An Inquisitive Analysis on the Temporal Variation of Return Stroke Current Essential for Producing Observed Remote Electro-Magnetic Fields

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Abstract— The gross characteristics of spatio-temporal current evolution in the return stroke phase of a cloud-to-ground lightning are rather well defined. However, they by themselves do not ensure the salient features for the resulting remote Electro-Magnetic Fields (EMFs). In spite of significant efforts in the engineering models wherein, the spatio-temporal current distribution all along the channel is specified by the design, all the salient features of remote EMFs could not be achieved. Only the current evolution that ensures the basic characteristics along with its ability to reproduce all the salient features of remote EMFs ranging from 50 m – 200 km from the lightning channel, can be considered as a realistic return stroke channel current. In view of this, the present work intends to investigate on the required fine features of the return stroke current evolution that yields all the desired features. To ensure that the current evolution is not arbitrary but obeys the involved basic physical processes, a recently developed physical model will be employed for the analysis.

Keywords- lightning, return stroke, remote electromagnetic fields, physical model

I. INTRODUCTION

The return stroke phase of a natural cloud-to-ground lightning is the major source of lightning caused hazards and disturbances to most of the modern systems [1,2]. The systems that are mainly affected are electrical and electronic systems, communication systems, chemical factories, detonation storage as well as avionics, missile and satellite launching systems. The direct effect, which is a consequence of the system or its component becoming a part of the return stroke path, can be catastrophic to most of the above systems, except for very high voltage power transmission networks. The indirect effect, which is a consequence of induction due to lightning produced Electro-Magnetic Fields (EMFs), is of serious concern to electronics, communication and distribution class power networks. In view of these, the study of return stroke phase of lightning assumes prime importance in engineering designs.

Any model for the return stroke phase must be able to predict the basic features of current evolution like the current should possess a faster rising portion followed by a relatively slow decaying tail, its amplitude and velocity should decay while, its rise time should increase with altitude etc., [1,2]. It may be adequate to emulate these in a return stroke model for a direct hit scenario. However, such a model need not qualify as a reliable return stroke model from the phenomena point of view. The first two features of the current listed above, at best, can ensure characteristics of measured EMFs in the near region (< 100 m from the channel), however, EMFs in the intermediate region (around 5 km from the channel) and far range (> 50 km from the channel) need not be satisfactorily emulated [3]. The associated intricacies of the EMFs will be dealt later.

On the other hand, models for remote EMFs due to the return stroke phase, which are generally termed as the engineering models, assume (based on some physical reasoning) a spatio-temporal distribution of return stroke current all along a vertical channel. Then the remote EMF is related to this spatio-temporal current distribution along the channel. The engineering models are further divided into Bruce–Golde (BG) model, Diendorfer–Uman (DU) model, Transmission Line (TL) models, Modified Transmission Line model with Linear decay (MTLL) and Modified Transmission Line model with Exponential decay (MTLE). A detailed review of all these engineering models along with their capabilities in predicting the salient features of observed remote EMFs is reported in [1,2]. In spite of having a freedom to choose the spatio-temporal current distribution, the engineering models are reported to be incapable of predicting all the basic salient features of remote EMFs.

In summary, a detailed investigation on the spatio-temporal current distribution along the channel, which not only possesses all the basic features of return stroke current but can also yield all the prominent characteristics of resulting EMFs is hard to find in the literature. The goal of the present work is to address this issue. The findings of this work will be of significant relevance in providing validation to the models for return stroke current evolution, as well as, in designing suitable engineering models. It may be noted here that to owing its dominance and practical significance, only negative downward cloud-to-ground stroke is considered.
II. Present Work

The intended analysis can be carried out by specifying a mathematical expression for spatio-temporal current variation as being done in engineering models. However, irrespective of the end results, the defined current evolution need not be physical. Of course, this aspect applies to all engineering models as well. A detailed review of the literature on return stroke models indicates the following [1-6]. The gas-dynamic models are models for channel core electro-gas-dynamics at a given point on the channel and employ current as the input. Therefore, they cannot be employed for emulation of return stroke evolution. The distributed circuit model mainly suffers from inherent assumption of quasi-TEM mode of wave propagation, which is in contrast to the TM mode prevailing in the channel. The electromagnetic models are more sophisticated; however, employ a lumped source excitation along with a simplified model for channel. In other words, the waveshape of the current is prefixed by the source definition along with linear/non-linear loading of the channel. In view of these, all the required analysis will be carried out with the help of a macroscopic physical model for the lightning return stroke, which was recently developed by the authors [3,7] and a brief account of the same will be given below.

A. Macroscopic physical model for return stroke current evolution

The macroscopic model considered deals with the return stroke current evolution for a downward strike to ground scenario. It takes into account the underlying physical processes: (i) excitation formed by the electric field due to charge deposited along the channel, that in the cloud and induced charge on the ground, (ii) the transient enhancement of conductance by several orders at the bridging regime, which initiates the return stroke (iii) the non-linear enhancement of channel conductance along with (iv) the associated dynamic EMFs that support the current evolution. The model is based on certain justifiable simplification on channel geometry and arc dynamics [3,7].

The required field computation involves evaluation of initial charge distribution, which is carried out using Charge Simulation Method (CSM) and dynamic EMFs associated with return stroke, which is determined by Time Domain Electric Field Integral Equation (TD-EFIE) [8]. The participating charge centre of the cloud is approximated to be spherical and its radius and magnitude of charge is evaluated by specifying channel length, channel root potential and gradient at the surface of the spherical charge center. The corona sheath surrounding the channel core is assumed to have formed during the leader phase with its radius calculated.
iteratively. For evaluating the transient change of conductance at the bridging/streamer region, Toepler’s spark law [9] is employed. With regard to the matured section of the channel (also includes matured streamer section), a first order arc equation [10,11] is used to describe the non-linear variation of channel conductance. The arc time constant for rising current, in an attempt to make them current dependent, is made to vary with altitude [3,7]. Also, the settling value of conductance is made a function of instantaneous current [3,7,11]. Further, the steady-state arc gradient, as well as, the critical gradient for corona inception is subjected to air density and temperature correction factor [12]. The conductivity of corona sheath is made field dependent, which makes it very prominent only during the traverse of wavefront through the given segment [3,7].

Selected simulation results for return stroke current evolution are presented in Figure 1, which will be referred to in the subsequent analysis. For all the three cases presented in Figure 1, it can be verified that the basic characteristics of stroke current evolution namely, waveforms at all heights have a fast front, which is followed by a relatively slow decay, decrease of current amplitude and velocity with altitude and an increase in rise time with altitude, are all satisfactorily depicted. The spatial current decay rate is not the same in all the three cases and so is the increase in time to front with altitude. It may be worth noting here that this macroscopic physical model is first of its kind and there is no similar modeling effort in the literature.

Before proceeding further, few points could be worth discussing here. Firstly, synthesis problem is not unique and hence, it may appear that remote EMFs could be produced by different spatio-temporal current distributions. However, this is not true in this case as EMFs are not specified at one particular distance but at several distances from the lightning channel. Further, along with the field, even the pattern of spatial current distribution is also specified. These aspects make the required spatio-temporal current pattern rather unique. In other words, as current distribution along the channel is responsible for the fields, their prominent characteristics can be clear identifiers for the salient features of spatio-temporal distribution of return stroke current. The typical measured EMFs due to first return stroke of a lightning
flash is reproduced in figure 2 [13]. Figures 2 (a), (c) & (e) are for vertical electrical field and (b), (d) & (f) are for azimuthal magnetic field both measured at 1m from ground. The salient features of the fields could be readily identified from the figure. For brevity in presentation, they will be discussed along with the simulation results of macroscopic model, which as mentioned earlier, is the only physical model available in the pertinent literature. Secondly, the measured fields presented in Figure 2 and the computed EMFs from the simulated return stroke current (using the macroscopic physical model) shown in Figure 3 are only the due to the return stroke phase.

B. EMF profile in the near region
The near region corresponds to horizontal distances within 100 m from the channel. Due to the dominance of static component of electric (Figure 2a) and magnetic fields (Figure 2b), the EMFs will be a replica of the charge and current in the channel respectively, in particular, in the region closer to the measurement point. The same is also evident from the computed EMFs from the simulated return stroke current shown in Figures 3(a) & 3(b) respectively. The charge deposited on the channel near ground by the return stroke phase governs the former and this charge deposition becomes stagnant once the neutralization of charge stored in corona sheath is (in the region closer to the measurement point) completed. This results in a flattening trend with time. As the charge deposited is higher for higher currents, the settling values of the field are also higher.

C. EMF profile in the intermediate region
The intermediate region corresponds to horizontal distances within 5 km from the channel. For the analysis here, field at 1 km distance is considered. It can be observed from Figures 2(c) & 2(d) that but for the initial kink associated probably with the bridging phenomena, these fields will be composed of both induction and static components. The latter will still be active due to the dominance of lower frequency components in the lightning energy spectrum.

Similar to Figure 2(c), the computed vertical electric field at 1 km (refer Figure 3c) from the simulated return stroke current shows that after the initial rising portion, field exhibits a slow increase, which can be attributed to continuous charge deposition along the channel by the evolving return stroke. The final saturating trend is found to be due to distance factor and lower deposition rate, which reduces the contribution from the higher altitude regions. Computed field due to median and lower end currents show a good matching with the field data, while that due to higher end currents are not that satisfactory.

With regard to the azimuthal magnetic field at 1 km, both measured (refer Figure 2b) and model predicted (refer Figure 3b) fields possess an initial fast rising portion due to the dominance of radiation term. A characteristic hump seems to follow the initial portion. In the simulation results, hump could be seen only for lower currents (< 80 kA). An analysis for the same revealed the following. The magnitude of the field is dependent on the spatial extension of the current along the channel and its average value. Due to the decay of current with both space and time, there could be an instant at which the combined action of the prevailing current and its spatial extension becomes highest. This leads to a hump in the magnetic field at distances in the range of 1 - 5 km. The simulation results corresponding to large return stroke current indicate a very fast spatial decay of current along with the fact that the point of bridging is quite elevated from the ground. These in turn eliminate separation between the instant of bridging and the instant at which the product of current and its spatial extension gets into a maximum. As a result, no hump could be seen for currents in the higher range.
Fig. 3. Vertical electric $E_z$ and azimuthal magnetic $H_\theta$ fields at different distances (All figures are normalized to their maximum value except (a))
Also, it may be recalled here that the simulations are carried out for vertically straight channel geometry without any branching. On the other hand, in reality there exists significant channel tortuosity and inclination along with branching. These are expected to contribute to remote EMFs and especially to field at intermediate range. This accounts for additional differences between the computed and measured data.

D. EMF profile in the far region

The measured vertical electric and azimuthal magnetic fields at distances of 50 & 200 km are given in figure 2 (e) – (h). The radiation component mostly dominates the fields at distances beyond 50 km. At a distance of 200 km, it is only the radiation component and hence, the electric and magnetic fields becomes almost replica of each other. There is a characteristic zero-cross over once, which takes place earlier when the field is measured at 200 km as compared to 50 km.

The corresponding fields computed from simulated return stroke currents are presented in figure 3(e) – (h). It can be verified that the characteristic zero crossover is very well depicted in the simulation results. Further, its relatively early occurrence with 200 km as compared to 50 km is also well depicted. An analysis for this zero crossover was carried out with the model. The current, which is the source for field, has two distinct regimes in space at every instant of time. The wavefront region is marked by strong \( \frac{di}{dt} \) while, the tail portion possesses relatively weak \( \frac{di}{dt} \) of opposite polarity. As the current propagates to higher altitudes, its peak amplitude decreases while, time to crest increases. This results in smaller \( \frac{di}{dt} \) in the wavefront region and hence, its contribution to the field decreases. On the other hand, the region spanned by the tail continuously increases, thereby, compensating for the smaller \( \frac{di}{dt} \) prevailing in this section. This at appropriate instant of time overcomes the field due to the wavefront region, which results in the zero cross-over of the field.

Extensive simulation was carried out for different rate of spatial current decay. It was found that a spatially fast decaying current can also produce a zero crossover. However, such a current evolution cannot depict the salient features of fields at intermediate region, as well as, successful current evolution throughout the channel length. Another very important aspect was also revealed by our physical model. The current peak should have an initial fast decay so as to produce a zero crossover of the far fields. This characteristic peaking of the current resulted from the field dependent conductivity of corona sheath. At the wavefront region, the neutralisation of the charge in corona sheath is very significant and the radial flow of current in corona sheath is necessary for the charge neutralisation. This aspect was critically verified by pertinent simulations.

With regard to the zero cross-over, another aspect may need attention. The cloud-end dynamics may contribute to this and its subsequent recovery. This aspect is not yet incorporated in our model and is left for future research. The initial rising portion of both intermediate and far field waveforms in the simulation results are noticeably faster or of higher magnitude than that measured in the field. There are two aspects, which leads to this deviation. Firstly, the simulated current possesses a swifter rise than median currents and secondly, the ground attenuation, which slows down the waveform of the EMF wave, is not incorporated in the simulation.

III. Conclusions

The salient features of spatio-temporal current evolution in the return stroke phase of a cloud-to-ground lightning define the prominent characteristics of the resulting remote electromagnetic fields. In spite of specifying the spatio-temporal current distribution along the channel as an input, none of the engineering models, which are primarily models for EMFs, could predict all the salient features of the measured remote EMFs. While other class of return stroke models are either not intended or not capable of emulating current evolution, as well as, salient features of remote EMFs. In light of this, the present work has made a successful attempt to deduce the fine features of the spatio-temporal distribution of return stroke current that is necessary to yield the salient features of the observed EMFs. A macroscopic physical model for the lightning return stroke was employed for the analysis. This model is shown to yield a stroke current evolution, which is capable of producing all the observed salient features of EMFs on ground at horizontal distances ranging from 50 m – 200 km from the lightning channel.

The findings of this work will be of great relevance in providing validation to the models for return stroke current evolution, as well as, in designing suitable engineering models.

REFERENCES


