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Considering on the Ground Reflection Effect on the Electromagnetic Fields due to Lightning Channel

Mahdi Izadi†, Mohd Zainal Abidin Ab Kadir* and Maryam Hajikhani**

Abstract – Lightning electromagnetic fields are important issues for the evaluation of lightning induced overvoltage on power lines and for setting the appropriate protection level for power networks. Such electromagnetic fields are strongly dependent on lightning return stroke currents at different heights along the lightning channel. On the other hand, the ground reflection factor due to the difference between the return stroke channel impedance and the equivalent ground impedance at channel base can have an effect on the shape of the return stroke currents by entering additional reflected currents into the channel. In this paper, the effect of the ground reflection factor on the return stroke currents at different heights along a channel and the electromagnetic fields associated with the lightning channel at close distances are considered. Moreover, the behavior of the electromagnetic fields versus the reflection factor changes and the radial distance changes are considered and the results are discussed accordingly. The results illustrate that the reflection factor has a direct relationship with the values of the electromagnetic fields while this is usually ignored in earlier studies.

Keywords: Lightning, Electromagnetic fields, Ground reflection factor

1. Introduction

The electromagnetic fields associated with a lightning channel can be effective on the lightning induced voltage on the power lines [1-3] whereas they are more dependent on the current wave shapes at different heights along the lightning channel and also a number of channel parameters and geometrical factors [4-7]. Several studies have been undertaken to evaluate the electromagnetic fields due to a lightning channel. These studies usually ignore the reflection of the ground at the striking point (channel base) [8-11] . On the other hand, the lightning current can be reflected at channel base due to the difference between the return stroke channel impedance and the equivalent ground impedances at connection point (channel base) and this can have an effect on the shape of the return stroke currents at different heights along a lightning channel.

In this study, the ground reflection will be taken into account in the calculation of the electromagnetic fields. Therefore, the lightning return stroke currents at different heights along the channel will be considered in the presence of the ground reflection. Moreover, the electromagnetic fields associated with lightning for different values of the ground reflection coefficient will be evaluated and the results will be discussed accordingly. In this paper, the current function and the current model are based on the Diendorfer and Uman(DU) current function [8, 12-14] and the general form of the engineering current model [4, 6, 15], respectively. The basic assumptions in this study are expressed as follows:

i. The lightning channel is perpendicular to the surface of the ground.
ii. The effects of branches are ignored.
iii. The surface of the ground is flat with uniform ground plane impedance.
iv. The observation point is set above the surface of the ground.
v. The lightning electromagnetic fields associated with a single return stroke due to a downward leader are considered.

2. Return stroke current

The lightning return stroke current can be considered in two areas i.e. the channel base and different heights along the lightning channel via current functions and current models, respectively. In this study, the current function is based on the DU function [12, 14, 16] to simulate the measured current wave shape at the channel base as expressed by Eq. (1) whereas it is based on the sum of two Heidler functions.

† Corresponding Author: Centre for Electromagnetic and Lightning Protection research (CELP), Faculty of Engineering, University Putra Malaysia (UPM) Serdang, Selangor, 43400, Malaysia. / Department of Electrical, Firoozkooh Branch, Islamic Azad University, Firoozkooh, Iran. (aryaphase@yahoo.com)
* Centre for Electromagnetic and Lightning Protection research (CELP), Faculty of Engineering, University Putra Malaysia, UPM, Serdang, Selangor, 43400, Malaysia
** Aryaphase Company, Tehran, Iran
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$$i(0,t) = \left[\frac{i_{01}}{\eta_1}\frac{\left(\frac{t}{\tau_{11}}\right)^{n_1}}{1+\left(\frac{t}{\tau_{11}}\right)^{n_1}}\exp\left(\frac{-t}{\tau_{12}}\right) + \frac{i_{02}}{\eta_2}\frac{\left(\frac{t}{\tau_{21}}\right)^{n_2}}{1+\left(\frac{t}{\tau_{21}}\right)^{n_2}}\exp\left(\frac{-t}{\tau_{22}}\right)\right] \quad (1)$$

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),

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

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

Likewise, the current model is set using the general form of the engineering model as presented by Eq. (2) [5, 15, 17].

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

Where:

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.

On the other hand, the lightning return stroke currents in the presence of ground reflections can be evaluated by Eq. (3) as follows [18-19]:

$$i_{gr}(z',t) = \left[P(z')i\left(0,t-\frac{z'}{v}\right) + \rho_g\, i\left(0,t-\frac{z'}{c}\right)\right] U\left(t-\frac{z'}{v_f}\right) \quad (3)$$

Where:

ρ_g is ground reflection coefficient equal to $\frac{z_{ch}-z_g}{z_{ch}+z_g}$
z_{ch} is the surge impedance of return stroke channel,
z_g is the ground impedance at connection point (channel base),
$i_{gr}(z',t)$ is the return stoke current at different heights along channel in presence of ground reflection factor.

Eq. (3) shows that the return stroke currents are more dependent on the ground reflection factor as a function of the channel and ground impedances. Therefore, in order to consider on the ground reflection effect on the values of electromagnetic field in next part, a sample of measured current is selected from [8, 13, 14, 20] and the current parameters are listed in table 1 whereas the channel base current parameters, velocity and constant parameter of current model are known in [8, 13, 14, 20]. Fig. 1 shows the current wave shapes at different heights along a lightning channel in the presence of the reflection factor. Noted that the MTLE (Modified transmission line with exponentially decay) current model [8, 20] is applied in this paper such that $P(z') = \exp\left(-\frac{z'}{\lambda}\right)$ [9]. It should be mentioned that, in the MTLE current model, the current attenuated along the lightning channel with an exponential rate depends on a constant decay factor that is typically between 1~2km [9]. Among different current models based on the general form of engineering current model, the MTLE model is set as a current model in this study because the simulated field based on this model showed a good agreement with measured fields in previous studies [8, 20, 13, 14] and it needs just a constant parameter (λ) to consider on the current at different heights along lightning channel that is obtained from [8,20,13,14] while some current models don't have physical meaning (such as BG, TCS and TL models) [9] and in a number of them the value of cloud height is needed (such as MTLL model)[9].

Table 1. The current parameters

i_{01}(kA)	τ_{11}(μs)	τ_{12}(μs)	i_{02}(kA)	τ_{21}(μs)
19.5	1	2	12	8
τ_{22}(μs)	n_1	n_2	λ(m)	V(m/s)
30	2	2	1500	1×10^8

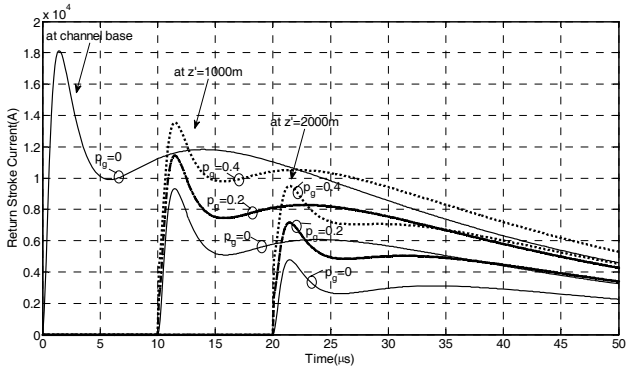

Fig. 1. Return stroke current wave shapes at different heights along lightning channel

Fig. 1 illustrates that the ground reflection factor has a direct relationship with the peak of the currents. Moreover, it shows that by increasing the ground reflection factor, the slope of the current wave shapes at the initial time periods (before the front time) are increased due to the control of the original and reflection currents by the return stroke front.

3. Lightning Electromagnetic Fields

The lightning electromagnetic fields associated with a lightning channel can be evaluated using the numerical field expressions as expressed by Eqs. (4) to (8) whereas the geometry of problem is illustrated in Fig. 2 [13]. Eqs.

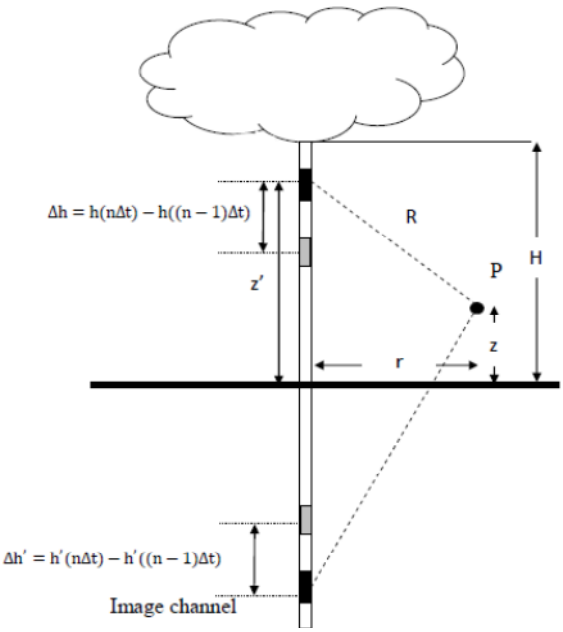

Fig.2. Geometry of problem [13]

(4, 5) and (6) present the magnetic flux density and the derivatives of horizontal and vertical electric fields to time, respectively whereas the internal terms of $F_{i,1}$, $F_{i,2}$ and $F_{i,3}$ are dependent on the lightning current wave shapes at different heights along lightning channel. Likewise, Eqs. (7) and (8) consider on the horizontal and vertical electric fields due to lightning channel, respectively. It should be mentioned that the Maxwell's equations, the FDTD and Trapezoid methods are used in the field expressions and they can support different current functions and models directly in the time domain without needing to apply any extra conversions.

$$\overrightarrow{B_\varphi}(r,z,t_n) = \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,1}(r,z,t_n,h_{m,i}) - a'mFi,1r,z,tn,h'm,i\} \tag{4}$$

$$\frac{d\vec{E}_r(r,z,t_n)}{dt} = \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,2}(r,z,t_n,h_{m,i}) - a'_m F_{i,2}(r,z,t_n,h'_{m,i})\} \tag{5}$$

$$\frac{d\vec{E}_z(r,z,t_n)}{dt} = \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,3}(r,z,t_n,h_{m,i}) - a'_m F_{i,3}(r,z,t_n,h'_{m,i})\} \tag{6}$$

$$\overrightarrow{E_r}(r,z,t_n) = \overrightarrow{E_r}(r,z,t_{n-1}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,2}(r,z,t_n,h_{m,i}) - a'_m F_{i,2}(r,z,t_n,h'_{m,i})\} \tag{7}$$

$$\overrightarrow{E_z}(r,z,t_n) = \overrightarrow{E_z}(r,z,t_{n-1}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,3}(r,z,t_n,h_{m,i}) - a'_m F_{i,3}(r,z,t_n,h'_{m,i})\} \tag{8}$$

Where:

$\overrightarrow{E_r}(r,z,t)$ is the horizontal electric field ,
$\overrightarrow{E_z}(r,z,t)$ is the vertical electric field ,
$\overrightarrow{B_\varphi}(r,z,t)$ is the magnetic flux density,
z is height of observation point,
c is light speed in free space,
r is radial distance from lightning channel,
β=v/c,

$$\chi = \sqrt{\frac{1}{1-\beta^2}},$$

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

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

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

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

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

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

$$F_{i,1}(r,z,t_n,h_{m,i}) = \left(\frac{\mu_0}{4\pi}\right)\left\{\begin{matrix} \frac{r}{R_m{}^3} i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right) + \\ \frac{r}{cR_m{}^2}\frac{\partial i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right)}{\partial t} \end{matrix}\right\}$$

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

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

$$F_{i,2}(r,z,t_n,h_{m,i}) = \left(\frac{1}{4\pi\varepsilon_0}\right)\left\{\frac{3r(z-h_{m,i})}{R_m{}^5} \times i_{gr}\left(\begin{matrix} h_{m,i}, t_n - \\ \frac{R_m}{c} \end{matrix}\right) + \frac{3r(z-h_{m,i})}{cR_m{}^4} \times \frac{\partial i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right)}{\partial t} + \frac{r(z-h_{m,i})}{c^2 R_m{}^3} \times \frac{\partial^2 i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right)}{\partial t^2}\right\}$$

$$F_{i,3}(r,z,t_n,h_{m,i}) = \left(\frac{1}{4\pi\varepsilon_0}\right)\left\{\frac{2(z-h_{m,i})^2 - r^2}{{R_m}^5} \times i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right) + \frac{2(z-h_{m,i})^2 - r^2}{c{R_m}^4} \times \frac{\partial i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right)}{\partial t} - \frac{r^2}{c^2{R_m}^3} \times \frac{\partial^2 i_{gr}\left(h_{m,i}, t_n - \frac{R_m}{c}\right)}{\partial t^2}\right\}$$

Fig. 3 shows the evaluated vertical electric fields at three close distances with respect to the lightning channel whereby by increasing the distance the corresponding vertical electric fields are also decreased. On the other hand, it illustrates that the evaluated fields have a direct relationship with the ground reflection factor whereby the first peaks of the evaluated fields based on reflection factors equal to 0.2 and 0.4 indicate a 15 % and 31 % increase with respect to the evaluated field based on $\rho_g = 0$, respectively.

Moreover, the vertical electric field is an important parameter in the estimation of the lightning induced voltage using a number of coupling models such as the Agrawal model [1, 21-25]. Therefore, consideration of the ground reflection factor can have a direct effect on the evaluated values of the lightning induced voltage on the power lines and for setting an appropriate protection level for the power system. It should be mentioned that the current parameters are obtained from Table 1 and the current model is based on MTLE model. Likewise, Fig. 4 demonstrates the behaviour of the derivative of the vertical electric field to time based on different ground reflection factors at three distances with respect to the lightning channel. It shows, $\frac{dE_z}{dt}$ has a direct relationship with the reflection factor and also an inverse relationship with the radial distance with respect to the lightning channel. It should be noted that all electromagnetic field components at time periods less than $\frac{\sqrt{r^2+z^2}}{c}$ are equal to zero.

Moreover, the behaviour of the horizontal electric field and also the magnetic flux density versus the reflection factor changes at different close radial distances with respect to the lightning channel as illustrated in Fig. 5 and 6, respectively. These figures show that by increasing the reflection factor, the value of the horizontal electric field will be increased while the behaviour of the evaluated horizontal electric field versus increasing radial distance is opposed to the reflection factor. It should be mentioned that the horizontal electric field and magnetic flux density are effective parameters on the values of the lightning induced over voltage (LIOV) in the Agrawal and Rachidi coupling models, respectively[3, 20, 25-27]. Therefore,

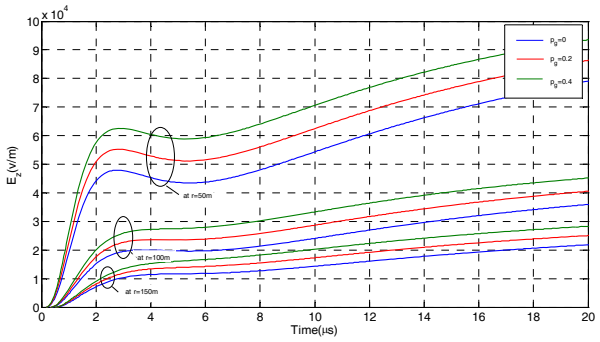

Fig. 3. Vertical electric fields at different distances with respect to lightning channel

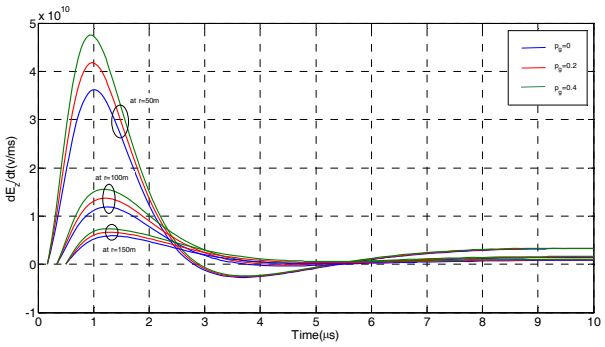

Fig. 4. Derivative of vertical electric fields to time at different distances with respect to lightning channel

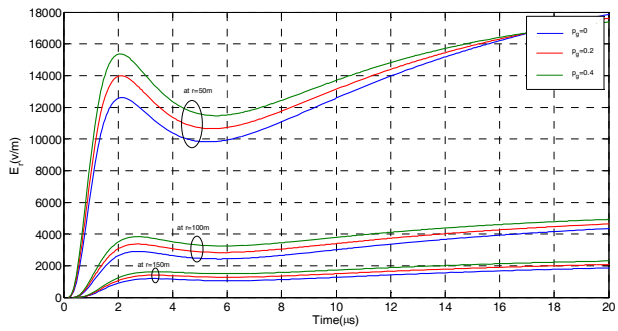

Fig. 5. Horizontal electric fields at different distances with respect to lightning channel

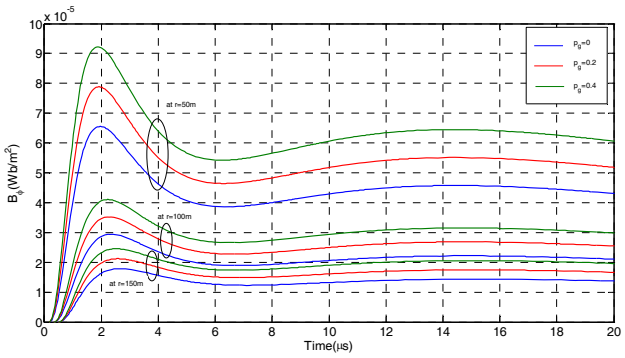

Fig. 6. Magnetic flux densities at different distances with respect to lightning channel

consideration of the ground reflection can be have a great effect on the evaluation of LIOV and on setting the appropriate protection level for the power lines.

On the other hand, the behaviour of the fields peaks versus reflection factor changes at r=50 m is considered as illustrated in Fig. 7, which shows that by increasing the reflection factor, the field peaks are increased in an approximate linear trend while the line slope for the magnetic flux density is higher than for the two other electric field components. Moreover, the increasing trend of the vertical electric field is higher than the horizontal electric field. Therefore, based on Fig. 7, by considering that the ground reflection is a function of the ground and channel impedances, the peak of the magnetic flux density and vertical electric field can be increased (at $\rho_g = 0.8$) to 1.8 and 1.6 of the corresponding fields at $\rho_g = 0$, respectively such that the magnetic flux density and vertical electric field values play very important roles in the evaluation of the LIOV.

Fig. 8 demonstrates the peak behaviour of the magnetic flux density versus radial distance changes under different ground reflection conditions. As shown in Fig. 8, by increasing the distance with respect to the lightning channel, the peak of the magnetic flux density is decreased in a non-linear trend. On the other hand, it shows that the peak of the magnetic flux density is directly dependent on the ground reflection factor and by decreasing the radial distance, this effect is increased.

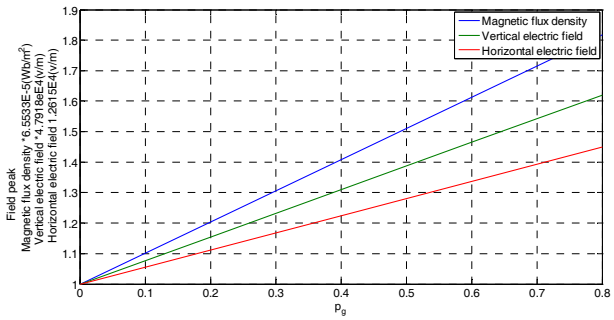

Fig. 7. Variation of Fields peaks versus reflection factor changes (r=50m, z=10m)

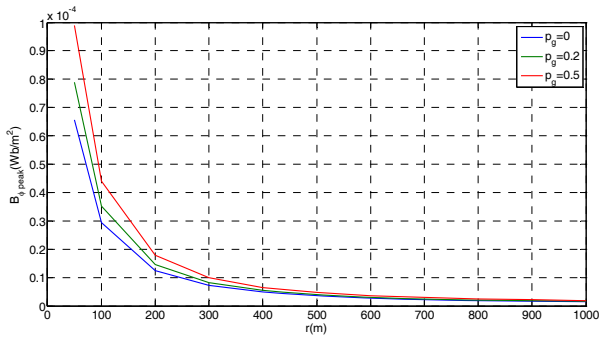

Fig. 8. The peak behavior of magnetic flux density at different distances with respect to lightning channel

Moreover, Fig. 9 illustrates the peak behaviour of the vertical electric field versus the radial distance changes under different ground reflection conditions. It shows that by increasing the radial distance, the ground reflection effect on the peak of the vertical electric field is decreased whereby the peaks of the vertical electric fields have a non-linear behaviour with a decreasing trend versus changes in the radial distance. Likewise, the peaks of the vertical electric fields have a direct relationship with the reflection factor values. It should be mentioned that the current parameters are obtained from table.1.

Moreover, the effect of ground reflection factor on the magnetic flux density is considered using measured field. Fig. 12 illustrates the comparison between simulated

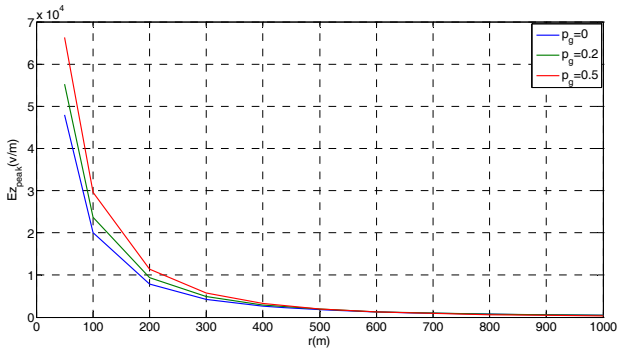

Fig. 9. The peak behavior of vertical electric filed at different distances with respect to lightning channel

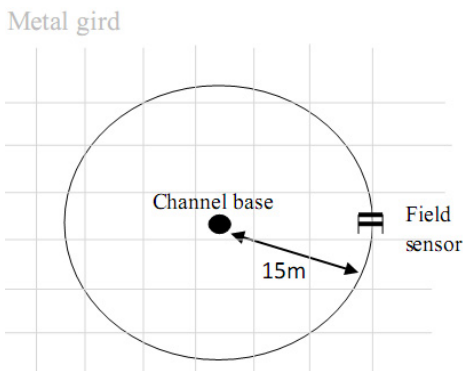

Fig. 10. Geometry of field sensor

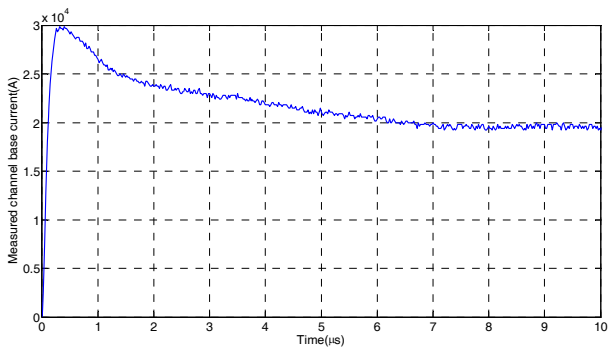

Fig. 11. Measured channel base current

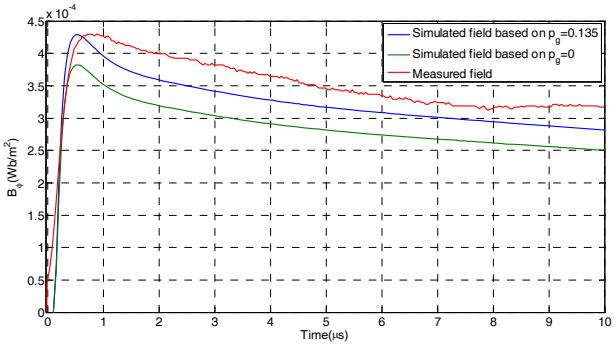

Fig. 12. Comparison between simulated magnetic flux densities to the corresponding measured field

magnetic flux densities that are evaluated based on different ground reflection factors while they are compared to the corresponding measured field (r=15m, z=0, v=$1.5 \times 10^8 \frac{m}{s}$, λ=2000m). It should be mentioned, the simulated and measured fields are due to a sample of measured channel base current (see Fig.11) from triggered lightning experiment based on the geometry of field sensor that is illustrated in Fig. 10. Fig. 12 demonstrates, the simulated field based on $\rho_g = 0.135$ is closer to the corresponding measured field compared to other (based on $\rho_g = 0$). Noted that the measured current and fields are obtained from triggered lightning experiment in Florida Campus whereas the specifications of experimental setup are presented as follow;

i. The rocket launcher was located underground whereas a metal rod with the height about 2m above ground surface is used as a striking object.
ii. The launcher and the rod were located at center of a grounded area (with metal gird) whereas the ground resistance was about 6Ω.
iii. The channel base current at base of metal rod was measured at metal rod place using current transformers (P 110A) and also the measured data were transferred to recorder using the Meret Fiber Optic cable and they were filtered by a 3-dB bandwidth-20MHz anti-aliasing filter .
iv. The rectangular loop antenna was used to measure magnetic flux density with the area about $0.56\ m^2$. Likewise, the measured data were transferred to recorder using the Meret Fiber Optic cable and they were filtered by using a 10MHz, 3dB anti-aliasing filter.

The results show that the electromagnetic field components are strangely dependent on the value of the ground reflection factor whereby by increasing the ground reflection factor the additional reflected currents will increase along the channel. Also, the ground reflection factor is dependent on the channel and ground impedance at the striking point while in reality, the striking point is unpredictable and the value of the ground impedance is variable in different places. On the other hand, the value of LIOV is dependent on the value of the electromagnetic fields due to the lightning channel whereby the lightning electromagnetic fields are strongly dependent on the ground impedance (ground reflection factor). Therefore, in order to set an appropriate protection level for the power networks, the values of LIOV under different conditions of the ground reflection factor using an average value of local ground impedance can be considered. It should be mentioned that the typical value of the channel surge impedance can be set at 330Ω.

4. Conclusion

In this paper, the effect of the ground reflection factor on the value of the return stroke current at different heights along a lightning channel and also the lightning electromagnetic fields are considered whereby the ground reflection factor is dependent on the channel impedance and ground impedance at the striking point. The results show that by increasing the ground reflection factor, the additional reflected currents in the channel and the value of the electromagnetic fields are increased. On the other hand, the effect of the ground reflection factor on the peak of the electromagnetic field at different distances is considered and the results are discussed accordingly. The electromagnetic fields due to a lightning channel are strangely dependent on the ground reflection factors which are used as input parameters for the coupling models for the evaluation of the lightning induced voltage on the power lines.

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Mahdi Izadi He was born in Tehran, Iran, at 1977. He received BSc in electrical power engineering from Azad University, Iran at 1999 and obtained MSc and PhD degrees in electrical power engineering from University Putra Malaysia (UPM), Malaysia at 2010 and 2012, respectively. Currently, he is a researcher in the CELP center, Department of Electrical and Electronics Engineering, Faculty of Engineering, University Putra Malaysia. He has authored and co-authored more than 40 scientific papers published in journals and conferences. His research interests include lightning effects on the power systems and lightning electromagnetic fields and protection of power systems.

M. Z. A. Ab Kadir He graduated with B. Eng degree in Electrical and Electronic from University Putra Malaysia in 2000 and obtained his PhD from the University of Manchester, United Kingdom in 2006 in High Voltage Engineering. Currently, he is a Professor in the Department of Electrical and Electronics Engineering, Faculty of Engineering, University Putra Malaysia. To date he has authored and co-authored over 100 technical papers comprising of national and international conferences proceedings and citation indexed journals. His research interests include high voltage engineering, insulation coordination, lightning protection, EMC/EMI, kerauna-medicine and power system transients.

Maryam Hajikhani She was born in Tehran, Iran at 1978. She graduated BSC and Msc in computer engineering from Azad University, Iran and MMU University, Malaysia at 2003 and 2011, respectively. She is currently pursuing her PhD in UPM and she has authored and co-authored more than 6 scientific papers published in journals and conferences. Her interests include algorithms and computer coding.