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Evaluation of lightning return stroke parameters using measured magnetic flux density and pso algorithm

Abstract.-*Return stroke current along lightning channel is reckoned as a fundamental factor for the prediction of electromagnetic fields at observation points, whilst it can be simulated by current models. The most common current model is the engineering model which is more dependent on the height dependent attenuation factor and the return stroke velocity. Yet, the estimation of constant parameters at attenuation factor and return stroke velocity value are complicated. Using measured values and the PSO (particle swarm optimization) optimization method, this paper aimed at determining the values of current velocity along lightning channel and constant parameters in MTLE and MTLL engineering current models and the behaviour of both current models with respect to measured field were processed where the observation point is set at intermediated distance from lightning channel. Moreover, the results were compared with the previous results and were validated with the measured fields. The results illustrated that the MTLL model cannot be as an appropriate current model compared to MTLE current model for the intermediate distance case. Also, the results based on the MTLE model and the initial data determined by PSO algorithm were in good agreement with the measured fields. The proposed method was also capable of setting up appropriate values for unknown parameters in return stroke current models. In addition, the simulated field using the MTLE current model and initial data from PSO algorithm improved the average difference in percent between simulated field and measured field compared to the initial data from previous studies.*

Streszczenie. *W artykule analizuje się prędkość prądu w kanale wyładowania piorunowego. Do tego celu wykorzystuje się dane pomiarowe i algorytm PSO. Metodę tę porównano z klasyczną metodą bazującą na określaniu tłumienia i szybkości uderzenia powrotnego. (**Analiza prądu w kanale wyładowania piorunowego na podstawie pomiaru indukcji magnetycznej z wykorzystaniem algorytmu PSO**)*

Keywords: Lightning, electromagnetic fields, lightning channel, PSO.
Słowa kluczowe: wyładowanie piorunowe, pole elektromagnetyczne, algorytm PSO.

Introduction

Evaluation of lightning current wave shape and return stroke velocity at the length of lightning channel are indispensible objectives that can be effective on the electromagnetic wave shapes and lightning induced voltages associated with the lightning channel[1]. Several models are known to predict the lightning current along the lightning channel that can be categorized into four important groups as follows[2]:
1-the Gas-Dynamic models
2-the Electromagnetic models
3-the Current Distributed models
4-the Engineering models

This study focuses on the MTLE (Modified Transmission line with Exponential Decay)and MTLL(Modified Transmission Line with Linear Decay) models from the fourth group[3, 4], while most of them can be expressed by a special function based on the channel base current, an attenuation height dependent factor, the return stroke current, and the wave front velocities. For that reason, the determination of attenuation height dependent factor and return stroke velocities are so important for the prediction of lightning current a long lightning channel. In this study, the values of attenuation height dependent factors and return stroke velocities based on MTLE and MTLL model will be determined using measured return stroke current wave shape at channel base, measure magnetic flux density at an observation point and the PSO (particle swarm optimization) optimization algorithm[5-7]. Besides, the results will be compared with the previous work as well.

Return stroke current

Lightning return stroke current can be considered in two areas: firstly, lightning return stroke current at channel base on the ground surface, and secondly lightning return stroke current along lightning channel. The channel base current can be evaluated by direct measurement using triggered Lightning Techniques[8] or inverse procedure algorithms using measured electromagnetic fields[9]. Moreover, the channel base current can be simulated by some channel base current functions when the most common and realistic channel base current function is Heidler function[10]. In this study, the improvement of Diendorfer-Uman on the Heidler current function is used for simulation of current wave shape on the ground surface as presented by equation(1)[11].

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

where: i_{01}, i_{02} are the amplitudes of the channel base current, Γ_{11}, Γ_{12} are the front time constants, Γ_{21}, Γ_{22} are the decay- time constants,
n_1, n_2 are the exponents (2~10),

$$\eta_1 = \exp\left[-\left({}^{\Gamma_{11}}/_{\Gamma_{12}}\right)\left(n_1\frac{\Gamma_{12}}{\Gamma_{11}}\right)^{\frac{1}{n_1}}\right],$$

$$\eta_2 = \exp\left[-\left({}^{\Gamma_{21}}/_{\Gamma_{22}}\right)\left(n_2\frac{\Gamma_{22}}{\Gamma_{21}}\right)^{\frac{1}{n_2}}\right].$$

On the other hand, the current wave shape along lightning channel can be simulated by current models as mentioned in the introduction part. The most engineering current models can be generalized by the equation (2)[1]. Table 1. Demonstrates the list of the most common engineering current models based on equation (2) where c is light speed in free space, λ is a constant factor and H is cloud height with respect to ground surface[1].

$$(2)\qquad I(z',t) = u\left(t-\frac{z'}{v_f}\right)P(z')I\left(0,t-\frac{z'}{v}\right)$$

where: z' is temporary charge height along lightning channel, I (z',t) is return stroke current at height of z' along lightning channel, I (0,t) is return stroke current at channel base, P (z') is attenuation height depend factor, v_f is return stoke front velocity, v is return stroke current velocity, u is Heaviside function.

The focal points in this study are the MTLE and MTLL models. In these models, the values of λ and H are regarded as unknown parameters. Although the λ value is suggested between (1~2 km)[3], the measurement of the exact value of H is complicated. On the other hand, the return stroke velocities is assumed to be constant and equal to return stroke wave front velocity; however, the measurements show that the return stroke velocity is a variable that is increased by channel height at short values of channel height, and then decreased at higher height values[12]. Therefore, the average value of velocity is imported to engineering current models while the recommended value is between c/3 to 2c/3[12].

Table.1.The most common engineering current models[1]

Model	Return stroke current at height of z' along lightning channel	Return stroke current velocity	P(z')
Bruce-Golde model (BG)	i(z',t) = i(0,t)	∞	1
Transmission Line model (TL)	i(z',t) = i(0,t-z'/v)	v_f	1
Traveling Current Source model (TCS)	i(z',t) = i(0,t+z'/c)	c	1
Modified Transmission Line Exponential decay model (MTLE)	i(z',t) = i(0,t-z'/v)exp(-z'/λ)	v_f	exp(-z'/λ)
Modified Transmission Line Linear model (MTLL)	i(z',t)=i(0,t-z'/v)(1-z'/H)	v_f	(1-z'/H)

Accordingly, for the evaluation of return stroke velocity, the measurement of wave front velocity at different heights along lightning channel are needed which is a complicated task. Therefore, in this study by using channel base current parameters, measured magnetic flux density at an observation point and PSO optimization algorithm ,the optimized values of λ, H, v is calculated and the simulated fields at observation point using new calculated values are compared with the previous work and also the MTLE and MTLL results are compared with each other.

Electromagnetic fields

The electromagnetic fields at an observation point above the perfect ground surface associated with the vertical lightning channel can be estimated by the equations (3) to (5)[13, 14], while the geometry of problem is shown in Figure.1 where $R=\sqrt{r^2+(z-z')^2}$, $\vec{E}_z(r,z,t)$ is vertical electric field, $\vec{E}_r(r,z,t)$ is the horizontal electric field, $\vec{B}_\varphi(r,z,t)$ is the magnetic flux density, z is the height of observation point, z' is the vertical space variable, $\varepsilon_0=8.85\times10^{-12}$, $\mu_0=4\pi\times10^{-7}$, β=v/c, $\chi=\sqrt{\frac{1}{1-\beta^2}}$, $A1=\sqrt{(\beta ct-z)^2+(\frac{r}{\chi})^2}$, $A2=\sqrt{(\beta ct+z)^2+(\frac{r}{\chi})^2}$, $H_u=\beta\chi^2\{-(\beta z-ct)-A1\}$, $H_d=-\beta\chi^2\{-(\beta z+ct)+A2\}$. Note that, all electromagnetic field components in the time period less than R(z'=0)/c are equal to zero.

(3) $\vec{E}_z(r,z,t)=\left(\frac{1}{4\pi\varepsilon_0}\right)\int_{H_d}^{H_u}\left(\frac{2(z-z')^2-r^2}{R^5}\int_0^t i\left(z',\tau-\frac{R}{c}\right)d\tau+\frac{2(z-z')^2-r^2}{cR^4}i\left(z',t-\frac{R}{c}\right)-\frac{r^2}{c^2R^3}\frac{\partial i\left(z',t-\frac{R}{c}\right)}{\partial t}\right)dz'$

(4) $\vec{E}_r(r,z,t)=\left(\frac{1}{4\pi\varepsilon_0}\right)\int_{H_d}^{H_u}\left(\frac{3r(z-z')}{R^5}\int_0^t i\left(z',\tau-\frac{R}{c}\right)d\tau+\frac{3r(z-z')}{cR^4}i\left(z',t-\frac{R}{c}\right)-\frac{r(z-z')}{c^2R^3}\frac{\partial i\left(z',t-\frac{R}{c}\right)}{\partial t}\right)dz'$

(5) $\vec{B}_\varphi(r,z,t)=\left(\frac{\mu_0}{4\pi}\right)\int_{H_d}^{H_u}\left(\frac{r}{R^3}i\left(z',t-\frac{R}{c}\right)+\frac{r}{cR^2}\frac{\partial i\left(z',t-\frac{R}{c}\right)}{\partial t}\right)dz'$

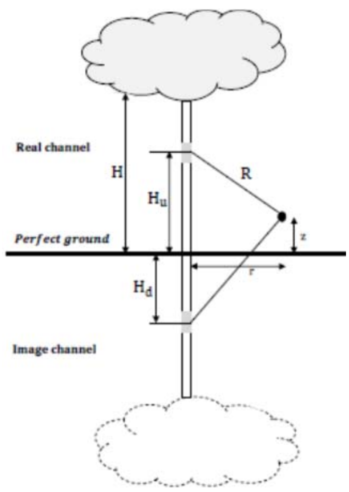

Fig.1.the geometry of vertical lightning channel

PSO Algorithm

A basic variant of the PSO algorithm can be run, when there is a swarm (the population) of particles (the candidate solutions). These particles are in movements to look for a space based on a few simple principles. In the search-space, the movements of these particles are conducted by not only the particle's known suitable position, but also the best recognized positions of the entire swarm. When the proper locations are detected, then they would control the movements of the swarm. This process is repeated many times, until hopefully a satisfactory solution is discovered. If f: Rn→ R is the condition or cost function which must be minimized, the function takes a candidate solution as a case in the form of a real number and accordingly produces a result with the figure of a real number which specifies the suitability of the given candidate solution. The inclination of f is unspecified. The purpose is to find an answer for which f (a) ≤ f (b), for all b in the search-space, which indicates a is the global minimum. In this study, the objective function is defined by equation (6) and it is imported to PSO algorithm obtained from the references [5-7] while the calculated magnetic flux density will be determined by using equation (5) in the time domain at k steps of Δt.

(6) $f=\min\left(\frac{\sum_{i=1}^{k}100\times\left|\frac{B^i_{calculated}-B^i_{measured}}{B^i_{measured}}\right|}{k}\right)$

Where: k is the maximum train of time, $B^i_{calculated}$ is the calculated magnetic flux density at time equal to iΔt , $B^i_{measured}$ is the measured magnetic flux density at time equal to iΔt .

It should be noted that, the λ, v values and the H, v values are applied as unknown parameters in the objective function in equation (6) at $B^i_{calculated}$ part for MTLE and MTLL current models, respectively.

Simulation and results

In this study, the basic information are obtained from a measured magnetic flux density field at an observation point with r=4.6 km and z=10m above the ground surface, while the channel base current parameters are known as listed in Table.2[14, 15]. The measured magnetic flux density is also illustrated in Figure.2. It should be mentioned that the channel base current is measured by triggered lightning technique.

Table.2.The channel base current parameters based on Diendorfer and Uman function[14]

i_{01} (kA)	i_{02} (kA)	Γ_{11} (μs)	Γ_{12} (μs)	Γ_{21} (μs)	Γ_{22} (μs)	n_1	n_2
17	8	0.4	4	4	50	2	2

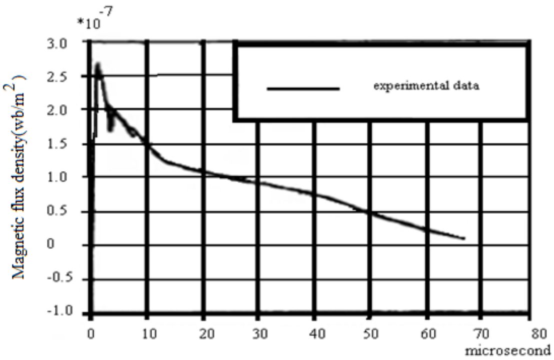

Fig.2. Measured magnetic flux density (B_φ) at the observation point (r=4.6km)[14, 15]

Consequently, by considering the channel base current from Table.2 and measured magnetic flux density from Figure.2 as the basic parameters and using PSO optimization algorithm, the values of λ, H, v is evaluated while the MTLE and MTLL current models are applied. Figure.3 shows the PSO objective function graph for the estimation of λ, v values, when the MTLE current model is applied. The PSO results illustrate the optimized values of λ, v for the MTLE current model are 1724.84 m and 1×10^8 m/s, respectively where the best value of objective function is equal to 10.5428 after 50 iterations with the population size equal to 50.

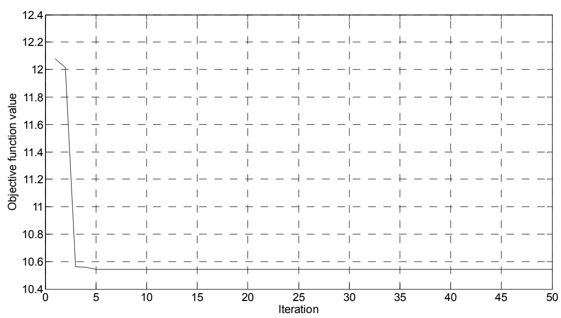

Fig.3.The PSO objective function graph for the MTLE current model

Figure.3 illustrates that the final value of objective function as expressed in equation (6) is equal to 10.5428, while the PSO algorithm is applied. This means that the percentage of the average value of the difference between simulated magnetic flux density and measured field is equal to 10.5428% where in this study, k and Δt values (in equation (6)) are set in 601 and Δt=10^{-1}μs, respectively. On the other hand, this problem is processed again using MTLL model. Therefore, the PSO objective function graph for the determination of H, v values using MTLL current model is demonstrated in Figure.4. The PSO algorithm evaluated 4 km and 1.02057×10^8 m/s for H and v, respectively where the best value of objective function is equal to 21.3004 after 50 iterations with the population size of 50. Figure.4 shows the percentage of average difference between simulated field using MTLE model and measured field (based on equation (6)) is equal to 21.3004%. Therefore,the results show MTLL model cannot be a suitable general model for predicting the current behavior along lightning channel in this problem compared to MTLE current model. However, the MTLL model is in good agreement with measured fields at close distance from lightning channel. It should be remarked that this problem is simulated by MTLE model with λ=1500 m and v=c/3 in references[15].

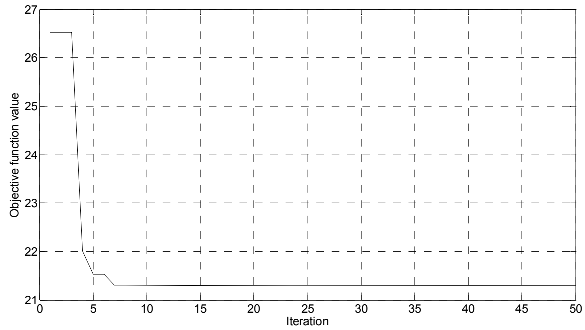

Fig. 4.The PSO objective function graph for the MTLL current model

Furthermore, Figure.5 shows return stroke current at channel base and z=2000 m height using initial data from previous works and initial data from the PSO results related to Figures.3 and 4. Note that, the channel base current parameters are obtained from Table.2.

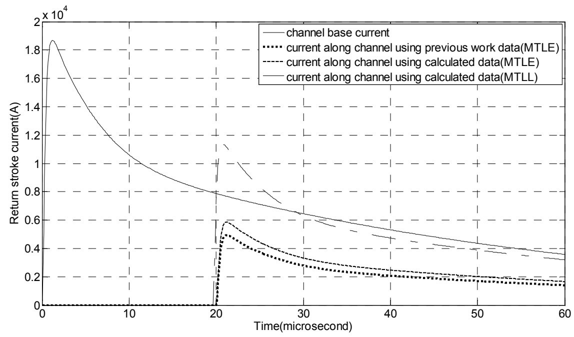

Figure.5. Comparison between return stroke currents at channel base and z'=2000 m height along lightning channel using initial data from reference [15] and calculated ones

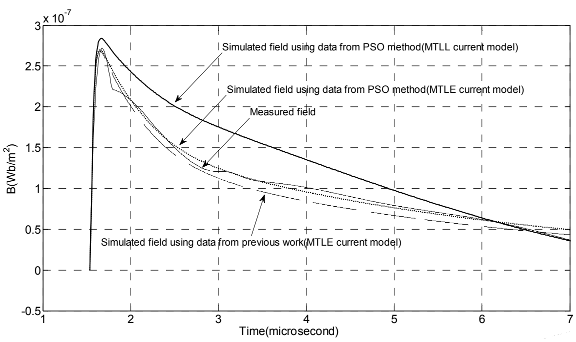

Fig.6. Comparison between measured and simulated magnetic flux densities using initial data from references [14-15] and calculated initial dada

In addition, the simulated magnetic flux density using initial data from references [14-15] and new determined values from the PSO algorithm are compared with the measured fields from Figure.2 as shown in Figure.6.

Moreover, the objective function based on equation (6) is calculated for simulated magnetic flux density using initial data from [14-15], it is equal to 14.0104. Table.3 tabulates the comparison between objective function in equation (6) for simulated magnetic flux densities using initial data from references [14-15] and the proposed method when MTLE current model is applied. Besides, the objective function for simulated magnetic flux density using proposed method and MTLL model is listed in Table.3. Note that, the objective function value based on equation(6) is equal to the percentage of the average difference between simulated field and measured field at k steps of Δt (k=601, Δt=0.1 μs). Furthermore, Table.3 clarifies that the PSO algorithm could improve the behavior of simulated magnetic flux density in MTLE model compared with the similar field using initial values from references [14-15].

Table.3.Comparison between objective function values using initial data from references [14-15] and calculated initial dada

MTLE Model		MTLL Model
Using previous work data	Using data from PSO	Using data from PSO
14.0104%	10.5428%	21.3004%

However, the MTLL model is not an appropriate current model for this problem (at intermediate distance from lightning channel), since the percentage of the average difference between simulated field and measured field is higher than MTLE ones. The determined values of the initial data improve the percentage of the average difference around 3.5% compared to initial values from references [14-15] in MTLE model. It should be pointed out that the MTLL model is usually used at close distances from the lightning channel[16]. In addition, the results illustrate that the calculated velocity values is highly in accord with the measured velocity in references [14-15] (in similar case) and the determined values of v, λ are also in acceptable ranges between c/3 to 2c/3 and 1000 m to 2000 m, respectively.

Conclusion

In order to increase the accuracy of predicted return stroke current along lightning channel different current models were considered and the MTLE and MTLL engineering current models were selected in this study. Therefore by applying the PSO optimization method, unknown parameters in MTLE and MTLL models were determined where the channel base current and the measured magnetic flux density at an observation point were used as the basic parameters. The results showed the MTLL model is not as an appropriate current model for intermediate distance case. While the MTLE model can well support the case, if it is at the intermediate distance from the lightning channel. The results also illustrated that the simulated magnetic flux density using the PSO algorithm and MTLE current model are in good agreement with the measured field and it could improve the percentage of the average difference between simulated field using initial data from references[14-15] and the measured field.

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