Evaluation of Lightning Location and Lightning Current Wave Shape Using Measured Lightning Magnetic Fields at Two Stations

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Abstract_ **In this paper, an algorithm is proposed to evaluate a lightning location as well as the lightning current wave shapes at different heights along a channel using lightning measured magnetic fields at two stations. The proposed algorithm is based on the captured return stroke part of the magnetic fields directly in the time domain. The proposed method can support different engineering current models and can also be developed for different distances. The proposed method can be helpful for creating lightning location and lightning current data banks as it can estimate the full shape of the current as opposed to the usual methods used previously.**

Keywords_ Lightning location, Lightning magnetic fields, Return stroke current

I. INTRODUCTION

The evaluation of a lightning location is one of the important issues for lightning mapping and also to consider the level of lightning risk for the protection of power systems. Several studies have been undertaken previously by various authors to evaluate lightning locations which are usually based on the time of arrival of a measured electric field (TOA), the values of measured electric fields at domain frequencies and the direction of the magnetic fields[1-7]. In addition, such studies usually consider the peak value of the current at the channel base. Moreover, some of the previous methods only consider the radiation components of the electric field that can be applied for far distances with respect to the lightning. Such methods have an inherent error at close and intermediate distances with respect to the lightning channel. Likewise, the selection of a return stroke current model is one of the important issues and the transmission line model (TL) is usually assumed in previous studies. On the other hand, the ground conductivity can play a very important role to change the electric field wave shape and it can create an inherent error when not considered as in some previous research in this subject. In this present study, the location of the lightning was evaluated using all components of the magnetic fields based on recorded data from two field stations whereby the effect of the ground conductivity on the magnetic field was negligible. Moreover, the proposed method uses the general form of the engineering current model and it estimates the full shape of the current wave shape at different heights directly in the time domain. The evaluated current and lightning location can be used for creating a data bank for use in lightning mapping and also for localising the necessary level of lightning protection required based on local information.

The basic assumptions in this study are listed as follows:

i. The lightning is a vertical channel without any branches.
ii. The general form of the engineering current model with unknown parameters is employed for modelling of current behaviour along the channel.
iii. The return stroke velocity was set to a constant value along channel that will be evaluated using the proposed algorithm.

II. LIGHTNING RETURN STROKE CURRENT

The lightning return stroke current can be considered in two areas as follows:

i. The channel base.
ii. Different heights along the channel above the surface of the ground.

The channel base current can be modelled using different current functions. In this study the sum of two Heidler functions is used for modelling of the current at the channel base as represented by Equation (1). On the other hand, the current wave shape at different heights along the channel can be modelled using different current models. In this work, the general form of the engineering current model with unknown parameters was selected for the study of the current behaviour at different heights along the channel as expressed by Equation (2)[8].

$$\mathrm{i}(0,\mathrm{t}) = [\frac{\mathrm{i}_{01}}{\eta_1}\frac{\left(\frac{\mathrm{t}}{\tau_{11}}\right)^{n_1}}{1+\left(\frac{\mathrm{t}}{\tau_{11}}\right)^{n_1}}\exp\left(\frac{-\mathrm{t}}{\tau_{12}}\right) + \frac{\mathrm{i}_{02}}{\eta_2}\frac{\left(\frac{\mathrm{t}}{\tau_{21}}\right)^{n_2}}{1+\left(\frac{\mathrm{t}}{\tau_{21}}\right)^{n_2}}\exp\left(\frac{-\mathrm{t}}{\tau_{22}}\right)] \quad (1)$$

$$i(z',t) = i\left(0, t - \frac{z'}{v}\right) P(z') U(t - \frac{z'}{v_f}) \quad (2)$$

Where:
$i(0,t)$ is the channel base current,
t is the time step,
i_{01} and i_{02} are amplitudes of the channel base current,
τ_{11} and τ_{12} are front time constants,
τ_{21} and τ_{22} are decay- time constants,
n_1 and n_2 are exponent (2~10),
$\eta_1 = \exp[-({}^{\tau_{11}}/{\tau_{12}})\left(n_1 \frac{\tau_{12}}{\tau_{11}}\right)^{\frac{1}{n_1}}]$,
$\eta_2 = \exp[-({}^{\tau_{21}}/{\tau_{22}})\left(n_2 \frac{\tau_{22}}{\tau_{21}}\right)^{\frac{1}{n_2}}]$.
z' is temporary charge height along channel,
v is return stroke current velocity along channel,
v_f is return stroke current velocity along channel,
$U(t - \frac{z'}{v_f})$ is Heaviside function.

In this study, the MTLE current model was used (P(z')=exp(-z'/λ)). However the proposed method can support other engineering current models.

III. LIGHTNING MAGNETIC FIELDS

The magnetic flux density at different distances with respect to the lightning channel can be evaluated using Equation (3) for which the geometry of the lightning channel with respect to the observation point is shown in Figure 1[9].

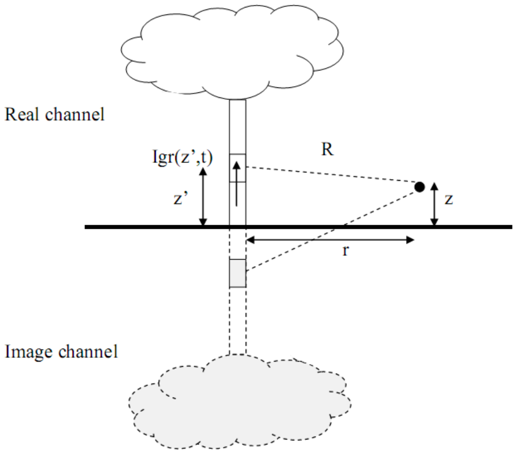

Figure.1.The geometry of lightning channel with respect to observation point

$$\overrightarrow{B_\varphi}(r,z,t_n) = \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_i(r,z,t_n,h_{m,i}) - a'_m F_i(r,z,t_n,h'_{m,i})\} \quad (3)$$

Where:

$\overrightarrow{B_\varphi}(r,z,t)$ is the magnetic flux density,
z is height of observation point,
r is radial distance from lightning channel,
β=v/c,
$\chi = \sqrt{\frac{1}{1-\beta^2}}$,

$$t_n = \frac{\sqrt{r^2+z^2}}{c} + (n-1)\Delta t \qquad n = 1,2,\dots,n_{max}$$

$$\Delta h_i = \begin{cases} \beta\chi^2\{(ct_i - ct_{i-1}) - \sqrt{(\beta ct_i - z)^2 + (\frac{r}{\chi})^2} + \sqrt{(\beta ct_{i-1} - z)^2 + (\frac{r}{\chi})^2}\} \\ \beta\chi^2\left\{-(\beta z - ct_i) - \sqrt{(\beta ct_i - z)^2 + \left(\frac{r}{\chi}\right)^2}\right\} \quad \text{for } i = 1 \end{cases}$$

$$\Delta h'_i = \begin{cases} \beta\chi^2\{(ct_{i-1} - ct_i) + \sqrt{(\beta ct_i + z)^2 + (\frac{r}{\chi})^2} - \sqrt{(\beta ct_{i-1} + z)^2 + (\frac{r}{\chi})^2}\} \\ \beta\chi^2\left\{-(\beta z + ct_i) + \sqrt{(\beta ct_i + z)^2 + \left(\frac{r}{\chi}\right)^2}\right\} \quad \text{for } i = 1 \end{cases}$$

$$h_{m,i} = \begin{cases} \frac{(m-1)\times\Delta h_i}{k} + h_{m=k+1,i-1} \\ \frac{(m-1)\times\Delta h_i}{k} \quad \text{for } i = 1 \end{cases}$$

$$h'_{m,i} = \begin{cases} \frac{(m-1)\times\Delta h'_i}{k} + h'_{m=k+1,i-1} \\ \frac{(m-1)\times\Delta h'_i}{k} \quad \text{for } i = 1 \end{cases}$$

$$R_m = \sqrt{r^2 + (z - h_{m,i})^2}$$

$$F_i(r,z,t_n,h_{m,i}) = \left(\frac{\mu_0}{4\pi}\right)\left\{\begin{array}{l} \frac{r}{{R_m}^3} i\left(h_{m,i}, t_n - \frac{R_m}{c}\right) + \\ \frac{r}{c{R_m}^2}\frac{\partial i\left(h_{m,i}, t_n - \frac{R_m}{c}\right)}{\partial t} \end{array}\right\}$$

$$a_m = \begin{cases} \frac{\Delta h_i}{2\times k} & \text{for } m = 1 \text{ and } m = k+1 \\ \frac{\Delta h_i}{k} & \text{for others} \end{cases}$$

$$a'_m = \begin{cases} \frac{\Delta h'_i}{2\times k} & \text{for } m = 1 \text{ and } m = k+1 \\ \frac{\Delta h'_i}{k} & \text{for others} \end{cases}$$

IV. INVERSE PROCEDURE ALGORITHM

Two magnetic field sensors were set at two known positions with related coordinates (x_1,y_1) and (x_2,y_2), respectively as illustrated in Figure 2. On the other hand, the position of the lightning striking point was unknown and set at (x_L,y_L). Therefore, the radial distance between the lightning channel and sensors 1 and 2 will be r_1 and r_2, respectively. Moreover, the values of the magnetic flux density at sensors 1 and 2 for different time steps can be expressed by Equation (4) and Equation (5), respectively.

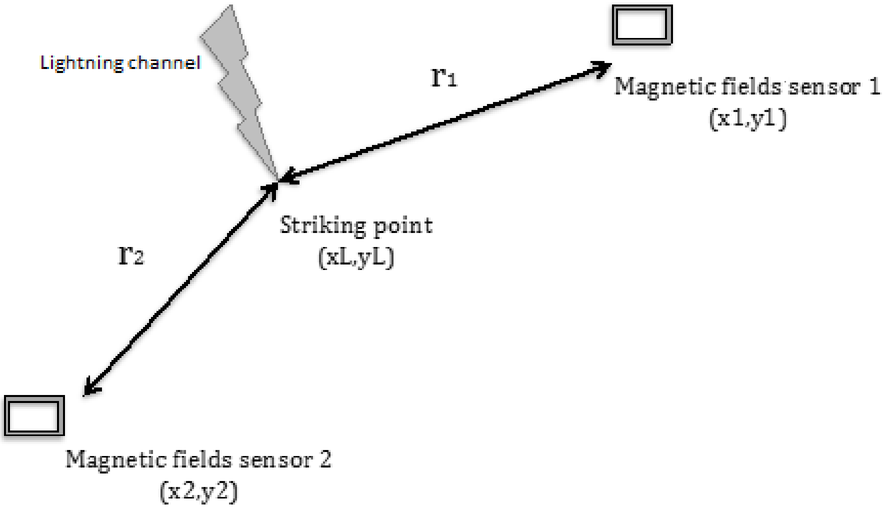

Figure.2. The geometry of problem

$$\begin{cases} B(\mathrm{measured}_{s1})(r_1, z=0, t_{n=2}) = \sum_{i=1}^{n=1}\sum_{m=1}^{k+1}\{a_m F_i(r_1, z=0, t_{n=2}, h_{m,i}) - a'_m F_i(r_1, z=0, t_{n=2}, h'_{m,i})\} \\ B(\mathrm{measured}_{s1})(r_1, z=0, t_{n=3}) = \sum_{i=1}^{n=2}\sum_{m=1}^{k+1}\{a_m F_i(r_1, z=0, t_{n=3}, h_{m,i}) - a'_m F_i(r_1, z=0, t_{n=3}, h'_{m,i})\} \\ \vdots \\ B(\mathrm{measured}_{s1})(r_1, z=0, t_n) = \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_i(r_1, z=0, t_n, h_{m,i}) - a'_m F_i(r_1, z=0, t_n, h'_{m,i})\} \end{cases} \tag{4}$$

$$\begin{cases} B(\mathrm{measured}_{s2})(r_2, z=0, t_{n=2}) = \sum_{i=1}^{n=1}\sum_{m=1}^{k+1}\{a_m F_i(r_2, z=0, t_{n=2}, h_{m,i}) - a'_m F_i(r_2, z=0, t_{n=2}, h'_{m,i})\} \\ B(\mathrm{measured}_{s2})(r_2, z=0, t_{n=3}) = \sum_{i=1}^{n=2}\sum_{m=1}^{k+1}\{a_m F_i(r_2, z=0, t_{n=3}, h_{m,i}) - a'_m F_i(r_2, z=0, t_{n=3}, h'_{m,i})\} \\ \vdots \\ B(\mathrm{measured}_{s2})(r_2, z=0, t_n) = \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_i(r_2, z=0, t_n, h_{m,i}) - a'_m F_i(r_2, z=0, t_n, h'_{m,i})\} \end{cases} \tag{5}$$

Where:

$$r_1 = \sqrt{(x_1 - x_L)^2 + (y_1 - y_L)^2}$$
$$r_2 = \sqrt{(x_2 - x_L)^2 + (y_2 - y_L)^2}$$

By combining Equation (4) and Equation (5), the nonlinear equation system can be expressed by Equation (6) where the number of equations is 2*(n-1) and the number of unknown parameters is 10 (2 for the position of the striking point, 6 for the return stroke current parameters, 1 for the return stroke velocity and 1 for the constant parameter in the current model in MTLE). It should be noted that the current function and current model were based on the sum of two Heidler functions and the MTLE model respectively, and also the values of current exponents were assumed as 2.

Therefore, by solving Equation (6) and finding the unknown parameters, the location of the lightning, the channel base current wave shape, the return stroke velocity and also the constant parameter of the current model can be estimated using the measured magnetic fields in the two stations. In order to solve Equation (6), different numerical methods can be used. However in this paper the PSO (particle swarm optimisation) method was used in which all sub equations must be minimised at the roots of the non linear equation system (unknown parameters)[10-12]. The proposed method covers different field components and it can be used for different distances with respect to the lightning channel. Moreover, the proposed algorithm uses measured magnetic flux density as the input data and therefore it is not dependent on the ground condition to a large extent. In addition, the proposed method can estimate the full shape of the current, the return stroke velocity and the constant parameter of the current model using measured fields.

V. RESULTS AND DISCUSSION

In this paper, the magnetic flux densities at two different stages were generated using a sample of channel base current based on the MTLE current model. Then, the generated magnetic flux densities were used in the proposed algorithm and the location of the striking point, the channel base current as well as the current model parameters were evaluated using the proposed method and the results compared with the corresponding original values. Figure 3 and Figure 4 show the generated magnetic flux densities at Station 1 and Station 2 (based on Figure 2), respectively where Station 1 was located at (0,0) and Station 2 at (50 km, 50 km) and also the striking point was located at (10km,8km) and the current parameters were obtained from Table 1 as follows:

$$\begin{cases} \sum_{i=1}^{n=1}\sum_{m=1}^{k+1}\{a_m F_i(r_1, z=0, t_{n=2}, h_{m,i}) - a'_m F_i(r_1, z=0, t_{n=2}, h'_{m,i})\} - B(\mathrm{measured}_{s1})(r_1, z=0, t_{n=2}) = 0 \\ \sum_{i=1}^{n=2}\sum_{m=1}^{k+1}\{a_m F_i(r_1, z=0, t_{n=3}, h_{m,i}) - a'_m F_i(r_1, z=0, t_{n=3}, h'_{m,i})\} - B(\mathrm{measured}_{s1})(r_1, z=0, t_{n=3}) = 0 \\ \vdots \\ \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_i(r_1, z=0, t_n, h_{m,i}) - a'_m F_i(r_1, z=0, t_n, h'_{m,i})\} - B(\mathrm{measured}_{s1})(r_1, z=0, t_n) = 0 \\ \sum_{i=1}^{n=1}\sum_{m=1}^{k+1}\{a_m F_i(r_2, z=0, t_{n=2}, h_{m,i}) - a'_m F_i(r_2, z=0, t_{n=2}, h'_{m,i})\} - B(\mathrm{measured}_{s2})(r_2, z=0, t_{n=2}) = 0 \\ \sum_{i=1}^{n=2}\sum_{m=1}^{k+1}\{a_m F_i(r_2, z=0, t_{n=3}, h_{m,i}) - a'_m F_i(r_2, z=0, t_{n=3}, h'_{m,i})\} - B(\mathrm{measured}_{s2})(r_2, z=0, t_{n=3}) = 0 \\ \vdots \\ \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_i(r_2, z=0, t_n, h_{m,i}) - a'_m F_i(r_2, z=0, t_n, h'_{m,i})\} - B(\mathrm{measured}_{s2})(r_2, z=0, t_n) = 0 \end{cases} \tag{6}$$

Table.1. The current parameters for field generation

i_{01} (kA)	i_{02} (kA)	τ_{11} (μs)	τ_{12} (μs)	τ_{21} (μs)
12	5	0.3	10	30
τ_{22} (μs)	n_1	n_2	λ (m)	V (m/s)
100	2	2	1800	$1.4 * 10^8$

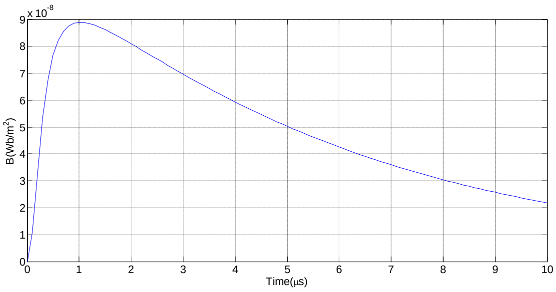

Figure.3. The generated magnetic flux density at station 1

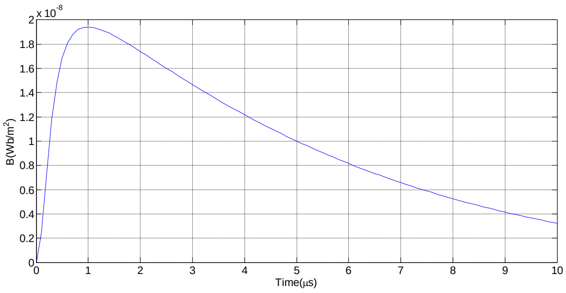

Figure.4. The generated magnetic flux density at station 2

The location of the striking point and the current parameters were evaluated using Figure 3 and Figure 4 as input parameters to the proposed algorithm. The location of the lightning was estimated at (9.72km,8.023km). Moreover, the channel base current parameters were evaluated using the proposed algorithm as shown in Figure 5 and compared with the corresponding original current that was used for field generation.

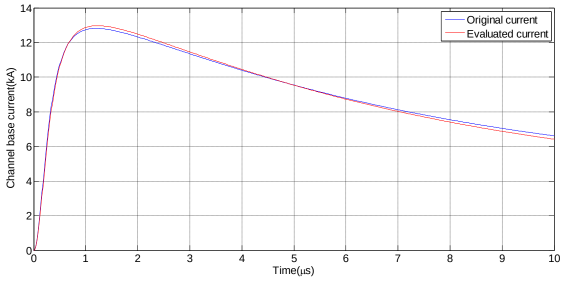

Figure.5. Comparison between evaluated and original channel base currents

Figure 5 shows a good agreement with the corresponding original current. Moreover, the difference percentage between the evaluated location and the exact position is about 2.8%, which is considered to be in the acceptable range. In addition, the estimated current model parameters are $\lambda = 1742$ and $V = 1.4483 * 10^8 m/s$ which also shows good agreement with the original values. Figures 6 and 7 show the comparison between applied fields and the corresponding evaluated fields based on evaluated parameters at locations of sensors 1 and 2 ,respectively whereas the maximum difference percentage between them is about 5.5%.

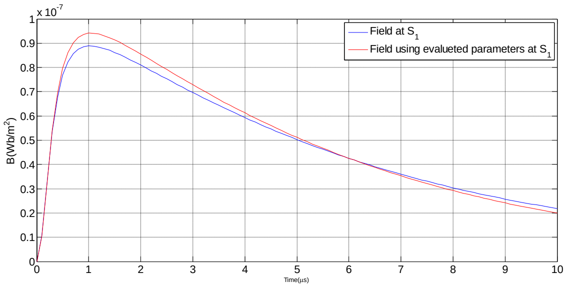

Figure.6. Comparison between applied field and the corresponding field based on evaluated parameters at location of sensor 1

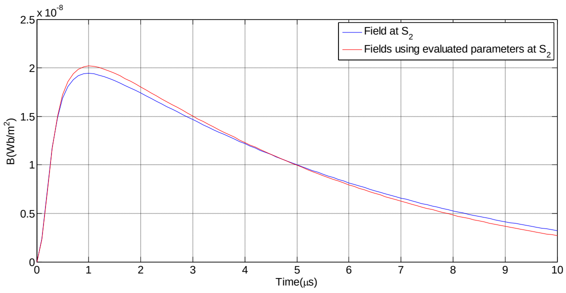

Figure.7. Comparison between applied field and the corresponding field based on evaluated parameters at location of sensor2

A feature of the proposed algorithm is that although the current function and the current model were based on the sum of two Heidler functions and the MTLE current model respectively in this study, however other functions and models can be applied with unknown parameters and these parameters will be estimated using the proposed method. The proposed method can be used for different distances whereby all the field components are taken into account. Therefore, the location of the stations can be varied. Moreover, the proposed method is based on magnetic flux density and the effect of the ground conductivity condition on the evaluated parameters can thus be reduced compared to other methods that are based on measured electric fields. In addition, the proposed method can estimate the full shape of the current, the current model parameters and the average value of the return stroke velocity as opposed to the usual previous methods [13-15]. Noted that, the MTLE model was used in this study [16] and by changing of attenuation height dependent function, the proposed method can support other current models as well. This can be helpful for generating data banks for lightning location as well as lightning current wave shapes that can be used for updating lightning protection standards based on local information. It should be mentioned that the proposed method is a development of time domain algorithm in references [11-12] for the case of lightning location.

The proposed method can cover a wide range of current functions and current models based on the general form of the engineering current model directly in the time domain and it can also be used for different locations of measured stations as it takes all field components into account.

VI. CONCLUSION

In this paper, an inverse procedure algorithm is proposed to evaluate the lightning location as well as the current parameters directly in the time domain using measured magnetic flux density from two field stations. Moreover, by using a sample of the return stroke current, the performance of the proposed method was considered and the results discussed accordingly. The proposed algorithm can estimate the full shape of the channel base current and also the current model parameters as well as the striking point as it takes all field components into account. The proposed method can be used for creating a data bank of lightning striking points and current wave shapes that can be applied in lightning mapping systems and for updating of local standards of lightning protection based on local information, respectively.

REFERENCES

[1] V. Bourscheidt, K. L. Cummins, O. Pinto Jr, and K. P. Naccarato, "Methods to overcome lightning location system performance limitations on spatial and temporal analysis: Brazilian case," Journal of Atmospheric and Oceanic Technology, vol. 29, pp. 1304-1311, 2012.

[2] D. Li, M. Azadifar, F. Rachidi, M. Rubinstein, G. Diendorfer, K. Sheshyekani, et al., "Analysis of Lightning Electromagnetic Field Propagation in

Mountainous Terrain and its Effects on ToA-Based Lightning Location Systems," Journal of Geophysical Research: Atmospheres, 2016.

[3] J. Lopez, E. Perez, J. Herrera, D. Aranguren, and L. Porras, "Thunderstorm warning alarms methodology using electric field mills and lightning location networks in mountainous regions," in Lightning Protection (ICLP), 2012 International Conference on, 2012, pp. 1-6.

[4] M. Ozaki, S. Yagitani, K. Miyazaki, and I. Nagano, "Development of a new portable Lightning Location System," IEICE transactions on communications, vol. 95, pp. 308-312, 2012.

[5] H. Pohjola and A. Mäkelä, "The comparison of GLD360 and EUCLID lightning location systems in Europe," Atmospheric Research, vol. 123, pp. 117-128, 2013.

[6] Z. Sun, X. Qie, M. Liu, D. Cao, and D. Wang, "Lightning VHF radiation location system based on short-baseline TDOA technique—Validation in rocket-triggered lightning," Atmospheric Research, vol. 129, pp. 58-66, 2013.

[7] T. Wu, T. Ushio, and S. Yoshida, "LF lightning location system (BOLT) in Osaka area and its applications," in Lightning Protection (ICLP), 2014 International Conference o, 2014, pp. 82-84.

[8] M. Izadi, A. Kadir, M. Z. Abidin, C. Gomes, and W. F. W. Ahmad, "An analytical second-FDTD method for evaluation of electric and magnetic fields at intermediate distances from lightning channel," Progress In Electromagnetics Research, vol. 110, pp. 329-352, 2010.

[9] M. Izadi, M. Ab Kadir, C. Gomes, and W. Ahmad, "Numerical expressions in time domain for electromagnetic fields due to lightning channels," International Journal of Applied Electromagnetics and Mechanics, vol. 37, pp. 275-289, 2011.

[10] M. Izadi, M. Z. Ab Kadir, C. Gomes, and M. T. ASKARI, "Evaluation of lightning return stroke parameters using measured magnetic flux density and PSO algorithm," Electrical Review Journal-Przeglad Elektrotechniczny, vol. 88, pp. 201-204, 2012.

[11] M. Izadi, M. Kadir, C. Gomes, and V. Coora, "Improved algorithm for evaluation of lightning current using measured field at far distances from lightning channel," in Lightning Protection (ICLP), 2012 International Conference on, 2012, pp. 1-4.

[12] M. Izadi, M. A. Kadir, V. Cooray, and M. Hajikhani, "Estimation of Lightning Current and Return Stroke Velocity Profile Using Measured Electromagnetic Fields," Electric Power Components and Systems, vol. 42, pp. 103-111, 2014.

[13] R. Said, M. Cohen, and U. Inan, "Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations," Journal of Geophysical Research: Atmospheres, vol. 118, pp. 6905-6915, 2013.

[14] S. Mallick, V. Rakov, D. Tsalikis, A. Nag, C. Biagi, D. Hill, et al., "On remote measurements of lightning return stroke peak currents," Atmospheric Research, vol. 135, pp. 306-313, 2014.

[15] M. Salut, M. Cohen, M. A. M. Ali, K. Graf, B. Cotts, and S. Kumar, "On the relationship between lightning peak current and Early VLF perturbations," Journal of Geophysical Research: Space Physics, vol. 118, pp. 7272-7282, 2013.

[16] C.A.Nucci,C. Mazzetti, F.Rachidi and M. Ianoz," On the lightning return stroke models fpor LEMP calculations",ICLP conference, Granz, Austria, 1988.