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# NEW RESULTS IN THE ANALYSIS OF THE ELECTROMAGNETIC FIELD NEAR THE LIGHTNING CHANNEL

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## Abstract

Nowadays one of the most important areas of the lightning researches is in the centre of the interest, the protection of different low voltage systems, against the overvoltages caused by the lightening.

The so-called secondary lightning protection system protects against overvoltages caused by the lightening. To plan this system, we have to investigate the electromagnetic field of the lightning strikes and the manner in which it causes damages.

The published lightning electromagnetic field models suppose that the so-called static component is negligible, because it decreases proportionally with the third power of the distances.

The results presented in this publication prove that this assumption is not acceptable in the case of close lightning strikes.

It means that a lightning can cause larger electric fieldstrength in a few hundred meters distance than it was supposed. The electric fieldstrength can reach the amplitude that causes breakdowns, corona discharges, or damages of electronic parts. It can cause dangerous voltages even on a small metallic part, that behaves like an aerial.

These facts have to be considered during the planning of the secondary lightning protection systems.

*Keywords:* lightning protection, overvoltage, field strength.

## 1. Introduction

The protection of different low voltages systems, against the lightning caused overvoltages, is nowadays one of the most important areas of the lightning researches.

Considering the time constants of the lightning, the lightning phenomenon obviously is not quasi-stationary, but in practice quasi-stationary models are used because of calculation difficulties. The secondary lightning protection systems planned on this base, in some case function not properly.

Beyond the direct lightning strikes, the lightning caused electromagnetic field represents the main danger for us. To estimate the necessary level of the secondary lightning protection, we have to analyse this electromagnetic field.

To determine the characteristic parameters of the electromagnetic field of a lightning, it is evident to use a model that considers the lightning channel as an aerial excited by the lightning current, and we calculate the electromagnetic field of this aerial.

Firstly we have to determine the time and the length dependencies of the lightning current. In the literature the most widely used method for this purpose is the so-called TCS (Travelling Current Source) (HEIDLER F., 1985). This model was also used to plan the LLP (Lightning Location and Protection, LLP Inc., Martin UMAN, 1980) and the LPATS (Lightning Position and Tracking System, Atmospheric Research System Inc. 1981) lightning observation systems (Helga JÓHANNSDÓTTIR, 1993, Troels SORENSEN, 1995).

Secondly we have to calculate the electromagnetic field of the aerial, excited with the known current.

The assumption of the field calculation procedures, published in the literature, is that the static component of the so-called near field is negligible. In the case of the above mentioned lightning observation systems this assumption is acceptable, because the aim of these systems is to observe lightning far from the observation points. But I supposed that if we wanted to predict the electromagnetic field of lightning flowing down in a downconductor, or striking in few hundred meters, this assumption would not be acceptable.

Regarding this assumption, I've made a model, which is appropriate for calculating the complete electromagnetic field of a lightning. I've made the calculations, published in this article, with the help of this model to clarify the fieldstrength conditions near a lightning channel.

## 2. The Modified Model for Calculating the Electromagnetic Field of a Close Lightning

I originated the calculation of the fieldstrength to a straight aerial that is excited by the lightning current. To determine the time and the length dependencies of the exciting current I used the so- called TCS model, applying in the literature generally used lightning current wave form, which is a 8/20 $\mu s$ pulse wave.

My model determined the complete electromagnetic field of the aerial, without any neglects, thus the results can be used in the planning of the secondary lightning-protection systems also in case of close lightning strike.

In the present article we do not deal with the effect of the environment (artificial and natural).

Determining these effects requires further researches.

### *2.1. Determining the Current Distribution of the Aerial on the Base of the TCS (Travelling Current Source) Model*

From the point of view of the secondary lightning protection, the main danger is the electromagnetic field of the aerial excited by the current of the return strike. To determine the current distribution of the aerial I used the TCS model, published by HEIDLER (1985).

In this model the current of the return strike originates from the remaining charge delivered into the channel by the downward leader. This charge could be modelled as a line charge, where $q_0(z')$ is the distribution function of the charge. This charge will be recombined by the charge delivered by the current of the return strike.

As the name of the model shows, the return strike discharge is considered as the current of a current source that 'travels' on the top of the channel towards the thunder cloud.

In the TCS model the current of the return strike channel is described by the following function:

$$\begin{aligned} i(z \cdot t) &= i_0(t + z/c_0), \qquad z \leq h, \\ i(z \cdot t) &= 0, \qquad\qquad\quad z > h, \end{aligned} \tag{1}$$

where $h$ is the height of the return strike channel at the time $t$ and the $i_0(t)$ is the current of the striking point.

I considered the $i_0(t)$, as it is usual in the literature, as a wave with 8 $\mu$s rise time, and 20 $\mu$s half-time.

After describing the time and height function of the return strike channel's current, the next step is evaluating the electromagnetic field of the aerial, that represents the return strike channel.

### *2.2. Evaluating the Electromagnetic Field of a Near Lightning Strike*

In the suggested model an aerial represents the lightning channel. The evaluations of this aerial's electromagnetic field can be originated in evaluations the electromagnetic field of Hertz dipoles (Costantine A. BALANIS, 1997). The following equations write down the electromagnetic field of a Hertz dipole in sphere coordinates:

$$\begin{aligned} \overline{E}_r &= \frac{I_0 l}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \left[1 + \frac{1}{j \cdot \beta \cdot r}\right] \cdot \cos\vartheta \cdot \frac{e^{j(\omega t - \beta r)}}{r^2}, \\ \overline{E}_\vartheta &= \frac{I_0 l}{4\pi} \cdot \sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot j \cdot \beta \cdot \left[1 + \frac{1}{j \cdot \beta \cdot r} + \frac{1}{(j \cdot \beta \cdot r)^2}\right] \cdot \sin\vartheta \cdot \frac{e^{j(\omega t - \beta r)}}{r}, \\ \overline{E}_\rho &= 0; \end{aligned} \tag{2}$$

where $\beta = \omega \cdot \sqrt{\mu_0 \varepsilon_0}$.

The part that is proportional to $1/r^2$ is the so-called induction field, and the part that is proportional to $1/r^3$ is the static field of a Hertz dipole.

If $\beta r \gg 1$, we have to consider only the part, that is proportional to $1/r$. This represents the so-called far field of the dipole, the other parts can be neglected.

The neglected part will be one of the order of the far field, if the following relation is fulfilled:

$$r\beta \leq 1; \quad r\frac{\omega}{c} \leq 1; \quad r \leq \frac{c}{\omega}. \tag{3}$$

Based on the equation the $\omega = 3 \cdot 10^5$ 1/s frequency part of the lightning current spectrum in the range $r < 1000$ m cannot be considered as far field. We have to calculate also upon the static field and the induction field as well.

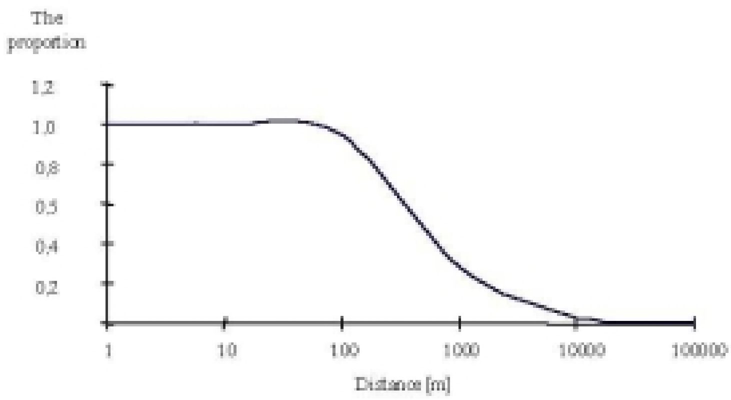


*Fig. 1.* The proportion of the near field and the complete field of a Hertz dipole ($\omega = 1 \cdot 10^6$ 1/s)

## 3. Results of the Model

In my calculation I used the 'standard' 8/20 $\mu$s current wave form. The peak value of the current was 50 kA (approximately 35% of all the lightning strikes are greater than this limit (HORVÁTH Tibor, 1980)). I neglected only the components of the spectrum, that were greater than $\omega = 10^6$ 1/s.

As it can be seen on the Bode diagram practically the complete spectrum ($\lambda \cong 1880$ m) was used. I assumed that the lightning channel was a vertical line. The time and height function of the lightning current was deducted from the TCS model.

The new feature of the model is that, exceeding the formerly used model, it does not neglect the static part of the near field.

The calculations were made in the frequency domain. With the help of the Fourier transformed exciting current, the complex amplitude of an elementary dipole's electromagnetic field, belonging to the wave length $\lambda$ component of the spectrum can be calculated with the following equations:

$$\begin{aligned}\overline{E}_\vartheta &= \frac{60\cdot\pi\cdot I_0}{\lambda r}dl\cdot\sin\vartheta\cdot\left[\cos\left(-\frac{r\cdot 2\cdot\pi}{\lambda}\right)+j\sin\left(-\frac{r\cdot 2\cdot\pi}{\lambda}\right)\right]\cdot\\ &\quad\cdot\left[j+\frac{\lambda}{r\cdot 2\cdot\pi}-j\left(\frac{\lambda}{r\cdot 2\cdot\pi}\right)^2\right],\\ \overline{E}_r &= \frac{60\cdot I_0}{r^2}dl\cdot\cos\vartheta\cdot\left[\cos\left(\frac{r\cdot 2\cdot\pi}{\lambda}\right)-j\sin\left(\frac{r\cdot 2\cdot\pi}{\lambda}\right)\right]\cdot\\ &\quad\cdot\left[1-j\frac{\lambda}{r\cdot 2\cdot\pi}\right].\end{aligned} \tag{4}$$

After the co-ordinate transformation, superpositioning the field of the dl length dipoles, we obtain the complex Fourier coefficient of the aerial's electromagnetic field, belonging to the wave length λ component of the spectrum.

$$\sum_l \overline{E}_{zdl}(j\omega_k)=\overline{E}_z(j\omega_k);\qquad \sum_l \overline{E}_{xdl}(j\omega_k)=\overline{E}_x(j\omega_k). \tag{5}$$

After the inverse Fourier transformation we obtain the $x$ and the $z$ component of the electromagnetic fieldstrength time function:

$$E_z(t)=\frac{1}{2\pi}\sum_k \overline{E}_z(j\omega_k)\cdot e^{-j\Delta\omega k\cdot t}\Delta\omega. \tag{6}$$

With the help of the two components we can easily solve the absolute value of the electric fieldstrength:

$$|E(t)|=\sqrt{E_z^2(t)+E_x^2(t)}. \tag{7}$$

The *Fig. 2* shows the time function of the absolute value of the electric fieldstrength, in 10 m distance from the lightning channel, at 50 m height (e.g. the top of a high building). In this case the absolute value of the electric fieldstrength exceeds the $10^6$ V/m.

The *Table 1* shows the peak value of the electric fieldstrength versus different current peak and in different distances. It can be seen that in the case of 50 kA current peak, the fieldstrength exceeds the $10^7$ V/m.

## 4. Measurement Results

RAKOV V.A., M.A. UMAN, R. THOTTAPPILLI, F. RACHIDI, M. RUBINSTEIN (1996) carried out an experimental research in California, with artificially triggered lightning. According to their publication in the observation point, 110 m far from the lightning channel, on the ground surface, the relation between the peak of the electric

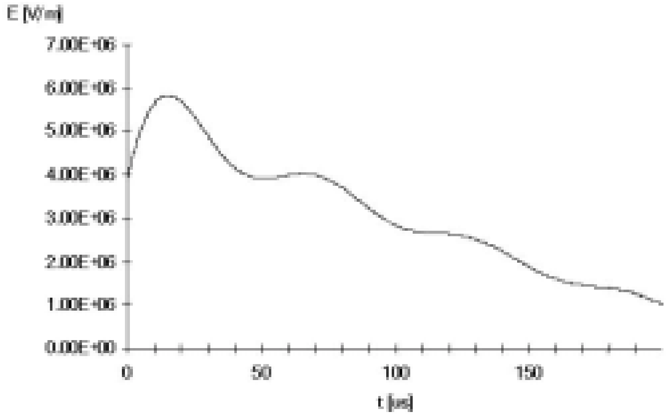


*Fig. 2.* The fieldstrength in 10 m distance from a 100 m long aerial at 50 m height

*Table 1.* The peak value of the electric fieldstrength

| The length of the aerial representing the lightning channel [m] | Distance from the channel [m] | The peak value of the lightning current [kA] | The peak value of the electric fieldstrength [V/m] |
|---|---|---|---|
| 10 | 10 | 50 | $2.9 \cdot 10^7$ |
| 10 | 50 | 50 | $2.0 \cdot 10^7$ |
| 10 | 50 | 13 | $1.3 \cdot 10^5$ |
| 10 | 30 | 13 | $7.3 \cdot 10^5$ |
| 250 | 50 | 13 | $2.9 \cdot 10^5$ |

fieldstrength and the peak current of the lightning channel can be approximated as follows:

$$E = (I + 0.73)/0.86, \tag{8}$$

where $I$ is the peak current of the lightning channel in kA, and $E$ is the measured electric fieldstrength in kV/m.

RAKOV V.A., M.A. ULMAN, (1994) report 250 V/m measured electric fieldstrength, 5 km far from the striking point, and 100 V/m in 6 km distance.

ZUNDL Th., F. FUCHS, Ch. HOPF, H. STEINBIEGLER (1996) in their publication report 3.1 kV/m electric fieldstrength, in case of 13 kA current peak, 200 m far from the lightning channel.

The published measurement results in comparison with the evaluated value can be seen on the *Table 2*. The *Table 3* shows the proportion of the measured value to the evaluated value.

On the base of *Table 2* and *Table 3* it can be established that the measured field-

*Table 2.* The measured fieldstrength in comparison with the evaluated value

| Distance [m] | Current peak [kA] | Complete electric fieldstrength calculated with the modified model | The measure fieldstrength | Calculated far field | Calculated induction field |
|---|---|---|---|---|---|
| 110 | 13 | 47 kV/m | 16 kV/m | 200 V/m | 12 kV/m |
| 110 | 50 | 184 kV/m | 60 kV/m* | – | – |
| 200 | 13 | 8.1 kV/m | 3.1 kV/m | 63 V/m | 1.1 kV/m |

* Extrapolation

strength is between the model predictions, calculated with the conventional model, which neglects the static field, and the fieldstrength containing both the static and the induction fields, calculated with the modified model.

So the measured fieldstrength is bigger than the fieldstrength calculated without the static field, in spite of the fact that during the calculation the effect of the ground was neglected.

When we judge the coincidence, we have to consider that the model neglects the effect of the environment. Thus we can suppose that the ground attenuates the amplitude of the electromagnetic wave.

It can be established that the model that neglects the static field, predicts smaller fieldstrength than the measured ones, thus the secondary lightning protection systems, based on these models, cannot be satisfying in the case of close lightning strike. It can also be established, that 110 m far from the channel, calculating with

*Table 3.* The proportion of the measured value to the evaluated value

| Distance [m] | Complete field/ measured field | Iduction field/ measured field | Far field/ measured field |
|---|---|---|---|
| 110 | 2.9 | 0.75 | 0.01 |
| 200 | 2.6 | 0.35 | 0.02 |

the mentioned 50 kA current peak, of the order of $10^5$ V/m electric fieldstrength occurs.

## 5. Summary, Results

A model was suggested for the analysis of the close lightning strikes. With the help of the model the electromagnetic field was investigated close to the lightning channel.

The lightning channel was considered as an aerial, excited by the lightning current. The distribution of the current was calculated on the base of the widely used TCS model.

The goal of the research was to establish the amplitude of the electric field-strength close to the lightning channel.

On the base of the model evaluations it can be established that the normally used neglect of the static field is not acceptable in these distances.

The results of the evaluation were compared with the results of RAKOV V.A., M.A. ULMAN, R. THOTTAPPILLI, F. RACHIDI, M. RUBINSTEIN (1996) and the results published by ZUNDL Th., F. FUCHS, Ch. HOPF, H. STEINBIEGLER (1996).

On the base of the model evaluation it can be established that close to the lightning channel the magnitude of the electric fieldstrength can exceed the $10^8$ V/m.

Two important consequences result from this.

As it is known, the breakdown fieldstrength of the air depends on the pressure, on the shape of the electrode, on the humidity, but under normal circumstances it is approximately $10^6$ V/m. It means, comparing with the results of the suggested model, that close to the lightning channel so great electric fieldstrength can occur, that in the worst case it can lead to breakdowns, corona discharge, and damaging of insulation materials.

We also have to take into consideration that in the case of this fieldstrength magnitude, on relatively small metal pieces – which behave like an aerial – (e.g. IC, or any conductors 'behind' the overvoltage protection) so high voltage can occur that damages the electronic component.

On the base of the results, it can be established that the electric fieldstrength, caused by a lightning strike, should be treated as a separate danger. The effect of the so-called static field cannot be neglected 1–2 km far from the lightning channel, and within a few hundred meters it is the main source of dangers.

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