Transient interaction model of electromagnetic field generated by lightning current pulses and human body

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Abstract. The lightning current generates time-varying magnetic field near the down-conductor and the down-conductors are mounted on the wall of the buildings where residential places might be situated. It is well known that the rapidly changing magnetic fields can generate dangerous eddy currents in the human body.The higher duration and gradient of the magnetic field can cause potentially life threatening cardiac stimulation. The coupling mechanism between the electromagnetic field and the human body is based on a well-known physical phenomena (e.g. Faradays law of induction). However, the calculation of the induced current is very complicated because the shape of the organs is complex and the determination of the material properties of living tissues is difficult, as well. Our previous study revealed that the cardiac stimulation is independent of the rising time of the lightning current and only the peak of the current counts.

In this study, the authors introduce an improved model of the interaction of electromagnetic fields of lighting current near down-conductor and human body. Our previous models are based on the quasi stationer field calculations, the new improved model is a transient model. This is because the magnetic field around the down-conductor and in the human body can be determined more precisely, therefore the dangerous currents in the body can be estimated.

1. Introduction

Persons may suffer lightning injuries in different ways such as: direct strike, contact injury, side flash or splash, ground current, upward streamer or leader. Beside these electrical injuries there is another deleterious effect of lightning strike [1][2]. The lightning current generates time-varying magnetic fields near to the 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 [1]. Our previous investigations revealed that the cardiac stimulation is independent of the rising time of lightning current only the peak of the current counts [3].

In this article the time dependent effect of the lightning current in the down-conductor will be investigated. Upon these calculations the dangerous eddy currents in the human body estimated more precisely. To be able to estimate of the currents generated in the human body by the lightning pulse in the down-conductor it is also necessary to have knowledge about the electric and magnetic properties of the tissues in the body.

For the calculations the median current value of the lightning current was used. It is well known, that the positive lightning has higher energy because of the higher peak currents, and longer rising and decay times [2] [4]. In our case, the polarity of the lightning has no effect on the calculations because the induced field depends highly on the rising steepness of the current, therefore we used the current with the highest probability.

2. Effect of time-varying magnetic fields

The health effects of intense gradient magnetic fields have been investigated since the beginning of the diagnostic application of magnetic resonance (MR) systems. The patients of MR examinations are exposed to time-varying magnetic fields beside the static magnetic and radio-frequency fields. The physiological reactions of intense gradient magnetic fields are peripheral nerve stimulation, muscle movement, discomfort and cardiac stimulation. The interaction of time-varying magnetic field and the human body is based on the induced current according to the Faradays induction law. The induced current depends on the intensity of the gradient field, the circumference of the exposed organ and the conductivity of the tissue, obviously.

Many research have been addressed to reveal the 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 [5].

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 ($\mathrm{d}B/\mathrm{d}t$). If the impulse is shorter than 10 µs, the product of the impulse duration and intensity give the threshold for the nerve stimulation [6]. 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. At excitation of a tissue by a time-varying magnetic field, the threshold can be expressed as a time derivative of magnetic flux density ($\mathrm{d}B/\mathrm{d}t$):

$$\frac{\mathrm{d}B}{\mathrm{d}t} = b \cdot \left(1 + \frac{c}{\tau}\right) \tag{1}$$

where b is the rheobase and c is the chronaxie, τ is the duration of the stimulus. This formula can be used when the exciting duration is higher than tens of µs.

Based on this nerve excitation model and a simple calculation of magnetic field encircling the down-conductor, the adverse health effects can be easily estimated. The previous results of the authors have revealed that positive lightning strikes can generate cardiac muscle stimulation, which can lead to fatal cardiac fibrillation. Moreover, the analysis of different lightning current parameters revealed that the probability of this life threatening interaction does not depend on the rise time of the lightning current [2].

3. Description of the model

The interaction model is a simplified model. The down-conductor is a straight wire. As our previous calculations showed, that the closeness of the ground affects the intensity of the magnetic field. Namely the magnetic field decreases around the ground point. Hence, this phenomenon also decreases the deleterious effects near to the ground [3]. As first the human body is modelled by a cylinder having 60 cm of diameter and 70 cm height. The cubic measures of the selected cylinder are close to the measures of the human torso. The electric parameters of the cylinder have the same parameters as the human muscle. Both the relative permeability (μ_r) and relative permittivity (ε_r) are selected for 1 and the conductivity is set for $\sigma = 0.11$ [S/m]. These values are equal to the measured values of the human muscle tissue [7] .

The organs inside the body have different electric properties. The muscle tissue was chosen as the material for the model because the body mainly consists of different muscles and the conductivity of the muscle tissue is also close to the conductivity of the nerve tissue.

The distance between the down-conductor and the closest point of the body model was set for 1 m in the calculation. The calculation uses a 1.2 µs rise time and 50 µs decay time lightning current pulse with 45 kA peek value. If the distance is higher than 1 m formation of dangerous effects in the human bodyis unlikely [2].

4. Results of the calculation

The down-conductor is not shown on the figures it is positioned outside the image, parallel to the right side. In the steady state model the eddy currents were calculated for 50 kA 50 Hz sinusoidal current. The results are shown in Figure 1. These calculations showed that the eddy currents are higher in parts located near to the down-conductor and decrease moving away from the down-conductor. Modelling the effects of the transient current – in other words calculating

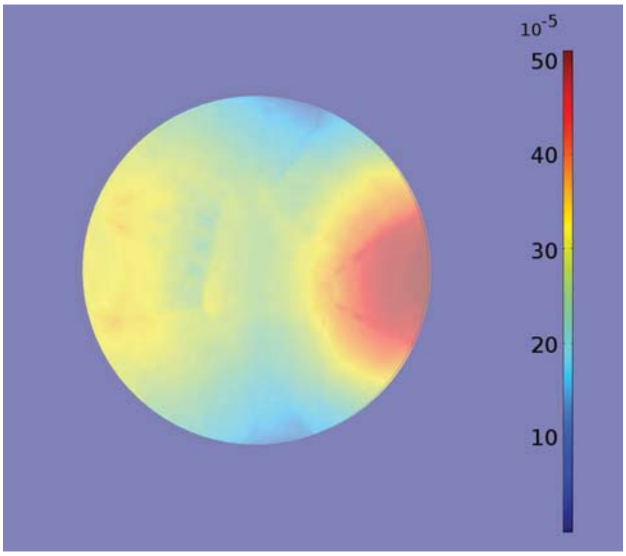

Figure 1. Calculated eddy currents in the model body (top view) for 50 Hz steady current. The measure for the calculated values is A/m^2

the eddy currents generated by a 1.2/50 current pulse with 45 kA peak value – the results are significantly different. The peak current density value is much higher and also the distribution differs a lot. On the top view in Figure 2 it is easy to observe the different current distribution compared to the steady state on Figure 1. In the transient case (Figure 2) the higher current density is located at the perimeters and the distance to the down-conductor has also an effect on the distribution. In the middle part of the model body the current density is much lower. On Figure 3 the calculated results are shown from a perpendicular plane (i.e. side view), where the skin effect caused by the rapidly changing current is clearly visible.

5. Conclusions

One of the dangerous effects of lightning strike is the magnetic field generated by the impulse current flowing in the down-conductor when a lightning strike hits the Franklin rod. There

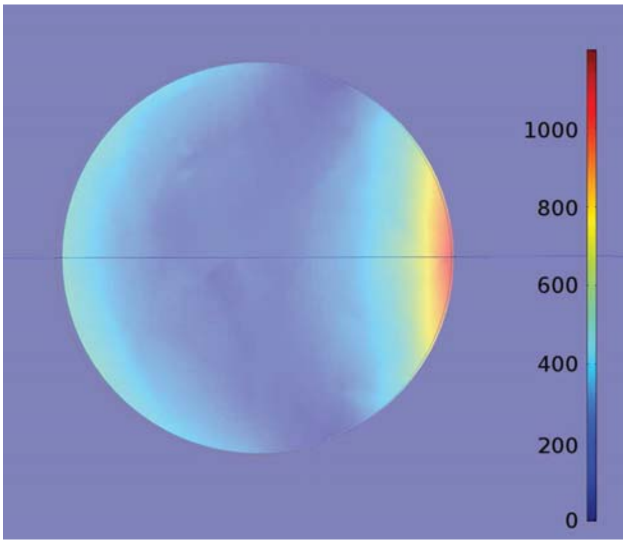

Figure 2. Calculated eddy currents in the model body (top view) for current pulse. The measure for the calculated values is A/m^2

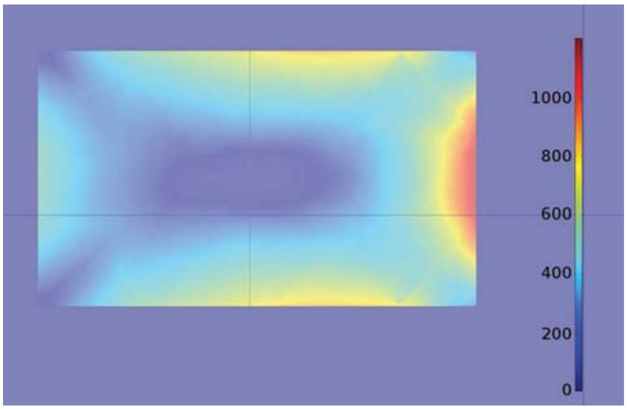

Figure 3. Calculated eddy currents in the model body (side view) for current pulse. The measure for the calculated values is A/m^2

are many factors which should be taken into consideration to determine the danger of the magnetic field around the down-conductor. The calculations showed that the pulse generated eddy currents inside the human body have an uneven distribution. The skin effect is not negligible; the currents on the surface of the body are higher than in the inner parts. Because of this in parts of the body the currents can be higher than the values calculated from the stationer model. Further investigations are needed about the different organs and how the electrical and magnetic parameters of the different tissues influence the eddy current distribution.

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