it's employed here.

2.1. Problem Presentation

Consider a filamentary current $I(r, t)$ flowing on path $C(r)$, along which length variable is s (see Fig.2).

Electric field it produces:

$$\mathbf{E}(\mathbf{r}, t) = -\nabla\phi(\mathbf{r}, t) - \frac{\partial}{\partial t} \mathbf{A}(\mathbf{r}, t) \quad (1)$$

$$\varnothing(r, t) = \frac{1}{4\pi\epsilon_0} \int_C \frac{q(r, t - R/v)}{R} ds' \quad (2)$$

$$A(r, t) = \frac{\mu_0}{4\pi\epsilon_0} \int_C \frac{q(r, t - R/v)}{R} ds' \quad (3)$$

v: Velocity of propagation.

r and t: Observation point location and time.

\mathbf{r}' and $t' = t - \mathbf{r}'/v$: Denote source location and time respectively.

$\mathbf{s} = \mathbf{s}(r), \mathbf{s}' = \mathbf{s}(r')$: Unit tangent vectors to $\mathbf{C}(r)$ at \mathbf{r} and \mathbf{r}' respectively.

Electric field integral representation due to filamentary current:

$$E(r, t) = -\frac{\mu_0}{4\pi} \int_C Y \, ds' \quad (4)$$

With:

$$Y = \left[\frac{S'}{R} \frac{\partial}{\partial t'} I(s', t') + v \frac{R}{R^2} \frac{\partial}{\partial s'} I(s', t') - v^2 \frac{R}{R^3} q(s', t') \right] \quad (5)$$

Assuming that $I(s', t')$ and $q(s', t')$ are confined to conductor axis (thin wire approximation), boundary condition on tangential electric field for a perfect conductor wire is:

$$s[E^s + E^i] = 0 \quad (6)$$

E^i : Applied field which induces the current I generating scattered field E^s

By applying this boundary condition to tangential electric field at the conductor surface in Eq. (6), for this conducting wire in the following form:

$$sE^i(r, t) = \frac{\mu_0}{4\pi} \int_C \left[\frac{sS'}{R} \frac{\partial}{\partial t'} I(s', t') + v \frac{sR}{R^2} \frac{\partial}{\partial s'} I(s', t') \right] \\ + \frac{\mu_0}{4\pi} \int_C \left[-v^2 \frac{sR}{R^3} q(s', t') \right] r \in C(r) + a(r) \quad (7)$$

And:

$$q(s', t') = \int_{-\infty}^{t'} \frac{\partial}{\partial s'} I(s', \tau) d\tau \quad (8)$$

Since integration path in Eq. (7) is along $C(R)$, while the wire radius displaces field evaluation path, R is always positive and therefore integral has no singularity, whose solution can be sought using moment method. Figure (4) shows that an incremental section of wire structure above a perfect ground, so image theory is used, in order to take into consideration ground effect.

As a result:

$$\begin{aligned} sE^i(r, t) = & \frac{\mu_0}{4\pi} \int_C \left[\frac{sS'}{R} \frac{\partial}{\partial t'} I(s', t') + v \frac{sR}{R^2} \frac{\partial}{\partial s'} I(s', t') - \right. \\ & v^2 \frac{sR}{R^3} q(s', t') - \frac{s s'^*}{R^*} \frac{\partial}{\partial t'^*} I(s', t'^*) + \\ & \left. v \frac{sR^*}{R^{*2}} \frac{\partial}{\partial s'} I(s', t'^*) - v^2 \frac{sR^*}{R^{*3}} q(s', t'^*) \right] ds' \quad (9) \end{aligned}$$

And

$$R = \sqrt{(s - s')^2 + a^2} \quad t' = t - \frac{R}{v}$$

$$R^* = \sqrt{(s - s'^*)^2 + a^2} \quad t'^* = t - \frac{R^*}{v}$$

angle of $\theta = 30^\circ$ with the Z axis (Fig.3).

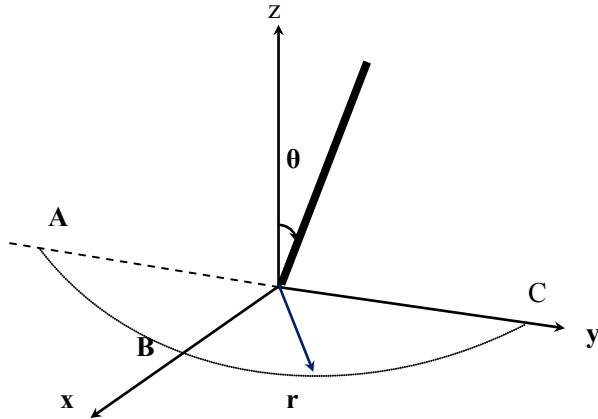


Figure 3. Inclined Channel

According antenna theory model, this channel is modelled as a monopole antenna which is feed at its base and radiates in free space. Once the current distribution along antenna is known using electric field integral equation, electromagnetic fields at any distance from channel can be computed.

Fig. (4) Shows adopted channel-base current which corresponds to a typical subsequent stroke.

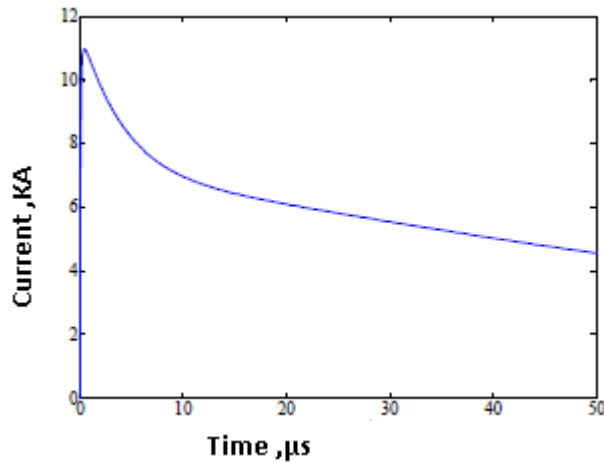


Figure 4. Current in base of channel[14]

The results for the electric fields and the magnetic flux densities are shown in figures 5, 6 and 7

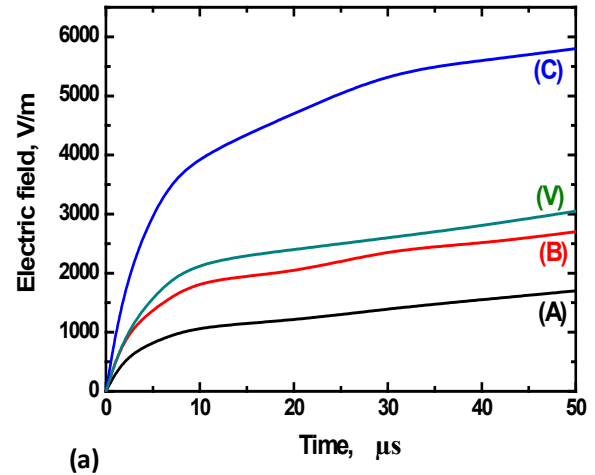
The observation points (A, B, and C), were assumed to be on ground and at different distances from the lightning striking point. While for the straight and vertical lightning channel the magnetic flux density in x-direction vanishes due to the radial symmetry, the inclined channel radiates small magnetic fields in x-direction, too. Due to the assumption of a perfectly conducting ground plane, the horizontal electric fields vanish for both channels.

According to figures, the fields associated with the straight and the inclined channel mainly differ in the maximum amplitudes. In the following paragraphs these properties are discussed in more detail.

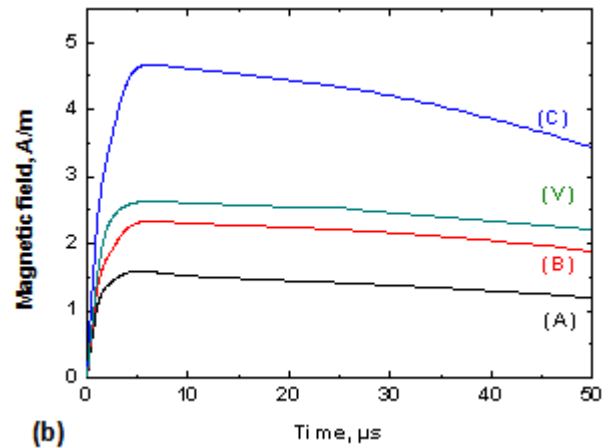
Zhao and Zhang[15] presented a similar discussion of the

electromagnetic fields radiated by tortuous return stroke channels. They investigated the azimuthal dependency of the remote fields (100m–100 km from the lightning striking point).

Our work, concentrate on the radial dependency of the surrounding return stroke fields (350 m from the lightning striking point). Thus, it can be regarded as a supplement to the discussion of Zhao and Zhang.



(a)



(b)

Figure 5. Electric and magnetic field at 0, 35 km from the channel at different observation points, (V):Vertical channel

Radiated electromagnetic fields are plotted for different observation points (A, B, and C in Fig. 4) and distances from the channel (0.35, 4 and 50 km). At close distances (Fig. 5a and b) inclination effect is clearly observed. At $t=50\mu s$, Electric field value at point C is almost doubled with respect to the vertical channel. At this range, Magnetic field maximum value has markedly increased due to the channel inclination. At medium distance ranges (Fig. 6a and 6b), electric field shows the typical increasing ramp at all points. At point C, the steepness of this ramp is three times greater than that of vertical channel and magnetic field shows a hump which is more apparent at this point. At far distances (Fig. 7a and 7b); channel inclination effect on the electromagnetic fields appears to be less important.

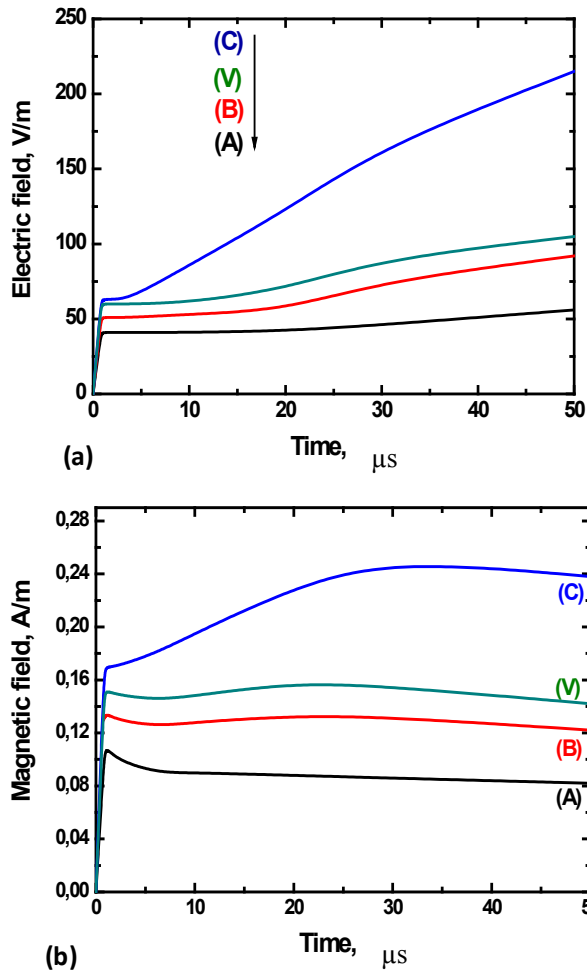


Figure 6. Electric and magnetic field at 4 km from the channel at different observation points, (V): vertical channel

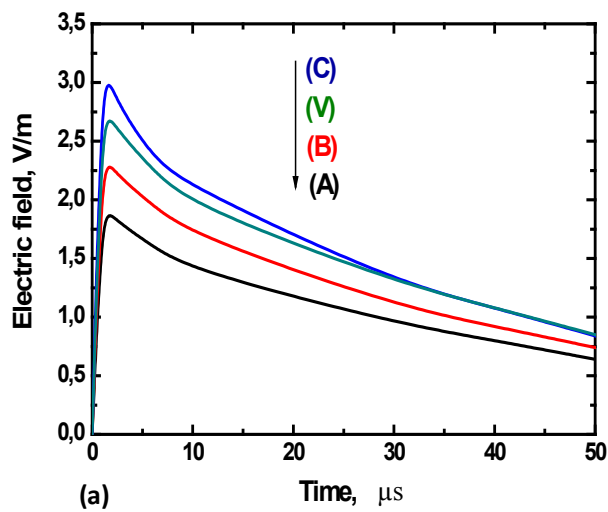


Figure 7. Electric and magnetic field at 50 km from the channel at different observation points, (V): vertical channel

4.1. Induced Voltages

Induced voltages have been evaluated for an overhead line composed of a single conductor, at height $h=12$ m above ground, parallel to the y - z plane, the length of the line is 1 km, at distances d of 100 m and 1500 m, we will consider 2 different geometries which are shown in Fig.8.

Starting from the vertical channel (Fig.8.a) then a straight inclined channel will be considered with a channel inclination angle with respect vertical $\alpha=30^\circ$.

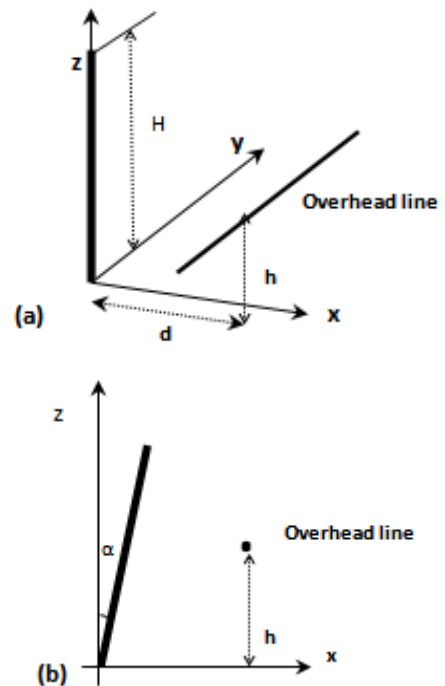


Figure 8. (a) Straight channel, (b) Inclined channel

It is clearly seen in Fig. 9, that for short and intermediate ranges, the effect of the inclination more important. Compared to the vertical channel, the amplitude of the induced voltage at a distance of 100 m is about 25% higher for points toward which the lowest segment is inclined. Similar behaviour is observed at 1500 m, although the induced voltage waveform exhibits a larger width. No overall tortuosity effect is noticed.

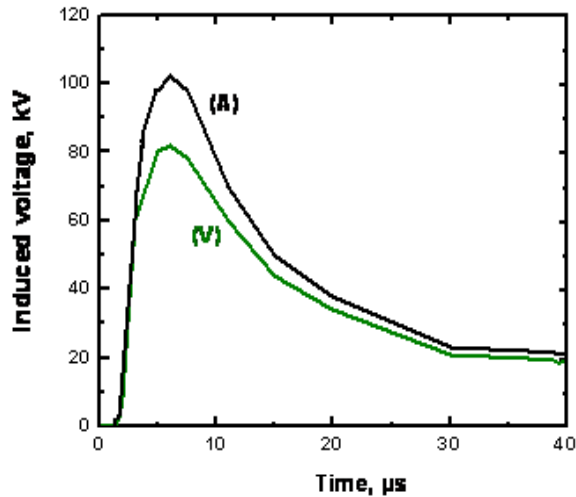


Figure 9. (a). Induced voltage, at 100 m from the channel, (A): Inclined, (V): Vertical

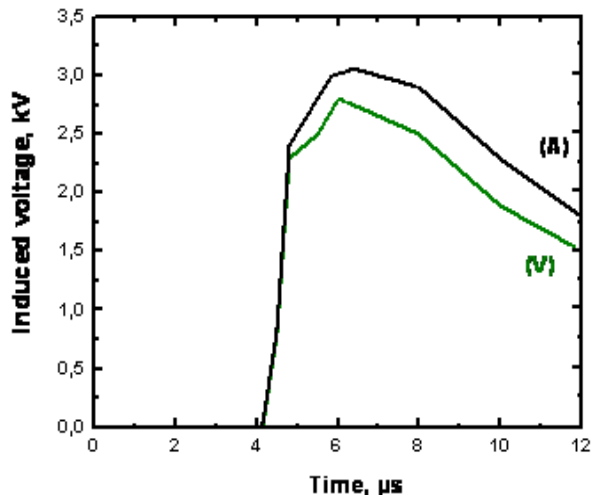


Figure 9. (b) Induced voltage at 1500 m from the channel, (A): Inclined, (V): Vertical

5. Conclusions

Antenna Theory model is applied to evaluate the electromagnetic field for an inclined return stroke channel. This method based essentially on solving the integral equation for electric field in time domain using method of moments.

The electromagnetic fields expressions for vertical dipole are completed to take account the dipole inclination. This fields for an inclined lightning channel are computed using

AT model at three different distances 0,350 (close), 4 (medium), and 50 km (far). The results prove that the vertical electric and azimuthal magnetic fields are clearly more affected at very close range by the lightning channel inclination than a vertical channel. Indeed, depending on the channel orientation and its relative position to the observation point or to the line, the channel inclination could result either in an increase or in a decrease of the electromagnetic field and induced voltage.

Given the statistical nature of lightning channel and high variability of key parameters (such as return stroke current, return stroke speed, etc.), one can state that the assumption of a vertical channel represent a reasonable approximation in the calculation of lightning radiated fields.

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