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Severity of Lightning Return Strokes: Simulation Study and Review Notes

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Abstract: *The literature on lightning stroke severity indicates that the magnitude of the electric field peak due to the first-return-stroke is nearly twice that of the field peak due to the subsequent return stroke. These reports are based on the data collected by lightning detection, and information and field measurement systems. In this paper, field results from the literature are summarised. These are then compared with the results obtained through simulation. Electromagnetic fields generated due to "typical" first (FS) and subsequent (SS) lightning return strokes have been computed using the "Modified Transmission Line with Linear current decay" (MTLL) model. These simulation results are discussed, keeping in view, the field data reported in several recent studies, which compare the severity of first and subsequent-return-strokes. The MTLL based engineering model is adopted to compare the severity of lightning return strokes (FS/SS) as a function of radial distance. The effect of worst-case-ground-conductivity on this ratio is reported. An MTLL model based comparison on em-field FS/SS ratio for both perfect and worst-case-ground conditions is also reported. These simulation results are compared with those from the "Modified Transmission Line with Exponential current decay" (MTLE) model. In general, the present simulation results not only substantiate the fact that the FS/SS ratio is nearly two times, but also assess a few parameters responsible for low FS/SS ratio (reported in some cases). The present simulation analysis shows that terrain electrical conductivity affects the FS/SS ratio. This may explain the cause for the low FS/SS ratios.*

Keywords: *Electromagnetic fields, First-return-strokes, Ground conductivity, Lightning, Stroke severity, Subsequent-return-stroke*

1. Introduction

Lightning is the most spectacular natural electrical phenomenon. Lightning, although of short duration, has the potential to cause significant damage to life and property, because it is an intense power source,. Attempts to understand this natural phenomenon, have been challenging, though is a well-researched area.

Cloud-to-Ground (CG) lightning discharges have many destructive effects. The more damaging effects have come to light due to its indirect effects on modern electronic gadgets, which are susceptible to surge voltages and currents. These are due to lightning electromagnetic fields (LEMF). LEMFs can induce over voltages in the objects they couple with. Hence, knowledge of electromagnetic (em) fields associated with lightning is essential to understand the indirect effects of lightning. The threat due to lightning indirect strokes and the Electro-Magnetic-Compatibility (EMC) studies depend on characteristics of both, (i) the objects to which LEMFs couple and (ii) the characteristics of lightning strokes. Return strokes of the lightning currents are intense and hence their effects are severe. A typical CG flash will have one first-return-stroke, and may have one or more subsequent-return-strokes. Based on the difference in their typical characteristics, lightning strokes are grouped into first-return-stroke (FS) and subsequent-return-strokes (SS). The field observation reports indicate that, the average number of subsequent-return-strokes can be 4 to 5 in a multiple-stroke flash of negative CG flashes (Thottappillil, 2002; Rakov et al., 1994; Rakov, 2010; Heidler et al., 2008). Also, 80 % of CG lightning flashes consist of multiple strokes (Thottappillil, 2002).

The lightning field parameters (peak and maximum rate of change of electric & magnetic fields) are dependent on lightning current parameters (peak current, maximum time rate of change of current, time to peak, time to reduce to half the peak value and total charge). These parameters are further responsible for characteristics of the induced over voltages. In spite of knowing lightning current parameters, the basic question that still remains to be fully addressed is of "first-return-stroke or subsequent-return-stroke, which one is more severe?"(Fernando and Silverio, 2009).

The relative magnitudes, in CG lightning flash of the electric field peak of first-return-stroke and subsequent-return-stroke, are important in comparing *severity of strokes* in a multiple-stroke flash. Such data, based on the lightning flashover data recorded in various countries, have been discussed and examined (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008; Loboda et al., 2009). Such field measurement efforts using lightning detection, information and field measurement system along with Lightning Location Systems (LLS) greatly add to the understanding of lightning phenomena from the point of view of stroke statistics and their generalisations. This present study is a unique attempt to aid such research by in that it uses a MTLL model to examine the relative magnitude of electric and magnetic field peaks using “typical” first and subsequent lightning return strokes..

Two most important lightning stroke current parameters (among the earlier stated) are: (i) current peak, (I_{peak}) and (ii) maximum time rate of change of current, $(di/dt)_{max}$. The “typical”, first-return-stroke of negative CG discharges is characterised by I_{peak} = 30 kA and $(di/dt)_{max}$ = 12 kA/μs; whereas “typical” subsequent-return-strokes of negative CG discharges are characterised by I_{peak} = 12 kA and $(di/dt)_{max}$ = 40 kA/μs as their numeric values (Rachidi et al., 2001; COST P18 Technical Report, 2005). The lightning research community accepts these as the “typical” representatives of first-return-strokes and subsequent-return-strokes. These are the widely used representative strokes, discussed in the literature (Thottappillil, 2002).

The literature related to the West Indies region states that the climate is hotter than in Europe; and thunder and lightning are more frequent and more violent than in temperate regions (Willich and Cooper, 1821). Some of the observations are: (i) a course of hot weather precedes a thunderstorm, and summer seldom terminates without it. (ii) The flash rate density (flashes/ km^2 /year) for 27 islands in the Caribbean region shows values of the order of 20 flashes/ km^2 /year, consistent with the general level over large continents (Williams et al., 2004). Thus, it can be said that lightning is global phenomena (not continent specific). Thus research effort here is to see the severity of two lightning-flash-components, namely, first-return-strokes and subsequent-return-strokes, across the entire globe. Thus, researchers in the Caribbean region might find the results and review notes in this paper useful.

The aim of the present study is to examine the relative magnitude of electric and magnetic field peaks using “typical” first and subsequent lightning return strokes, through modeling and simulation. The severity of FS versus SS is analysed through simulation process and compared with field-measured-data, reported in the literature (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008; Loboda et al., 2009). The simulation effort also attempts to bring out the influence of finite ground conductivity (of worst case) on relative magnitude of electric field peaks. Low ratios of FS/SS are observed and reported in some cases of field measurements (Amitabh and Rakov, 2007). These simulation results seem to give some clue as to the cause for low ratios observed in some cases. Before reporting the simulation results, a brief review of FS/SS ratios found in the literature is provided (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008; Loboda et al., 2009).

2. Review related to FS/SS ratio

In general, a lightning event will have multiple flashes with each flash containing multiple strokes (on an average of 4 to 5 strokes). In a few cases it can be a single stroke flash. Each stroke exhibits a different peak. These statistical data are analysed by computing the averages. The method of analysis adopted can differ. In the literature (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008; Loboda et al., 2009), the field-measured-data, related to first-return-stroke and subsequent-return-strokes (peak e-fields) are analysed by adopting three (one or more) different methods. In evaluation and analysis, although arithmetic means (AM) are used, some of the researchers have tried to analyse by evaluating the geometric means (GM), in arriving at the FS/SS ratio. These three methods are as given below:

Method A1: This accounts for many flashes of multi strokes. For each stroke order, the average of all the corresponding stroke-order (sequential number of a stroke in a flash) magnitude (taken from all the flashes) is calculated as the first step. Then the FS/SS ratios of these mean values are evaluated for each stroke order as the second step. Finally, the mean values of these FS/SS are evaluated (including single stroke flashes).

Method A2: This accounts for flashes of multi strokes only (excluding single stroke flashes). For each stroke order, the average of all the corresponding stroke-order (sequential number of a stroke in a flash) magnitude (taken from all the flashes) is calculated as the first step. Then, the FS/SS ratios of these mean values are evaluated for each stroke order as the second step. Finally, the mean values of these FS/SS are evaluated (excluding single stroke flashes).

Method B: The ratio of FS peak field to mean value of peak fields of all the SS strokes in each multiple stroke flash is calculated. Then the mean value of such FS/SS ratios of multiple flashes is evaluated.

One of the reasons for differences in the results reported from different researchers (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008; Loboda et al., 2009) is probably due to difference in methodology adopted in arriving at FS/SS ratio in analysing the data (Amitabh et al., 2008). These are the reported results from different countries and research groups, with field data pertaining to the lightning events in their continents.

LLS, with multiple stations, help in locating the lightning strike position. They also give a peak current estimate for each stroke. The estimate is based on magnetic radiation field peaks and distances. In arriving at the current estimate, current peaks are assumed to be proportional to the field peaks. Amitabh et al. (2008) discusses some of these results of FS/SS current ratios. The AM of such peaks is in the range of 1.6 to 2.1 (Amitabh et al., 2008). Comparisons of LLS systems can also be found in the literature (Biagi et al., 2007; Rodger et al., 2006). The effort in these articles is to determine the relative merit and accuracies of these detection systems which are being used in different countries.

In general, as observed from the literature (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008), AM of FS/SS ratio varies in the range 1 to 2.4. This wide variation (especially the lower values of FS/SS in Austria studies) has been the subject of discussion in the literature. Some of the probable reasons for these discrepancies are thought to be due to one or more of the following (Amitabh et al., 2008):

1) Differing methodologies adopted for calculations involved.
2) Difference in instrumentation.
3) Uncertainties in the accuracies of the LLS systems, at least as far as the peak estimations of first-return-stroke are concerned.
4) Reporting of the highest percentages of flashes with at least on subsequent stroke field peak greater that the first-return stroke, particularly in the Austrian studies. This could be the reason for lower FS/SS ratio.
5) Intensities of the lightning stroke magnitudes may be differing, depending on geographic location. This needs some more field data and observations to ascertain.

The topic thus has given rise to a wide scope for further study and research, particularly in knowing the relative severity of first-return-stroke in relation with that of subsequent return stroke. With this in mind, the present study has attempted to evaluate the FS/SS ratio with "typical" first and subsequent strokes, through a simulation process. In the present study, for computing LEMF, MTLL model has been adopted (Rakov and Dulzon, 1991). The MTLL model is one of the widely accepted simulation processes. Some of the specific details of this simulation, adopted in this study are described in the next section.

3. Particulars of Simulation

Computing LEMF using the lightning engineering-return-stroke model, in general, involves following two major steps (Master and Uman, 1984):

1) Modeling of spatial-temporal distribution of current due to lightning return stroke, along the lightning channel.
2) Calculating of LEMF produced by making use of current model of the lightning-return-stroke, over the perfectly conducting ground.

The evaluation of LEMF at the ground surface and above the ground, for situation of finite ground conductivity is made by adopting the Cooray-Rubinstein approximations (Cooray, 1992; Rubinstein, 1996). Details of these simulation steps specific to the present study are similar to those given by Master and Uman (1984). A brief description is given in this section.

3.1 Lightning Return Stroke Current

For determining the electric and magnetic fields, it is necessary to model the return stroke current distribution along the channel. The lightning channel is assumed to be straight and vertical, above the ground plane and perpendicular to it, starting from the striking point at ground (at the channel base). The geometry of the simulated lightning return stroke above the perfectly conducting ground plane and the associated observation point is shown in Figure 1.

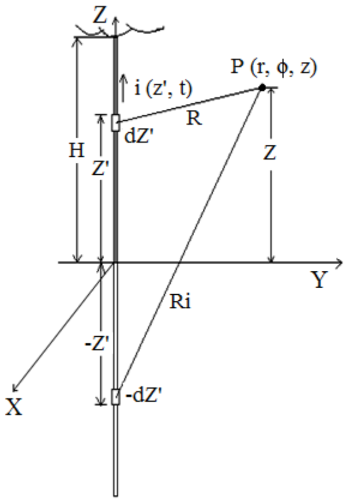

Figure 1. Geometrical details of lightning channel used for lightning electromagnetic field calculations

In the MTLL model, the lightning current is allowed to decrease linearly with the height, while propagating upward along the channel. A current-element idZ′ is chosen along the path. The infinite ground plane is simulated using an equivalent image current-element at –Z′, below the ground plane.

The observation point above the ground plane is at P(r, Φ, z); Where "r" is the radial distance and "z" is the height of the observation point above the ground.

The height "H", of the cloud above the ground plane is assumed to be 8 km. The current through the lightning channel, in the MTLL model as adopted from Rakov and Uman, (1998) is given by the equation (1)

$$i(z', t) = u(t-z'/v)\,(1- (z'/H))\ \ i(0, t-z'/v) \tag{1}$$

where 'v' is the velocity of the return stroke, u(t) is the Heaviside function and i(0,t) is the current at ground.

Using this lightning return stroke current model in simulation, the em-fields surrounding the lightning discharge at typical observation point are calculated.

3.2 EM Fields Due To Lightning

Vertical and horizontal components of the electric fields; and the azimuth component of magnetic field due to an elemental dipole of current I(Z´,t), for an infinitesimal lightning channel length dZ′ at a height Z′ from the ground, are calculated at an observation point 'P'. For perfectly conducting ground, adopting the expressions given by Master and Uman (1984), a computer code was developed. Because of the cylindrical symmetry of the problem, the em-field at any point is obtained with ease in cylindrical coordinate system. For this purpose the return stroke channel is placed along the Z-axis. The total field at the observation point is obtained by integrating over the length of the current channel accounting for its image.

3.3 Ground Conductivity and EM Fields

For a finitely conducting ground the horizontal electric field is computed using Cooray-Rubinstein approximation (Cooray, 1992; Rubinstein, 1996), widely known as CR-approximation. In the case of finite conductivity ground, the horizontal component of the electric field gets altered at the surface of the ground. In CR-approximation the horizontal electric field is computed by adding an appropriate term to electric field values obtained for infinite ground situation. This added term is obtained from surface impedance calculations (Cooray, 1992).

3.4 Parameters used in Computing EM-Fields

Code is used to calculate LEMPs, for a typical observation point at a height, "z"= 10 m above the ground plane and at radial distances of "r"= 500 m to 100 km from the lightning channel in discrete steps. "Typical", first return and subsequent-return-strokes are characterised by their specific, important lightning current parameters are used (Rachidi et al., 2001) for the simulations. The finite ground condition is simulated with the worst case of finite ground conductivity of 0.0001 S/m. In the present simulation the return stroke velocity of the lightning current used are 130 m/µs (for FS) and 190 m/µs (for SS). The typical range of return stroke velocity, as stated in the literature, is c/3 to 2c/3; "c" being the velocity of light (Uman, 1988).

4. Results and Discussion

The simulation results of LEMPs for the typical observation point (z=10 m and r= 100 km) above the perfect ($\sigma = \infty$ S/m) and finitely ($\sigma = 0.0001$ S/m) conducting ground are given below.

The total e-field has static, induction and radiation as three components (Rachidi et al., 2001). Of these, induction and radiation fields are combined and are plotted, as they contribute to the indirect effect of lightning stroke. The third component, namely the static field, is separated and is not shown. At very close distances of 100 m or less from the lightning channel, both static and induction field components add to the radiation component. For distances 100 m and beyond, up to 1000 m both induction and radiation fields contribute to the peak. At distances above 1000 m, the fields are solely due to the radiation component (Master and Uman, 1984). From the point of view of indirect lightning influences, induction and radiation fields are of importance. Though their contributions are smaller (in magnitude and duration), they are responsible for induced over voltages in the coupled objects illumined by em-fields (Master and Uman, 1984). In the region of interest of present study (500 m to 100 km from the lightning channel) both induction and radiation components are computed for "typical" first-return-stroke and subsequent-return-stroke. To validate the code implemented in this study, the authors have successfully reproduced some of the results of electric fields available for subsequent return stroke as given by Moini et al. (2000). Further, the same code is used for numerical experimentation discussed in the subsequent sections.

4.1 Ground with Infinite Conductivity

Perfect ground is the one with infinite ground conductivity. For such a perfect ground, the variation of vertical and horizontal components of electric field corresponding to first and subsequent strokes are as shown in Figures 2 and 3, respectively. These are for a typical observation point (z = 10 m and r = 100 km), above the perfect ground. The code can also be used to compute the variation of the azimuth component of magnetic field at this or any observation point.

The results presented in Figures 2 and 3 which give computed electric field, as far as the general trend of these graphs are concerned, are in good agreement with those of Rakov and Dulzon (1991). The important observation based on comparisons of peaks of these plots is that the field peak is larger for the first-return-stroke than that of subsequent return stroke. It is nearly 2 times large for FS when compared to SS. These simulation results of FS/SS ratio match well, in general, with those of field-measured-data that are reported by several authors (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008).

The purpose of present study is solely to compare the severity of typical first-return-stroke to that of typical subsequent return stroke through simulation. Hence, the

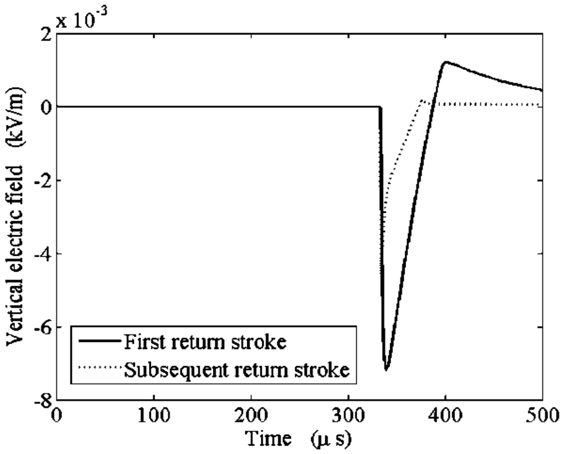

Figure 2. Vertical component of electric field due to first and subsequent return stroke above the perfectly conducting ground at z=10 m, r=100 km, obtained using MTLL model

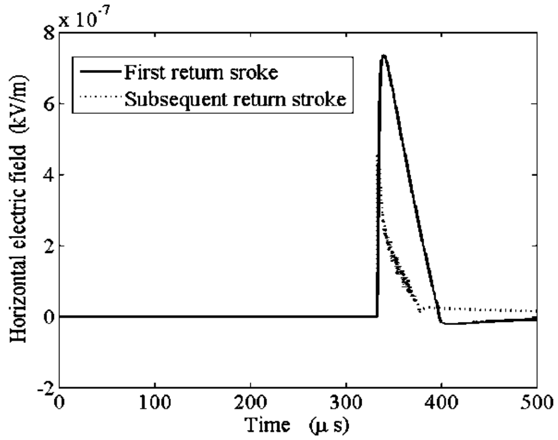

Figure 3. Horizontal component of electric field due to first and subsequent return stroke above the perfectly conducting ground at z=10 m, r=100 km, obtained using MTLL model

FS/SS ratio at different radial distances from the lightning channel is computed. Figure 4 gives both horizontal and total electric field ratios of FS/SS, thus computed. The computed results for plotting Figure 4 are obtained using the simulation model based on MTLL. A similar trend is observed with the MTLE model. The ratios of the vertical electric field to that of total electric field are nearly equal, as the magnitude of horizontal component is relatively quite small.

In spite of this fact, it is worth noting that, it is the horizontal component which is of importance in calculating the induced voltages due to field coupling with transmission lines (Agrawal et al., 1980; Paolone et al., 2009). These ratios of FS/SS obtained by simulations are lower for the total electric field compared to the horizontal electric fields. The FS/SS ratio for the horizontal component of the electric field is in the range of 1.5 to 2.8 and is a non-linear function of distance.

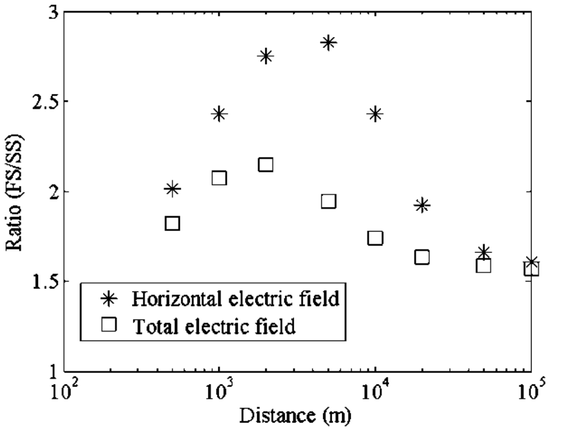

Figure 4. Ratio of first to subsequent return stroke electric field peaks as function of distance for the observation points at a height of z=10 m, above the perfectly conducting ground, obtained using MTLL model

The FS/SS ratio for the total electric fields is in the range of 1.5 to 2.2. Electric field strengths being a function of distance, these ratios are spread over a range. The field measurement results of FS/SS ratio, as discussed by several authors (Amitabh and Rakov, 2007; Amitabh et al., 2008; Schulz et al., 2005; Schulz and Diendorfer, 2006; Oliveira et al., 2007; Schulz et al., 2008), can be compared with those obtained by simulation. In general, the simulation results match well with the global average of experimental measurements, as discussed by Amitabh et al. (2008): These measurements were gathered through observations of actual lightning environment. Amitabh et al (2008) mention of some discrepancies in FS/SS ratio reported from different studies.

Paolone (2009) contends that the horizontal component of electric field is much smaller compared to the vertical component of electric field. Similar observations of smaller horizontal components could be made from the results of present simulations. The important additional observation from the present study is that, it is the horizontal component of the electric field, which is affected by the ground conductivity, although its contribution to the total electric field is smaller. The magnitudes of FS/SS ratios of the horizontal component of electric field, along with the total electric fields are presented in Figure 4. At any given radial distance from the lightning channel, the FS/SS ratio of the horizontal component is higher than that of the total electric field. Also, it should be noted that in both cases (horizontal and total) the ratio is greater than unity.

4.2 Ground with Finite Conductivity

The simulation results showing variation of horizontal electric fields, above a finitely conducting ground with worst case of conductivity (0.0001 S/m) are presented in

Figure 5, for an observation point (z = 10 m and r = 100 km). Horizontal electric fields due to "typical", first-return-stroke and subsequent-return-stroke are compared. From the simulation results corresponding to a typical observation point, the variation of horizontal electric fields are bipolar in nature which is in agreement with what has been reported by Cooray (2010), for a finite ground conductivity situation. It is to be noted that in Figure 5 (similarly in Figures 2 and 3) the initial delay of 325 µs (approximate) is due to the time taken to cover the radial distance up to the observation point.

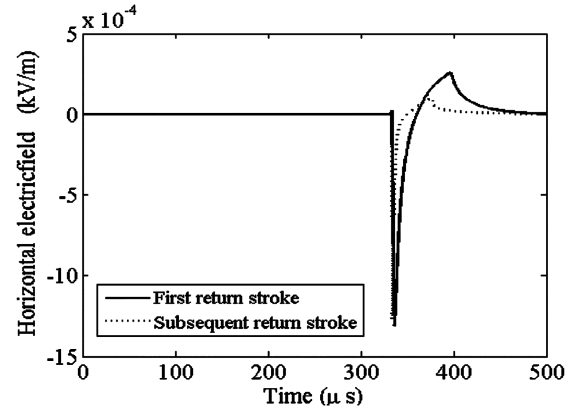

Figure 5. Horizontal electric field due to first and subsequent return stroke above ground at z=10 m, r=100 km for finitely (σg = 0.0001 S/m) conducting ground, obtained using MTLL model

The plot of FS/SS ratio of peaks of electric field for first to subsequent strokes obtained using the simulation code is as given in Figure 6. FS/SS ratio for both the total electric field and horizontal component of the electric field is given for the sake of comparison.

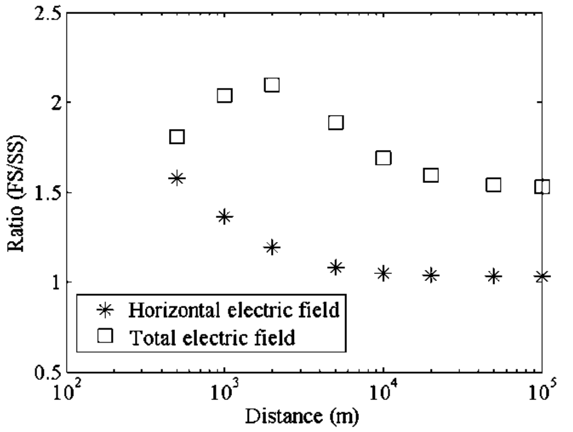

Figure 6. Ratio of first to subsequent return stroke electric field peaks as a function of radial distance (for the observation points at a height of z=10 m, above the ground plane) for finite ground conductivity (0.0001 S/m; worst case) obtained using MTLL model

It is the FS/SS ratio of horizontal component of electric field which is affected by the ground conductivity, and this ratio is lower than that of total electric field, unlike what is seen in Figure 4 (for perfectly conducting ground). The FS/SS ratio for the horizontal electric field is in the range of 1.0 to 1.5. It varies as a function of distance nonlinearly. Also, these FS/SS ratios (with worst case ground conductivity) are smaller compared to those of perfect ground (1.5 to 2.8).

Simulation results given in Figures 4 and 6 are useful in noting the effect of change in ground conductivity on first and subsequent lightning return strokes. They can be used to compare the effect of ground conductivity on the horizontal component of electric fields. The field peak obtained by summing induction and radiation components in the case of a finite ground situation is higher in magnitude when compared with infinitely conducting ground. Even for the case of subsequent-return-strokes, the field peak obtained by summing induction and radiation components is higher for finite grounds (see Figures 3 and 5).

One of the fundamental inferences from the present simulation is that the ground conductivity will affect the FS/SS ratio of the horizontal component of the field. Hence, terrains differing in their ground conductivities can influence and play a major role as far as the severity of return strokes and their indirect effects are concerned.

5.1 Electric field FS/SS ratios: Comparison of MTLL and MTLE model

In the literature apart from the MTLL (Rakov and Dulzon, 1991) model, the MTLE (Rachidi et al., 2001) model is also commonly used in calculations of LEMF. To compare the present simulation study more general FS/SS electric field ratios are computed by adopting the MTLE model as well. The comparisons of simulation results using both these models with specific reference to FS/SS ratio are given in Tables 1 and 2. The results (given in Table 1) compare for the perfect ground condition, whereas results (given in Table 2) compare the simulation results for a finitely conducting ground (σ_g= 0.0001 S/m). The FS/SS ratios being compared here are obtained by keeping the rest of the parameters identical for the two models.

The general trend of variation of FS/SS as a function of distance from the lightning channel for MTLE based model is similar to that of the MTLL model. The numerical values of FS/SS ratio for the MTLE model for both perfect ground (∞ S/m) and finite ground are lower compared to the MTLL model (from Tables 1 and 2). The differences in the numerical values are in the range of 0.05 % to 26 %. The variation is a non-linear function of distance (from the lightning channel).

Table 1. FS/SS ratios compared for MTLL and MTLE model for perfectly conducting ground

Distance (m)	FS/SS field ratio			
	For Peak of horizontal electric field		For Peak of total electric field	
	MTLL model	MTLE model	MTLL model	MTLE model
500	2.016	2.015	1.818	1.792
1000	2.430	2.414	2.070	1.938
2000	2.752	2.609	2.146	1.857
5000	2.828	2.333	1.945	1.608
10000	2.433	1.800	1.738	1.480
20000	1.921	1.547	1.635	1.430
50000	1.658	1.455	1.584	1.423
100000	1.605	1.411	1.571	1.392

Table 2. FS/SS ratios compared for MTLL and MTLE model for finitely (σ_g= 0.0001 S/m) conducting ground

Distance (m)	FS/SS field ratio			
	For Peak of horizontal electric field		For Peak of total electric field	
	MTLL model	MTLE model	MTLL model	MTLE model
500	1.576	1.481	1.808	1.765
1000	1.364	1.267	2.039	1.904
2000	1.191	1.116	2.096	1.811
5000	1.080	1.029	1.889	1.546
10000	1.048	1.000	1.690	1.440
20000	1.038	0.990	1.592	1.397
50000	1.034	0.983	1.539	1.367
100000	1.032	0.982	1.529	1.359

5.2 Induced over voltages

LEMFs couple with the nearby electrical and electronic systems induce over voltages. The induced over voltages depend on the orientation and vicinity of the system to which the LEMFs couple. As a typical case, induced over voltages due to coupling with a single conductor overhead line (with 1,000 m long, located at a height of 10 m from the ground) are computed using the simulated LEMFs (based on the MTLL model) due to typical first-return-stroke and subsequent-return-stroke. The lightning striking point is considered to be at a distance of 500 m from the line center and equidistance to the line termination. In computing the induced over voltages the field-to-overhead line coupling model by Agrawal et al. (1980) is adopted. The computed induced over voltage peaks are 16.36 kV and 8.7 kV for first-return-stroke and subsequent-return-stroke, respectively. These results are for the case of perfect ground conductivity. The induced over voltage peaks of first-return-stroke is 1.88 times that of subsequent-return-stroke.

6. Conclusion

Lightning return strokes severities of first and subsequent "typical" strokes are compared through the simulation process by adopting the MTLL model. These simulation results are compared with the field-measured-data available in the literature. The important observations are:

1) Both for perfect and finitely conducting grounds, the electric field intensity peaks due to first-return-stroke are higher compared to subsequent return strokes.
2) FS/SS ratios as obtained by the MTLL based simulation (range of values), match fairly well with the literature—reported, field-measured global averages.
3) The FS/SS ratio of the horizontal component of electric field intensity is lowered due to a decrease in ground conductivity (when compared to infinite ground conductivity situation). This implies terrains and the associated ground conductivities can affect the FS/SS ratio.
4) Simulation results of the MTLL based FS/SS are comparable with those from the MTLE based model.

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