GROUND REFLECTION EFFECT ON THE LIGHTNING ELECTROMAGNETIC FIELDS

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ABSTRACT

The ground reflection at channel base is as an important factor on the values of lightning electromagnetic fields and lightning induced voltage on the power line that is due to difference between the return stroke channel and the ground impedances. In this paper, the effects of ground reflection factor on the values of lightning return stroke currents at different heights along lightning channel and also lightning electromagnetic fields are considered and the results are discussed accordingly.

INTRODUCTION

Lightning electromagnetic fields is an important effect of lightning that can create lightning induced voltage on the power lines and systems [1-3]. The electromagnetic fields associated with lightning channel is strangely dependent on the channel base current and current wave shapes at different heights along lightning channel and a number of geometrical parameters[4-7]. On the other hand, the current wave shapes along channel are dependent on the reflection factor at striking point that can enter additional reflected currents into channel and change the values of lightning electromagnetic fields while the additional reflected currents are usually ignored in the fields calculations[8]. It should be mentioned that the ground reflection factor is due to difference between the surge impedance of channel and ground impedance. In this paper, the effect of ground reflection factor on the wave shapes of currents along lightning channel and also the electromagnetic fields associated with lightning channel are considered and the results are discussed accordingly. Moreover, the behaviours of field peaks against ground reflection changes are studied and the relationships between them are considered accordingly. The basic assumptions of this study are listed as follow;

1- The lightning channel is assumed to be vertical without any branches.
2- The ground surface is assumed to be flat.

LIGHTNING RETURN STROKE CURRENT AND ELECTROMAGNETIC FIELDS

Lightning return stroke current can be considered into two areas i.e. the channel base current and current wave shapes at different heights along lightning channel. Several functions consider on the simulation of channel base current whereas in this study the sum of two Heidler function is used as a current function as expressed by equations (1)[9].

$$i(0,t) = \left[\frac{i_{01}}{\eta_1}\frac{\left(\frac{t}{\tau_{11}}\right)^{n1}}{1+\left(\frac{t}{\tau_{11}}\right)^{n1}}\exp\left(\frac{-t}{\tau_{12}}\right) + \frac{i_{02}}{\eta_2}\frac{\left(\frac{t}{\tau_{21}}\right)^{n2}}{1+\left(\frac{t}{\tau_{21}}\right)^{n2}}\exp\left(\frac{-t}{\tau_{22}}\right)\right] \quad (1)$$

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),

$$\eta_1 = \exp\left[-\left(\tau_{11}/\tau_{12}\right)\left(n_1\frac{\tau_{12}}{\tau_{11}}\right)^{\frac{1}{n1}}\right],$$

$$\eta_2 = \exp\left[-\left(\tau_{21}/\tau_{22}\right)\left(n_2\frac{\tau_{22}}{\tau_{21}}\right)^{\frac{1}{n2}}\right].$$

On the other hand, in order to model the current wave shapes at different heights along lightning channel, different current models are proposed whereas they can be classified into four main groups as follow;

1- The gas dynamic current models
2- The distributed current models
3- The electromagnetic current models
4- The engineering current models

In this study, the general form of engineering current models is applied whereas the current wave shapes at different heights along lightning channel are expressed based on the channel base current and a particular attenuation height dependent factor as presented by equation(2)[5, 10-11].

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

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.

Likewise, in presence of ground reflection at channel base, the current function (equation 2) can be converted to equation (3) as follow[12];

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

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.

It should be mentioned that the return stroke velocity is usually entered into field calculations with a value between c/3 to 2c/3 where c is speed of light in free space[13]. On the other hand, the lightning electromagnetic fields at an observation above ground surface can be evaluated by equations (4) to (6) as follow[14-15];

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

$$\overrightarrow{E_r}(r,z,t_n)=\overrightarrow{E_r}(r,z,t_{n-1})+\Delta t\times\sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,2}(r,z,t_n,h_{m,i})-a'_m F_{i,2}(r,z,t_n,h'_{m,i})\} \quad (5)$$

$$\overrightarrow{E_z}(r,z,t_n)=\overrightarrow{E_z}(r,z,t_{n-1})+\Delta t\times\sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_{i,3}(r,z,t_n,h_{m,i})-a'_m F_{i,3}(r,z,t_n,h'_{m,i})\} \quad (6)$$

Where:

z is height of observation point,

c is light speed in free space,

r is radial distance from lightning channel,

β=v/c,

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

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

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

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

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

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

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

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

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

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

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

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

$\overrightarrow{E_r}(r,z,t)$ 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.

RESULTS AND DISCUSSION

In order to consider on the ground reflection effect on the values of lightning return stroke at different heights of lightning channel and also the lightning electromagnetic fields components, a sample of channel base current based on equation(1) is selected in this study whereas the corresponding current parameters are listed in Table.1 as follow;

Table.1.The channel base current parameters[7]

i_{01} (kA)	i_{02} (kA)	τ_{11} (μs)	τ_{12} (μs)	τ_{21} (μs)	τ_{22} (μs)	n_1	n_2
10.5	9	2	4.8	20	26	2	2

On the other hand, the current model is set on the Modified Transmission line with Exponential Decay model (MTLE) whereas the corresponding attenuation height dependent factor is P(z')=exp(-z'/λ)[7]. It should be mentioned that the values of v and λ are set at 1.5×10^{8}m/s and 2000m, respectively. Figure.1 shows the behavior of current at different heights along channel under different values of ground reflection at channel base. It illustrates, the ground reflection factor increases the values of lightning current at different time periods due to entering of additional reflected current into channel.

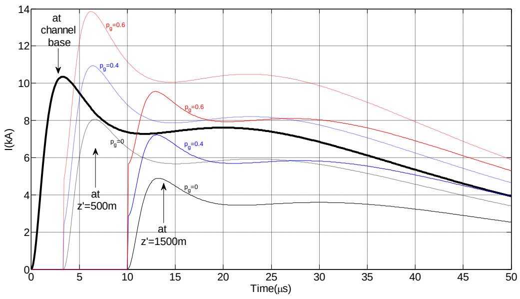

Figure.1.The current wave shapes at different heights along lightning channel under different conditions of ground reflection

Moreover, it demonstrates that the current values at a same value of time (in the same height level) have a direct relationship with the values of ground reflection factor. It should be mentioned that the ground reflection factor can be obtained from a function based on channel and ground impedance at channel base $\left(\frac{z_{ch}-z_g}{z_{ch}+z_g}\right)$. Therefore, by striking of lightning to grounds with different values of ground impedances, the current wave shape along lightning channel can be changed due to ground reflection changes at channel base whereas these currents are the sources of electromagnetic fields at an observation point above ground surface as expressed by equations (4) to (6). Likewise, The behavior of current peak at z'=1000m height along lightning channel under different values of ground reflection is shown in figure 2 whereas it illustrates a direct and a linear relationship between the current peak and the value of ground reflection factor.

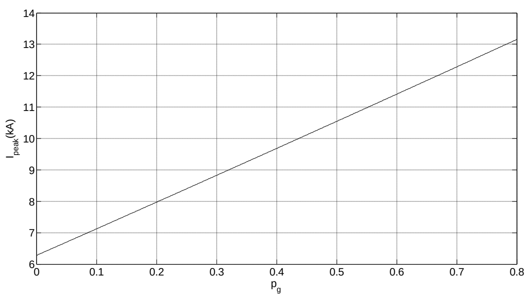

Figure.2.The behavior of current peak at z'=1000m height along lightning channel under different values of ground reflection

On the other hand, the effects of ground reflection factor on the values of electromagnetic field components at an observation point with r=150m and z=10m are considered as shown in figures 3 ,4 and 5 for magnetic flux density ,horizontal electric field and vertical electric field, respectively.

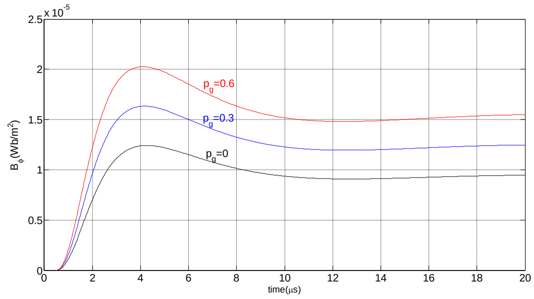

Figure.3.The simulated magnetic flux densities under different values of ground reflection (r=150m, z=10m)

Figures (3) to (5) illustrate that the ground reflection factor is directly effective on the values of lightning electromagnetic fields at different time periods. On the other hand, different coupling models are strangely dependent on the electromagnetic field components due to lightning channel to evaluate lightning induced voltage on the power lines[1-3].

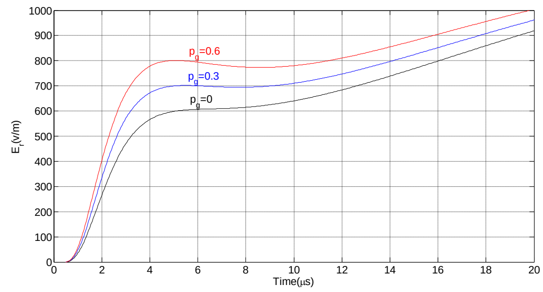

Figure.4.The simulated horizontal electric fields under different values of ground reflection (r=150m, z=10m)

Therefore, in order to set appropriate protection level on the lines versus lightning induced voltage, the impedance of ground around line should also be considered by entering of ground reflection factor into calculations. Likewise, the behaviours of B_Φ and E_z peaks versus ρ_g changes are considered as shown in figures 6 and 7, respectively.

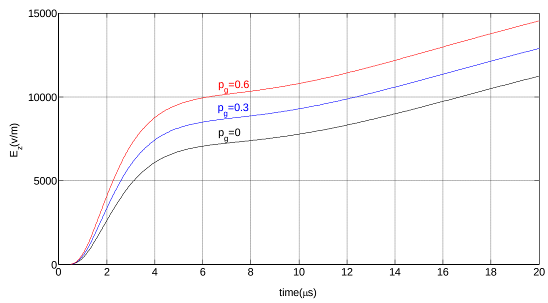

Figure.5.The simulated vertical electric fields under different values of ground reflection (r=150m, z=10m)

Figures 6 and 7 illustrate, the B_Φ and E_z peaks have a direct and almost a linear relationship with the values of ground reflection factor whereas the peak of vertical electric field can be increased about 30% (at $\rho_g = 0.8$) compared to the corresponding field peak (at $\rho_g = 0$) as shown in figure 7.

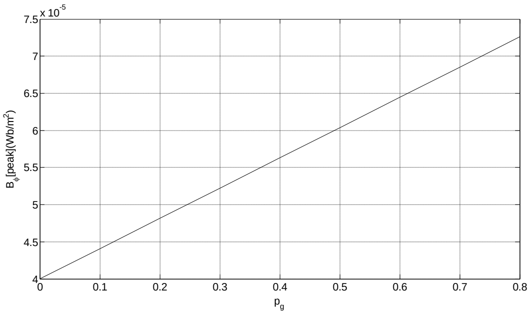

Figure.6.The behavior of B_Φ peaks versus ρ_g changes (r=50m, z=10m)

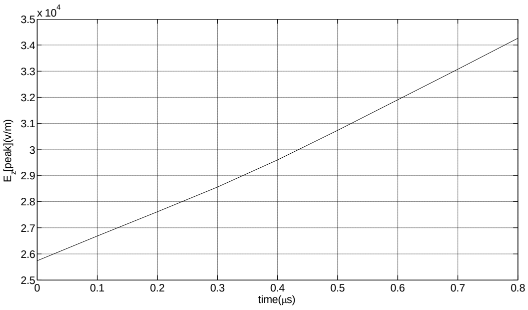

Figure.7.The behavior of E_z peaks versus ρ_g changes (r=50m, z=10m)

On the other hand, the peak of magnetic flux density can be increased about 80% (at $\rho_g = 0.8$) compared to the corresponding field peak (at $\rho_g = 0$) as illustrated in figure 6. Therefore, the effect of ground reflection factor on the peak of magnetic flux density is higher than similar effect on the peak of vertical electric field in similar conditions.

CONCLUSION

In this paper, the effects of ground reflection factor on the values of lightning currents at different heights along lightning channel and also on the electromagnetic fields due to lightning channel are considered and the results are discussed accordingly. The results showed, the current and field values have a direct relationship with the values of ground reflection factor whereas the ground reflection factor is dependent on the ground impedance at striking point and also the lightning induced voltage on the power lines is strongly dependent on the lightning electromagnetic field components at different points along power line. Therefore, in order to set appropriate protection level on the power lines, considering on the ground impedance around power line and entering of this factor into calculations can be useful for evaluation of lightning electromagnetic fields and lightning induced voltage on the power line.

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