LIGHTNING FIELD PEAKS RADIATED BY LIGHTNING TO TALL TOWERS

W.Schulz G.Diendorfer
OVE-ALDIS, Austria, Kahlenberger Str. 2A, A-1190 Vienna

Abstract - Recently Diendorfer et al. [2002] compared lightning peak currents measured at the Gaisberg tower with correlated lightning peak currents reported by the Austrian lightning location system ALDIS. They found a surprisingly good agreement between the measurements at the tower and the peak currents reported by the lightning location system (LLS).

These lightning strikes to the tower radiate higher field peaks due to the presence of two current wavefronts traveling in opposite directions when an elevated object is struck by lightning [Diendorfer and Uman, 1990]. Therefore also the peak currents reported by the LLS should be enhanced compared to lightning to flat ground.

In this paper we will show the reason why there is no significant enhancement in the LLS data. We will do this with the aid of a return stroke model for field calculation and taking into account finite ground conductivity along the propagation path. In addition the limited sensor bandwidth affects the value of measured peak field and therefore the inferred peak current of the strokes.

1 - INTRODUCTION

There are several effects which might influence the relation between the directly measured current at the tower and the corresponding current reported by the LLS:

- The height of the tower construction, because lightning striking an elevated object radiates higher field peaks due to the presence of two current wave fronts traveling in opposite directions [Diendorfer and Uman, 1990; Borghetti et al., 2003]
- Lightning current parameters (front duration)
- The return stroke velocity
- The applied signal normalization factor of the LLS
- The field attenuation along the traveling path from the tower to the sensors caused by finite ground conductivity
- The performance of the field measurement (bandwidth of the sensor)

In this paper we focus on the influence of the tower height. We show model based calculations of the tower enhancement and we will compare the peak current data recorded at the Gaisberg tower with data from the European LLS EUCLID (about 90 sensors during 2000-2002) and with data from the closest sensor to the Gaisberg tower.

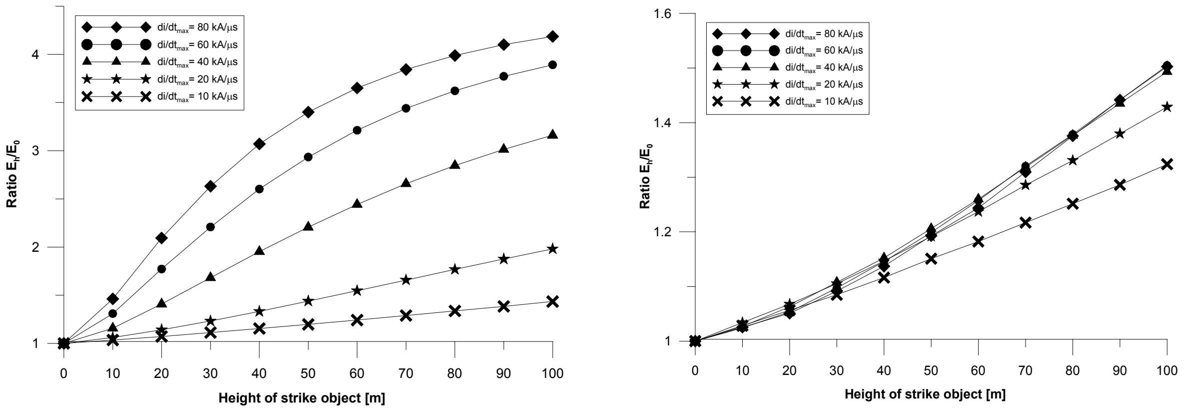
2 - NORTON APPROXIMATION

For the calculation of electromagnetic field propagation over ground of finite conductivity and with arbitrary heights of the transmitting and receiving antenna, it is mathematically distinguished between space wave (direct wave and ground reflected wave) and the surface wave [Norton, 1941]. In case both antennas, the transmitting and the receiving antenna, are located at ground level the direct wave and the ground reflected wave cancel each other and only the surface wave remains. For the application of lightning peak current calculation by LLS (cloud to ground strokes) only the first microseconds of the field are interesting. The length of the lightning channel that contributes to the radiated field (ground level up to the return stroke front) is therefore in the range of a few hundred meters (assuming a return stroke speed of about 10^8 m/s). The sensor is practically located at ground level. At distances interesting in lightning detection (>20km) these heights can be ignored and therefore only the surface wave is of interest.

For the case of flat earth (flat earth approximation) Norton [1936] presented an attenuation function for the surface wave taking into account finite ground conductivity and homogenous ground. The so called Norton flat-earth attenuation function A is given in Eq (1)

$$A = \left| 1 + j\sqrt{\pi p}\ e^{-p} erfc(-j\sqrt{p}) \right| \quad (1)$$

where p is the numerical distance and erfc is the complementary error function (see Norton [1936] for details). For the frequencies interesting in LF lightning location systems (1kHz - 400kHz) the flat earth approximation is only valid up to a distance of about 100km ($d_{\max}[km] = 80/(f[MHz])^{1/3}$ [Norton, 1942]). For larger distances the received signals attenuate more quickly because the curvature of the earth is neglected in the Norton approach. For those larger distances a comprehensive model has to take into account also the diffraction of the electromagnetic field.



A) B)

Fig. 1: Field enhancement as a function of height and di/dt when lightning strikes an elevated object (v_{rs}=1.3e8 m/s, τ_{bd}=0.3µs).
A) infinite ground conductivity and unlimited sensor bandwidth
B) Norton flat earth approximation at 100km distance and limited sensor bandwidth 1kHz – 350 kHz

3 - INFLUENCE OF THE TOWER HEIGHT AND LIGHTNING CURRENT STEEPNESS di/dt

We estimate the influence of the tower height with field calculations based on the Diendorfer-Uman (DU) return stroke model [Diendorfer and Uman, 1990]. In our calculations we ignore current reflections at the tower top and the tower base and we calculate fields over infinitely and finitely conducting ground. In the case of infinitely conducting ground the results of the relative field enhancements are independent of the distance to the stroke. In our calculations we use the lightning current waveform CURRENT 1 in Diendorfer and Uman [1990] and vary the front time constant of the breakdown current τ_{b1} to simulate different di/dt values. All di/dt values given in the following figures are maximum di/dt values.

Fig. 1 shows the field enhancement when lightning strikes an elevated object and the electromagnetic fields propagate over perfectly conducting ground. A return stroke speed of v_{rs}=1.3e8 m/s and a breakdown time constant of τ_{bd}=0.3µs are assumed for the field calculation with the DU model. Fig.1A shows the theoretical maximum enhancement when the finite ground conductivity and the sensor bandwidth are ignored whereas Fig.1B takes into account the finite ground conductivity and the limited sensor bandwidth. Field propagation over ground of finite conductivity is calculated with the Norton flat earth approximation for a conductivity σ=0.0033 S/m (corresponds to a ground resistance of 300 Ωm) and ε_r = 5. The sensor is modeled with a Butterworth bandpass filter of 2nd order with a lower cutoff frequency of f_l=1kHz and an upper cutoff frequency of f_u=350kHz, representing the frequency response of an IMPACT sensor.

In Fig. 1 E_0 is the reference field for an object of height h=0m and E_h is the field for an object of height h. It can be seen from Fig. 1A that with increasing di/dt the field enhancement due to the tower increases significantly. Fig.1B shows that taking into account the finite ground conductivity and the sensor bandwidth reduces the ratio E_h/E_0 significantly - especially for large di/dt values.

Because the radio tower at the Gaisberg has a height of 100m, we calculated the field enhancement for a 100m high tower for different di/dt values (Fig. 2). For a di/dt_{max} of 20 kA/µs and a 100m high tower our calculation results in a field increase of about 100% (E_{100}/E_0=2) when we ignore the finite ground conductivity and the sensor bandwidth. Even for small di/dt values as 20 kA/µs consideration of finite ground conductivity and limited sensor bandwidth reduces the enhancement to about 50% (40%) at a distance of 30km (100km). It can be further seen that for increasing distance the enhancement becomes almost independent of di/dt. A further decrease of the enhancement is expected for distances greater than 100km by including a spherical earth field propagation model.

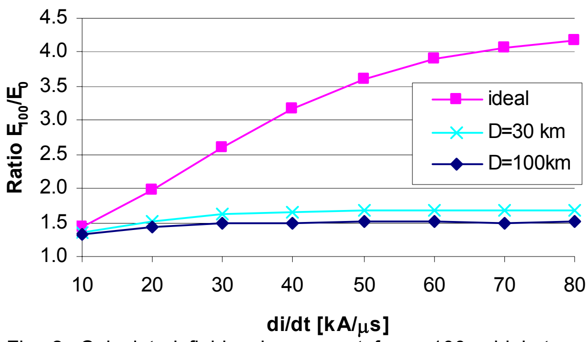
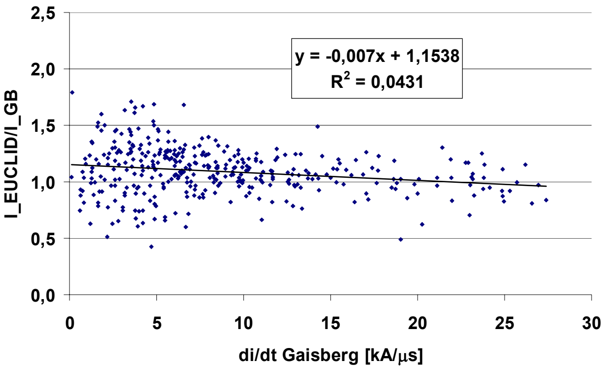
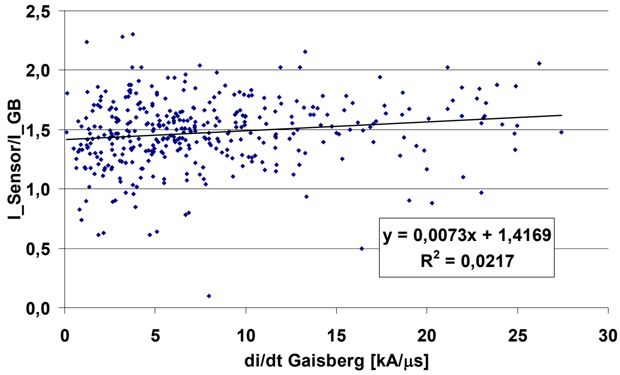


Fig. 2: Calculated field enhancement for a 100m high tower (v_{rs}=1.3e8 m/s, τ_{bd}=0.3µs) as a function of di/dt. Curves D=30km and D=100km are calculated with a conductivity σ=0.0033 S/m and ε_r = 5 and a filter representing the limited sensor bandwidth.



A)



B)

Fig. 3: Enhancement versus di/dt measured at the Gaisberg tower for peak currents inferred from A) all EUCLID sensors and B) peak currents inferred from sensor 1 data only (both calculated with a signal normalization factor of 0.23 and without applying an attenuation model)

4 – COMPARISON WITH REAL DATA

From the Gaisberg data of 2002 a mean di/dt_{max} of -7.5 kA/µs (maximum di/dt of the individual stroke waveshapes) was determined from the current measurements with the shunt. Comparing with our recently started direct di/dt measurements with higher bandwidth we get an agreement if we filter the di/dt measurement with a low pass with cutoff frequency of 500 kHz. If the cutoff frequency is increased to 5 MHz we also see reflections in the di/dt records and the di/dt_{max} increases to about 25kA/µs. This value is similar to values reported by Fuchs [1999] for measurements at the Peissenberg tower. For the small mean di/dt values observed at the Gaisberg the calculated field enhancement is almost independent of the peak current, the return stroke speed and the time constant τ_{bd} of the DU-model. In case of assuming infinite ground conductivity there is also no dependence on the distance.

To see if the effect of an increasing peak field enhancement for higher di/dt values is also evident in the real data we evaluated current data measured at the Gaisberg tower and compared them with correlated data from the EUCLID network and data from the sensor closest to the tower. Fig. 3 shows the ratio of the peak currents determined with the EUCLID network and the currents measured at the Gaisberg (I_{EUCLID}/I_{GB}) and the ratio of the peak currents inferred from sensor 1 and the currents measured at the Gaisberg (I_{Sensor}/I_{GB}) as a function of di/dt. Sensor 1 is the sensor of the network next to the Gaisberg tower at a distance of about 40km.

It is interesting to note from Figure 3 that there is no correlation between the enhancement and the di/dt measured at the Gaisberg tower for the EUCLID peak current I_EUCLID and the peak current determined from sensor 1 I_Sensor. This is similar to what the simulation in Figure 2 including ground conductivity and the sensor bandwidth showed. It is further interesting that there exists no field enhancement in the EUCLID data (Figure 3A). In Figure 3B it can be seen that the enhancement factor is about 50% for peak currents inferred from sensor 1. This is also in agreement with the calculations in Figure 2.

5 – SUMMARY

We have shown that based on calculations with the DU model, including the Norton flat earth approximation (σ=0.0033 S/m and ε_r = 5) and taking into account the limited bandwidth of the sensor, the tower theoretically enhances the electromagnetic field peaks in distances between 30km and 100km by about 30-40% for lightning currents with di/dt_{max} of about 10kA/µs. The simulations have also shown that there is only a small enhancement increase to about 50-60% for higher di/dt values. This enhancement increase is getting smaller for smaller ground conductivities.

In the available EUCLID data there is no evidence for such a peak enhancement with higher di/dt values (see Fig. 3A). Possible reason for this observation is more pronounced field attenuation over larger distances (>100km) because for propagation distances of up to 100km the calculations still show an enhancement between 30% and 50% (σ=0.0033 S/m and ε_r = 5). To include field propagation over large distances in a theoretical model the diffraction of the electromagnetic field over a spherical earth has to be taken into account. Further investigations are necessary to clarify this issue.

6 - REFERENCES

Borghetti A., C.A. Nucci, M. Paolone: Effect of Tall Instrumented Towers on the Statistical Distributions of Lightning Current Parameters and Its Influence on the Power System Lightning Performance Assessment, ETEP Vol. 13, No. 6, November/December 2003.

Diendorfer G. and Uman M.A.: An improved return stroke model with specified channel-base current. J. Geophys. Res. Vol. 95, No. D9, p. 13621-13644, 1990.

Diendorfer G., Hadrian W., Hofbauer F., Mair M., Schulz W.: Evaluation of Lightning Location Data Employing Measurements of Direct Strikes to a Radio Tower. CIGRE

Fuchs F.: Ströme und Nahfelder von Blitzeinschlägen in hohe Bauwerke als Störquelle für elektronische Systeme. Ph.D. Thesis, Universität der Bundeswehr München, 1999.

Norton K.A.: The propagation of radio waves over the surface of the earth and in the upper atmosphere Part 1. Proc. IRE, Vol. 24, 1936.

Norton K.A.: The calculation of ground wave field intensity over a finitely conducting spherical earth. Proc. IRE, Vol. 29, 1941.

Contact address:
Dr. Wolfgang Schulz
Austrian Electrotechnical Association (OVE)
Dept. ALDIS
Kahlenberger Str. 2A
A-1190 Vienna, Austria
E-mail: w.schulz@ove.at
Tel.: +43-1-3705806-212