МАТЕРИАЛОВЕДЕНИЕ

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УЛУЧШЕНИЯ В РАСЧЕТАХ ЭЛЕКТРОМАГНИТНОГО ПОЛЯ МОЛНИИ С ИСПОЛЬЗОВАНИЕМ МОДЕЛЕЙ МОДИФИЦИРОВАННОЙ ЛИНИИ ПЕРЕДАЧ

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IMPROVEMENTS IN LIGHTNING ELECTROMAGNETIC FIELD COMPUTATION USING MODIFIED TRANSMISSION LINE MODELS

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Представлены модели модифицированной линии передач для ударов молнии, факторы затухания тока в канале и канальные функции тока. Для расчета электромагнитного поля молнии используются модели, основанные на электромагнитной теории, а также аппроксимация канала молнии с использованием тонких проводников. Для того чтобы получить сходимость с экспериментальными результатами, предложены две новых модели и трёх-пиковые канальные функции тока. Результаты были сравнены с результатами, полученными с помощью модели модифицированной линии передач с линейным разложением, и с результатами модели модифицированной линии передач с экспоненциальным разложением. Лучшее согласование с экспериментальными данными было получено в зависимости от расстояния до основного канала.
Ключевые слова: расчет электромагнитных полей, инженерные модели, удар молнии, модифицированная линия передачи

Some modified transmission line models of lightning return strokes, their channel current attenuation factors and channel-base current functions are presented in this paper. These models, electromagnetic theory relations and thin wire approximation of a lightning channel are used for lightning electromagnetic field (LEMF) computation. Two new models together with the three-peaked channel-base current function are proposed in order to obtain the features noticed in experimental LEMF results. Their results are compared to results obtained by using Modified transmission line model with linear decay (MTLL) and Modified transmission line model with exponential decay (MTLE). Better agreement with measurements is obtained at different distances from the channel-base.
Keywords: electromagnetic field computation, engineering models, lightning strokes, modified transmission lines

1. Introduction

Modified transmission line models are engineering models used to represent lightning strokes so that lightning induced effects on objects, electrical installations and equipment can be estimated and protective measures can be taken. A model is better than other if it better achieves experimental results for lightning electromagnetic field (LEMF) components and satisfies more of the noticed features in their waveshapes at different distances from the channel-base, so as measured channel-base currents.

A review of lightning return stroke models is given in [1], so as results of their application on lightning electromagnetic field computation [1,2]. Calculated LEMF results of the models given in literature significantly differ from experimental results [3-6] at different distances from the lightning channel base as usually used for comparison. Some features of LEMF waveshapes [1] are obtained with some of the models, whereas others are not. As an engineering model assumes, the current along the channel which includes the channel-base current function and the channel-current attenuation factor, consequently, results depend on the choice of both. Relevant parameters are also the channel height and return stroke speed. The simplest way to calculate LEMF is to assume that the lightning channel is vertical and the ground is perfectly conductive. One-peaked functions are usually used for channel-base currents as defined in IEC 62305 standard for the first and subsequent negative strokes and first positive strokes. However, currents with two dominant peaks are noticed in experimental results for the first negative strokes at Monte San Salvatore [5] and at Morro do Cachimbo Station [6]. Two new models give LEMF results in better agreement with the measured for the first and subsequent negative strokes [4].

After presenting some engineering models and their attenuation factors, channel-base currents functions are given in this paper. One-, two-, three- and multi-peaked functions were proposed in [7-10]. LEMF results of the four modified transmission line models at different distances from the channel-base, obtained for the same three-peaked channel base current, are compared.

2. Engineering Models of Lightning Strokes

An engineering model is characterized with the current $I(z',t)$ at the time t and the height z' above the channel base, decaying from the channel-base current $I(0,t)$ with the attenuation factor $P(z',t)$ while propagating along the channel:

$$I(z',t) = h(t-z'/v_f)\, I(0,t-z'/v)\, P(z',t). \qquad (1)$$

In this equation $h(t-z'/v_f)$ is the Heaviside function (with zero value for $t < z'/v_f$ and 1 for $t > z'/v_f$). The current is propagating along the channel with the current pulse propagation speed v and return stroke speed v_f.

Current attenuation factors in the often used engineering models are presented in Table, together with factors for the two new models MTLT and MTLTQ. These models are denoted with MTLT and MTLTQ suggesting for modified transmission line model with the attenuation factor being the third degree of the linear function (MTLT) and quadratic function of the same expression (MTLTQ). In MTLT model the attenuation factor is $P(z') = [1 + (1-2z'/H)^3]/2$, and in MTLTQ this factor is $P(z') = [1 + (1-2z'/H)^3]^2/4$, or simply $P_{\mathrm{MTLTQ}} = P_{\mathrm{MTLT}}^2$. These factors overtake some advantages of MTLL and MTLE models, but give better results in LEMF calculations. In MTLT the current peak near the channel base decays faster than in MTLL, so as in MTLTQ faster than in MTLE, but slower for greater heights above the ground and closer to the channel end.

Transmission line model (TL) has no attenuation, and in the equation for this engineering model the attenuation factor is taken as $P(z') = 1$.

Parameters of some engineering models of lightning return strokes

Engineering model	Attenuation factor	Channel current	Current pulse propagation speed
TL	1	$I(0,t-z'/v)$	v_f
MTLL	$1-z'/H$	$I(0,t-z'/v)\,P(z')$	v_f
MTLE	$\exp(-z'/\lambda)$ $\exp(-z'/H)$	$I(0,t-z'/v)\,P(z')$	v_f
MTLT	$[1+(1-2z'/H)^3]/2$	$I(0,t-z'/v)\,P(z')$	v_f
MTLTQ	$[1+(1-2z'/H)^3]^2/4$	$I(0,t-z'/v)\,P(z')$	v_f
BG	1	$I(0,t)$	∞
TCS	1	$I(z',t+z'/c)$	$-c$

Modified transmission line models (MTL) have various attenuation factors such as: linear in MTLL, exponential in MTLE, or some other function in MTLD introducing distortion of the current along the channel which may depend on both height and time $P(z',t)$. There is no attenuation of the current peak in Bruce-Golde (BG) model and traveling current source (TCS) model. The attenuation factors for all these models are given in Fig.1.

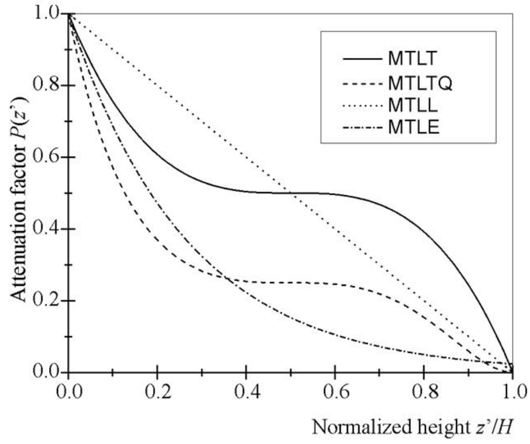


Fig.1. Attenuation factors in modified transmission line models

In MTLL the peak of the current pulse decays linearly while the current is propagating along the channel, so that $P(z') = 1-z'/H$. In MTLE the peak of the current pulse decays exponentially, so that $P(z') = \exp(-z'/\lambda)$, with the usually taken value $\lambda = 2000$ m for this constant. For $H = 7500$ m this attenuation factor is taken as $P(z') = \exp(-7500z'/2000H) = \exp(-3.75\, z'/H)$ in Fig.1, so to compare it with others for the normalized height z'/H.

3. Channel-base Currents

In most of the papers one-peaked functions are used for LEMF calculations. Often used functions are double-exponential function (DEXP) [11] and Heidler's function [12].

DEXP function for the approximation of a channel-base current (at $z' = 0$) is given with

$$I(0,t) = I_m[\exp(-\alpha t) - \exp(-\beta t)], \qquad (2)$$

for constants α, β and the maximum current I_m. Heidler's function is given with

$$I(0,t) = \frac{I_m}{\eta} \frac{(t/\tau_1)^n}{(t/\tau_1)^n + 1} \exp(-t/\tau_2), \qquad (3)$$

for parameters τ_1 and τ_2, degree n, and the peak correction factor $\eta = \exp[-(\tau_1/\tau_2)(n\tau_1/\tau_2)^{1/n}]$.

Heidler's function is also used in IEC 62305 for representation of the first and subsequent negative strokes and first positive strokes [13]. The ability of the channel-base current function NCBC to represent the IEC 62305 standard currents is demonstrated in [8], and its expression is

$$i(0,t) = \begin{cases} I_m \left(\dfrac{t}{t_m}\right)^a \exp\left[a\left(1-\dfrac{t}{t_m}\right)\right], & 0 \le t \le t_m, \\ I_m \displaystyle\sum_{i=1}^{n} c_i \left(\dfrac{t}{t_m}\right)^{b_i} \exp\left[b_i\left(1-\dfrac{t}{t_m}\right)\right], & t_m \le t < \infty \end{cases} \qquad (4)$$

for t_m the rise time to the maximum current value, whereas n is the number of terms in the decaying part, a and b_i are parameters, and c_i weighting coefficients, so that $\sum_{1}^{n} c_i = 1$.

Two-peaked currents measured in experiments at Monte San Salvatore [6] and at Morro do Cachimbo Station [7] are represented with the linear combination of seven Heidler's functions [14], but also with the two-rise front function (TRF) proposed in [9]. This function is given with the following expression:

$$i(t)=\begin{cases} I_{m1}\sum\limits_{i=1}^{m} d_i\left[\dfrac{t}{t_{m1}}\exp\left(1-\dfrac{t}{t_{m1}}\right)\right]^{a_i}, \ 0\le t\le t_{m1}, \\ I_{m1}+I_{m2}\sum\limits_{i=1}^{l} f_i\left[\dfrac{t-t_{m1}}{t_{m2}-t_{m1}}\exp\left(1-\dfrac{t-t_{m1}}{t_{m2}-t_{m1}}\right)\right]^{b_i}, \ t_{m1}\le t\le t_{m2}, \\ (I_{m1}+I_{m2})\sum\limits_{i=1}^{n} g_i\left[\dfrac{t}{t_{m2}}\exp\left(1-\dfrac{t}{t_{m2}}\right)\right]^{c_i}, \ t_{m2}\le t<\infty, \end{cases} \tag{5}$$

for parameters a_i, b_i, c_i, and weighting coefficients d_i, f_i, g_i, so that $\sum_1^m d_i=\sum_1^l f_i=\sum_1^n g_i=1$.

Three-peaked function (TPF) given in [10] is used in this paper for LEMF calculation as:

The advantages of these functions are analytically calculated first derivative and integral needed for LEMF calculations in the case of perfectly conducting ground. Fourier transform is needed for calculations above lossy ground, and it is also analytically calculated for (4), (5) and (6). The integral of the square of the CBC function is needed for calculating specific energy of lightning strokes, as in [16].

$$i(t)=\begin{cases} I_{m1}\sum\limits_{i=1}^{j} e_i\left[\dfrac{t}{t_{m1}}\exp\left(1-\dfrac{t}{t_{m1}}\right)\right]^{a_i}, \ 0\le t\le t_{m1}, \\ I_{m1}+I_{m2}\sum\limits_{i=1}^{k} f_i\left[\dfrac{t-t_{m1}}{t_{m2}-t_{m1}}\exp\left(1-\dfrac{t-t_{m1}}{t_{m2}-t_{m1}}\right)\right]^{b_i}, \ t_{m1}\le t\le t_{m2}, \\ I_{m1}+I_{m2}+I_{m3}\sum\limits_{i=1}^{l} g_i\left[\dfrac{t-t_{m2}}{t_{m3}-t_{m2}}\exp\left(1-\dfrac{t-t_{m2}}{t_{m3}-t_{m2}}\right)\right]^{c_i}, t_{m2}\le t\le t_{m3}, \\ (I_{m1}+I_{m2}+I_{m3})\sum\limits_{i=1}^{n} h_i\left[\dfrac{t}{t_{m3}}\exp\left(1-\dfrac{t}{t_{m3}}\right)\right]^{d_i}, \ t_{m3}\le t<\infty, \end{cases} \tag{6}$$

for parameters a_i, b_i, c_i, d_i, weighting coefficients e_i, f_i, g_i, h_i, and j, k, l, n the number of terms chosen for approximation in the corresponding time interval, so that $\sum_1^j e_i=\sum_1^k f_i=\sum_1^l g_i=\sum_1^n h_i=1$, which simplifies the current approximation procedure.

Parameters of (6) to approximate experimental results from [15] are the following: the first current peak $I_{m1}=11$ kA at $t_{m1}=2\mu s$, the second peak $I_{m1}+I_{m2}=8.3$ kA at $t_{m2}=22\mu s$, and the third current peak $I_{m1}+I_{m2}+I_{m3}=4.4$ kA at $t_{m3}=110\mu s$, whereas other parameters are: $a_1=2.2$, $a_2=0.5$, $e_1=0.37$, $e_2=1-$ e1, $b_1=2$, $b_2=0.5$, $f_1=0.9$, $f_2=1-f_1$, $c_1=2$, $g_1=1$, $d_1=5$, $d_2=0.55$, $h_1=0.6$, $h_2=1-h_1$.

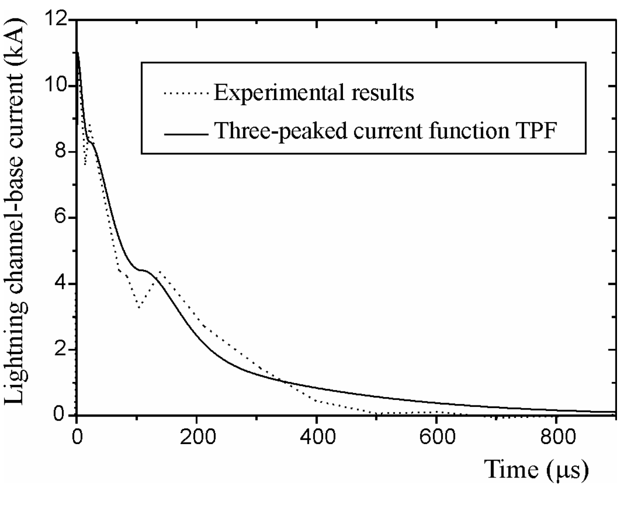


Fig.2. Lightning channel-base current TPF approximating the measured current [15]

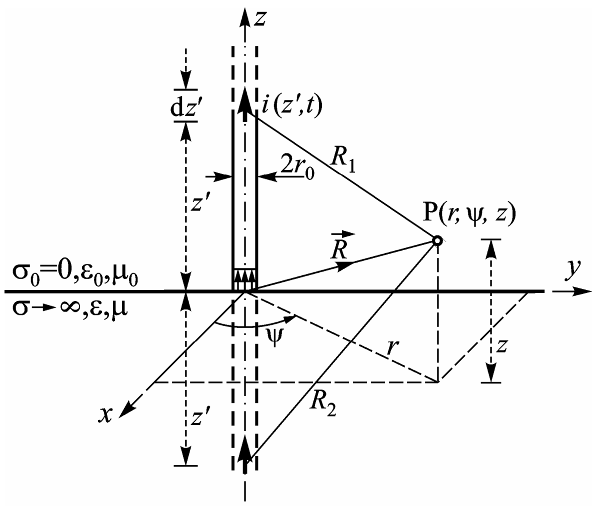
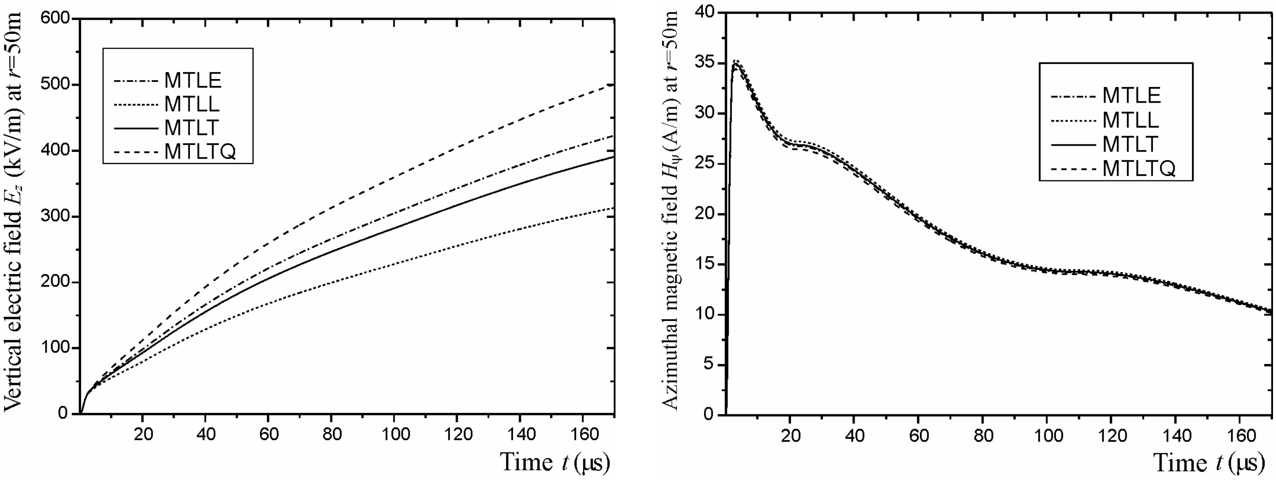


Fig.3. Lightning channel above perfectly conducting ground

4. LEMF Computation

A lightning channel is modeled as a thin wire antenna with the current propagating and decaying in peak while propagating above the ground from the channel-base towards the channel end, according to (1). The current image in plane mirror of the surface is used to substitute the influence of perfectly conducting ground for LEMF calculation in the upper half space, so as electromagnetic theory relations. At ground surface points electric field has vertical component and magnetic field just azimuthal component, whereas other components of electric and magnetic field do not exist.



a b

Fig.4. Vertical electric field (a) and azimuthal magnetic field (b) at r = 50 m from the channel-base

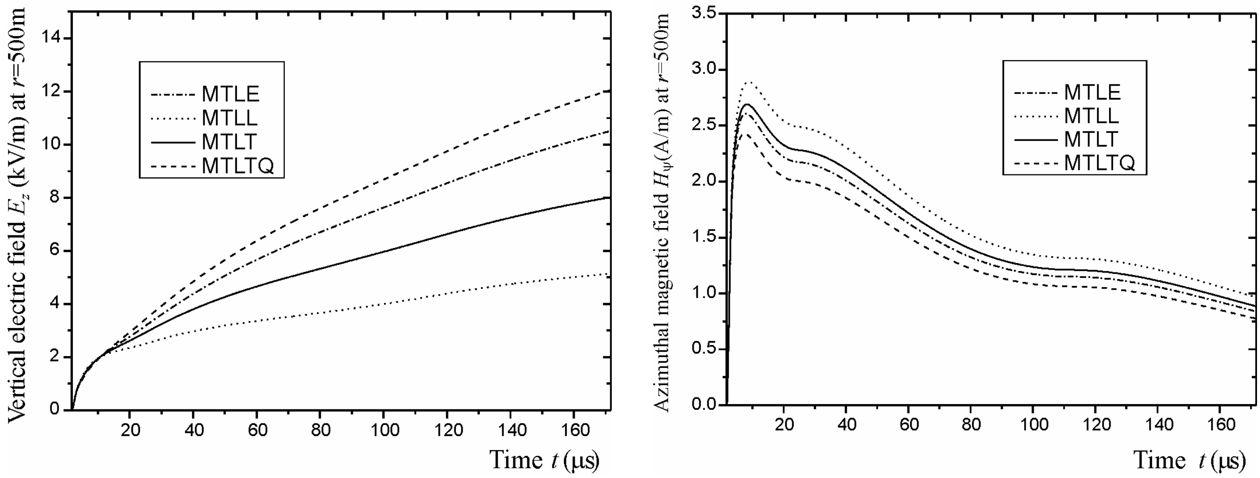


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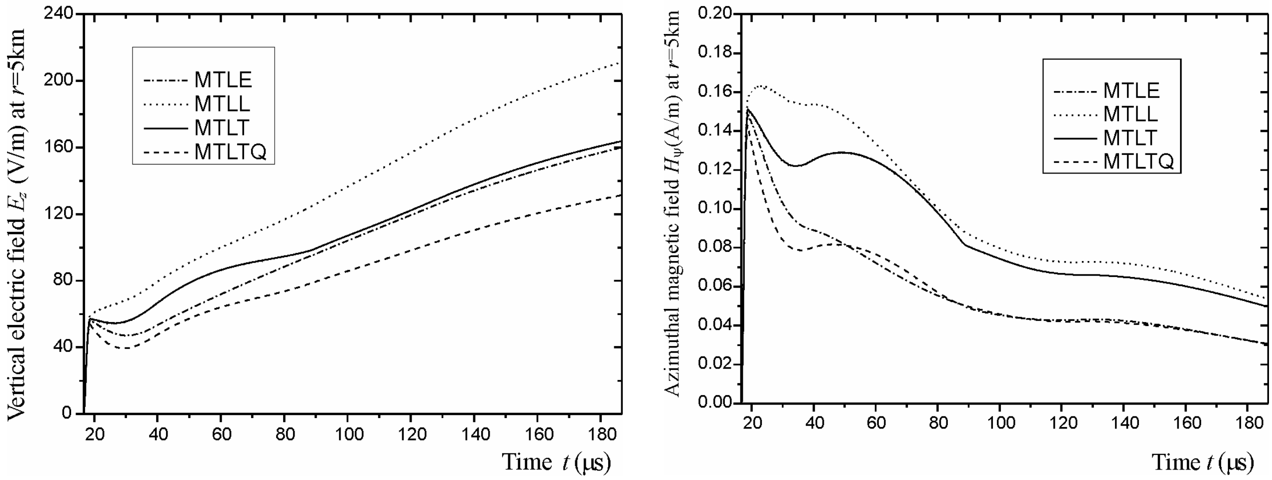
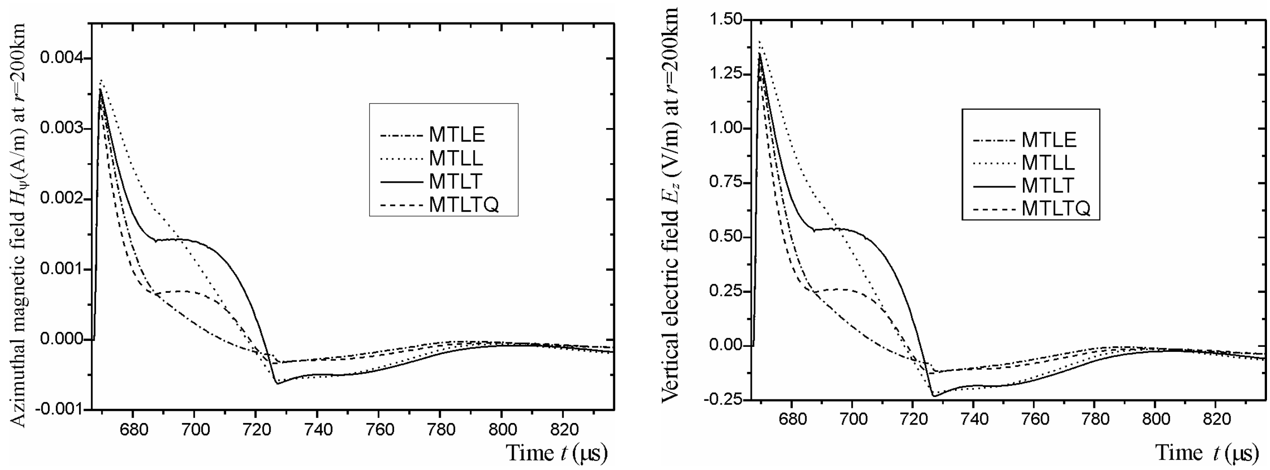
Fig.5. Vertical electric field (a) and azimuthal magnetic field (b) at r = 500 m from the channel-base



a b

Fig.6. Vertical electric field (a) and azimuthal magnetic field (b) at r = 5 km from the channel-base



a b

Fig.7. Vertical electric field (a) and azimuthal magnetic field (b) at r = 200 km from the c
annel-base

Vertical electric field at the ground surface can be calculated from

$$E_z(\vec{R},t)=\frac{1}{4\pi\varepsilon_0}\int_{-H}^{H}\left[\frac{2(z-z')^2-r^2}{R^5}\int_{\tau=0}^{\tau=t} i\left(z',\tau-\frac{R}{c}\right)d\tau+\right.$$

$$\left.+\frac{2(z-z')^2-r^2}{c\,R^4}i\left(z',t-\frac{R}{c}\right)-\frac{r^2}{c^2R^3}\frac{\partial i\left(z',t-\frac{R}{c}\right)}{\partial t}\right]dz', \quad (7)$$

and azimuthal magnetic field from

$$H_\psi(\vec{R},t)=\frac{1}{4\pi}\int_{-H}^{H}\left[\frac{r}{R^3}i\left(z',t-\frac{R}{c}\right)+\frac{r}{cR^2}\frac{\partial i\left(z',t-\frac{R}{c}\right)}{\partial t}\right]dz', \quad (8)$$

for R the distance from the elementary current source to the field point P(r,ψ,z).

Vertical electric field and azimuthal magnetic field at the distances of r = 50 m, 500 m, 5 km, and 200 km from the channel-base are calculated and presented in Figs.4-7. For 50 m the lightning electromagnetic pulse appears at t_1 = 1/6μs after the current pulse starts propagating from the channel base at t = 0. For 500 m this time is t_2 = 5/3μs, for 5 km t_3 = 50/3μs, for 200 km t_4 = 2000/3μs. All results are presented for the first 170μs of the pulse appearing at the corresponding distance.

5. Device for Registration of the Lightning Electromagnetic Field

Magnetoelectric (ME) composites that simultaneously exhibit ferroelectricity and ferromagnetism have been of recent research interest due to their potential for applications in multifunctional devices [17].

In contrast to the well known methods of registration of lightning we offer the use of device based on the ME effect which allows to measure both electric and magnetic components of the electromagnetic field [18]. The design of the sensor is shown in Figure 8.

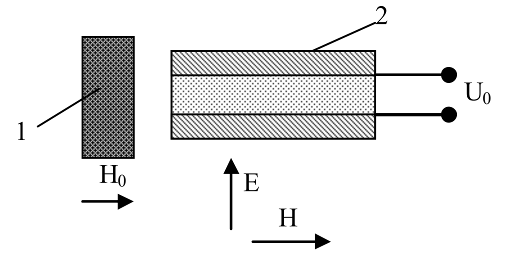


Fig.8. ME sensor of electromagnetic field, 1 — permanent bias magnet, 2 — ME sensor

The operation principle of this device is based on the direct ME effect. ME sensor consists of the piezoelectric layer of PZT and two magnetostrictive layers of Metglas, as shown in Fig. 8. Generated electric potential is measured on Metglas layers. At placing a sensor in the lightning electromagnetic field one obtaines the electric potencial on the output of the ME element due to direct ME effect. In order to set the correct mode activity of magnetostrictive material in ME element one needs to produce the bias magnetic field. This field is supplyed with the help of permanent bias magnet.

6. Conclusion

MTLT results are in better agreement with experimental results for the first return strokes, and MTLTQ results for subsequent return strokes. If using three-peaked channel-base current all models perform zero crossing in waveshapes of vertical electric and azimuthal magnetic field at far distances, a ramp in vertical electric field and a hump in azimuthal magnetic field at a few km. These features are noticed in experimental results. It should be noted that MTLL and MTLE do not result in a hump in azimuthal magnetic field at a few km if one-peaked channel-base currents are used.

These improvements in LEMF modeling are based on the assumption that far electric and magnetic field approximately follow the waveshape of the channel-base current. The influence of the return stroke speed and channel heights on LEMF results remains to be further studied. It was proposed the ME sensor for measuring of lightning electromagnetic field.

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1. Rakov V.A., Uman M.A. Review and evaluation of lightning return stroke models including some aspects of their application // IEEE Trans. Electromagn. Compat. 1998. V.40. №4. P.403-426.
2. Nucci C.A., Diendorfer G., Uman M.A. et al. Lightning return stroke current models with specified channel-base current: A review and comparison // J. of Geophys. Research. 1990. V.95. №D12. P.20395-408.
3. Berger K., Anderson R.B., Kroeninger H. Parameters of lightning flashes // Electra. 1975. V.41. P.23-37.
4. Lin Y.T., Uman M.A., Tiller J.A. et al. Characterization of lightning return stroke electric and magnetic fields from simultaneous two-station measurements // J. of Geophys. Research. 1979. V.84. P.6307-6314.
5. Anderson R.B., Eriksson A.J. Lightning parameters for engineering applications // Electra. 1980. V.69. P.65-102.
6. Visacro S., Soares Jr. A., Schroeder M.A.O., et al. Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbo station // J. of Geophys. Research. 2004. V.109. P.D01105.
7. Javor V. New functions for representing IEC 62305 standard and other typical lightning stroke currents // J. of lightning research. 2011. Ref. BSP-JLR-2011-4.
8. Javor V., Rancic P.D. A channel-base current function for lightning return-stroke modeling // IEEE Trans. Electromagn. Compat. 2011. V.53. №1. P.245-249.
9. Javor V. Approximation of a double-peaked channel-base current / COMPEL. 2012. V.31. №3. P.1007-1017. doi: 10.1108/03321641211209870.
10. Javor V. Multi-Peaked Functions for Representation of Lightning Channel-Base Current // 31st Int. Conference on lightning protection. Vienna, Austria, Sep. 2012. doi: 10.1109/ICLP.2012.6344384.
11. Golde R.H. Lightning currents and related parameters // Lightning. V.1. Physics of Lightning / Ed. R.H.Golde. L.: Academic press, 1977. P.309-350.
12. Heidler F. Travelling current source model for LEMP calculation // Proc. of 6th Int. Zurich Symp. EMC, Zurich, Switzerland. 1985. P.157-162.
13. Protection against lightning. Part I: General principles, IEC Std. 62305, 2006. 67 p.
14. De Conti A., Visacro S. Analytical Representation of single- and double-peaked lightning current waveforms // IEEE Trans. Electromagn. Compat. 2007. V.49. №2. P.448-451.
15. Delfino F., Procopio R., Rossi M., Rachidi F. Prony series representation for the lightning channel base current // IEEE Trans. Electromagn. Compat. 2012. V.54. №2. P.308-315.
16. Javor V. Parameters of lightning stroke currents defining their mechanical and thermal effects // 2012 IEEE Symposium on EMC: Proc. of papers. Pittsburgh, Pennsylvania, USA. Aug. 2012. Vol.1. P.334-339.
17. Nan C.-W., Bichurin M.I., Dong S.X., et al. Multiferroic magnetoelectic composites: Historical perspective, status, and future directions // J. Appl. Phys. 2008. V.103. P.031101:1-031101:35.
18. Soloviev I.N., Bichurin M.I., and Petrov R.V. Magnetoelectric Magnetic Field Sensors // Progress In Electromagnetics Research Symposium Proceedings. Moscow, Russia. Aug. 2012. P.1359-1362.