Health effects of electromagnetic field generated by lightning current pulses near down conductors

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Abstract. The lightning current generates a time varying magnetic field near down conductors, when lightning strikes the connected Franklin-rod. The down conductors are mounted on the wall of buildings, where residential places can be situated. It is well known that the rapidly changing magnetic fields could generate dangerous eddy currents in the human body. If the duration and the gradient of the magnetic field were high enough, the peripheral nerves are excited. In this study, the authors introduce an improved model of the interaction of electromagnetic fields of lighting current near a down conductor with the human body. The interaction model has two parts: estimation of the magnetic fields surrounding the down conductor and evaluation of health effects of rapid changing magnetic fields on the human body.

1. Introduction
People may suffer electrical lightning injuries in different ways [1, 2]:
- Direct strike: The lightning current flows directly down through the human body.
- Contact injury: The person is contacted to a subject that is connected to the lightning.
- Side flash or splash: The lightning flash jumps to the human from a tree or a building.
- Ground current: The lightning strikes near the person and the finite conductivity of the ground causes potential differences and a dangerous step voltage can appear at the legs of the person.
- Upward streamer or leader: The leader does not attach to the main lightning discharge and a person who is a source of the leader can be shocked.

Besides these electrical injuries of lightning, the authors brought up another deleterious effect of a lightning strike [3]. The lightning current generates time varying magnetic fields near down conductors. The down conductors are mounted on the wall of buildings, where residential places can be situated. It is well known that rapidly changing magnetic fields can generate dangerous eddy currents in the human body and if the duration and the gradient of the magnetic fields are high enough, the peripheral nerves are excited. Gradient magnetic field having higher intensity can cause cardiac stimulation, which may result in fatal cardiac fibrillation.

In this article, an improved model of the interaction of electromagnetic fields of lighting current near down conductor with the human body is introduced. The interaction model has been improved in
its two parts: health effects of rapid magnetic fields on human body and estimation of the probability of the dangerous magnetic fields surrounding the down conductor.

2. Excitation of nerves by time varying magnetic fields

Many research groups have addressed interaction between a patient and time varying magnetic fields since the beginning of clinical application of magnetic resonance imaging systems. These studies have resulted in many interaction models, which have been summarized and published elsewhere [4].

The threshold level of excitation of nerves depends on the duration of stimulation, i.e. higher-level stimuli are needed for shorter exciting pulses. If a nerve is excited by a time-varying magnetic field this gradient field induces an electric field in it and this induced field can stimulate the nerve. For long gradient magnetic fields (\(\tau > 1\) ms) the minimum threshold is expressed by the time derivative of the magnetic flux density (dB/dt). If the impulse is shorter than 10 \(\mu\)s, the product of the impulse duration and intensity give the threshold for the nerve stimulation [5]. Between these time intervals, the threshold for nerve excitation depends on the duration of the stimuli. This rule of neurophysiology is summarized in a very simple hyperbolic formula, namely in the Lapicque-formula.

\[
\frac{dB}{dt} = \frac{b}{\tau} \left(1 + \frac{c}{\tau}\right)
\]

where \(b\) is the rheobase and \(c\) is the chronaxie, \(\tau\) is the duration of the stimulus. The rheobase is the asymptotic \(dB/dt\) for long duration stimuli and the chronaxie is the duration of the stimulus at which \(dB/dt\) is twice the rheobase (Fig. 1.). This formula can be used when the exciting duration is higher than tens of \(\mu\)s.

![Figure 1. Strength-duration curve of nerve stimulation by time-varying magnetic field](image)

3. The new interaction model

Calculations based on the first interaction model [3] show that the rising edge of the lightning current pulse can cause nerve excitations hence the magnetic field generated by the falling edge was not examined in this case.

In our new model, the probability of nerve excitation, which can lead to harmful heart fibrillation, has been examined as a function of distance from a down conductor, when lightning strikes the connected Franklin-rod. The investigation has two parts regarding the rise time of the lightning current:

- The rise time of the lightning current <10 \(\mu\)s: The product of the strength and the duration (dB/dt) has been used for a threshold, which was 0.19 T [4]. The case of positive and negative lightning have been also examined, since both polarities of lightning occurs in this time range.
- The rise time of the lightning >10 \(\mu\)s: the Lapicque-formula has been used for the calculations. These calculations have been made for positive lightning since only 5% of negative lightning has higher rise time than 28.6 \(\mu\)s, while the 50% of positive lightning has longer rise time than 35 \(\mu\)s. In this case, two rise times were calculated 35 \(\mu\)s for 50% probability and 250 \(\mu\)s for 5% probability [6]. For cardiac muscle 3 ms and 63 T/s were assumed for chronaxie and rheobase, respectively [7].
4. The magnetic field of lightning current surrounding down conductor
Assuming that the down conductor is filamentary and infinite, the following equation is valid for $dB/dt$:

$$\frac{dB}{dt} = \frac{\mu_0}{2\pi x} \frac{di}{dt}$$

(2)

where $di/dt$ is the time derivative of the lightning current and $x$ is the distance from down conductor. If the threshold $dB/dt$ is given, the corresponding threshold $di/dt$ can be calculated at distance $x$ from the down conductor by the arrangement of (2):

$$\frac{di}{dt} = \frac{2\pi x}{\mu_0} \frac{dB}{dt}$$

(3)

If the rise time is shorter than 10 $\mu$s, the product of $dB/dt$ and $\tau$ is the threshold for the excitation therefore, Eq. (3) can be simplified:

$$i = \frac{2\pi x}{\mu_0} B,$$

(4)

where $i$ is the peak current of lightning, and $B$ is the threshold.

5. Calculations
When lightning strikes the Franklin-rod, the gradient magnetic field surrounding the connected down conductor depends on the peak and the rise time of the lightning current. If the product of $dB/dt$ and $\tau$ is the threshold for excitation, the current peak determines the adverse health effects. The probability distribution of lightning peak current is described by a lognormal distribution. The parameters of lognormal distribution are in Table 1. according to the IEC 62305-1 standard.

| Polarity | Mean [kA] | $\sigma_{ln}$ |
|----------|-----------|--------------|
| $< 20$ kA | 61        | 1.33         |
| $> 20$ kA | 33.3      | 0.605        |
| +        | 33.9      | 1.21         |

Table 1. Lognormal distribution parameters of lightning current [6]

Table 2. The threshold current and probability of cardiac stimulation in the case of positive and negative lightning. Rise time $< 10\mu$s

| Distance [m] | Threshold current peak [kA] | Probability (+) | Probability (-) |
|--------------|-----------------------------|-----------------|-----------------|
| 0.1          | 95                          | 19.72%          | 4.16%           |
| 0.25         | 237.5                       | 5.38%           | 0.06%           |
| 0.5          | 475                         | 1.46%           | 0.00%           |
| 0.75         | 712.5                       | 0.59%           | 0.00%           |
| 1            | 950                         | 0.29%           | 0.00%           |

Table 2. The threshold current and probability of cardiac stimulation in the case of positive and negative lightning. Rise time $< 10\mu$s

5.1. The probability of excitation, when rise time is lower than 10 $\mu$s
The results of the calculations (Table 2, Figure 2) show that the probability of cardiac stimulations by the down conductor was quite high (>0.29%) when positive lightning strikes the Franklin-rod and the distance is less than 1 meter. The probability of this dangerous effect is negligible in the case of negative lightning strike if the distance from the down conductor was greater than 0.5 m. This requirement is generally satisfied in practical conditions.
5.2. The probability of excitation when rise time is higher than 10 $\mu$s

In this case, the thresholds ($dB/dt$) are determined by Eq. 1, and from Eq. 3 the threshold currents for stimulations can be calculated (Table 3).

Table 3. The threshold current of cardiac stimulation in the case of positive lightning. Rise time: 35 $\mu$s and 250 $\mu$s.

| Distance [m] | 0.1  | 0.25 | 0.5  | 0.75 | 1    |
|--------------|------|------|------|------|------|
| Threshold current peak (35 $\mu$s) [kA] | 95.6 | 239.0| 478.0| 717.0| 956.0|
| Threshold current peak (250 $\mu$s) [kA] | 102.4| 255.9| 511.9| 767.8| 1023.8|

The results of the calculations show that the threshold for cardiac stimulation does not depend on the rise time of the lightning current. This results from the heart muscle chronaxie, which is higher by one order of magnitude than the highest rise time of the lightning current.

6. Conclusion

The harmful effect of time varying magnetic fields generated by lightning current surrounding a down conductor has been investigated. The results show positive lightning strikes can generate cardiac muscle stimulation, which can lead to fatal cardiac fibrillation. Moreover, the analysis of different lightning current parameters bring out that the probability of this life threatening interaction does not depend on the rise time of the lightning current. This results from the excitation characteristic of heart muscle.

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