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Effects of Lightning Current and Ground Conductivity on the Values of Vertical Electric Fields

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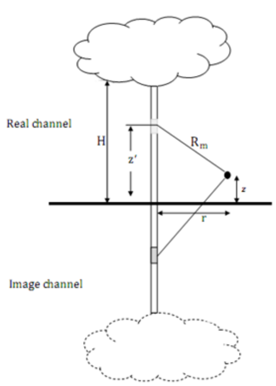
Graphical abstract



Abstract

In this paper, the relationship between current front time and front time of vertical electric field due to lightning channel at non perfect ground is considered. Results showed that the peak of simulated vertical electric fields under non perfect ground conductivity condition is decreased compared to the corresponding field at perfect ground while the front time of field is increased at non perfect case compared to the perfect one. Likewise, the effect of ground conductivity on the peak and front time of simulated vertical electric field is considered and the results are discussed accordingly.

Keywords: Electric field; lightning; ground conductivity

Abstrak

Dalam artikel ini, hubungan antara masa hadapan arus dan masa hadapan medan elektrik menegak disebabkan saluran kilat ke atas keadaan kekonduksian tanah tak-sempurna dipertimbangkan. Hasil kajian menunjukkan, puncak medan elektrik menegak yang disimulasi bagi keadaan kekonduksian tanah tak-sempurna menurun berbanding dengan bidang yang sama bagi tanah yang sempurna manakala masa hadapan bidang meningkat pada kes tak-sempurna berbanding dengan kes tanah yang sempurna. Begitu juga, kesan kekonduksian tanah ke atas masa puncak dan hadapan bagi medan elektrik menegak yang disimulasi telah dipertimbangkan dan keputusannya dibincangkan dengan sewajarnya.

Kata kunci: Medan elektrik; kilat; kekonduksian bawah

1.0 INTRODUCTION

Several studied have been done to evaluate electromagnetic fields associated with lightning channel at perfect and non-perfect ground conductivity conditions [1-6] whereas the lightning return stroke current wave shape and the parameters of ground can be more effective on the peak and the rise time of generated electromagnetic fields[6]. Moreover, the current rise time is more effective on the first peaks of electromagnetic fields [7] while it has a direct relationship with radiation component of electromagnetic fields. Therefore, in this study, the effects of current rise time and also the ground conductivity parameters on the values of vertical electric fields at different distances with respect to lightning channel are considered and the results are discussed accordingly. The basic assumptions in this study are listed as follow;

1- The lightning channel is as a vertical channel
2- The branches effects are ignored
3- The ground surface is assumed to be flat.

2.0 RERURN STROKE CURRENT

Lightning returns stroke current can be considered in two particular areas i.e. channel base and different heights above ground surface [8-9]. Several functions are proposed to simulate channel base current [10-13]. Heidler function [13] is usually used as a channel base function with good agreement with respect to measured currents in previous researches. In this study, the Heidler current function is applied to simulate the behavior of current at channel base as expressed by equation (1).

$$i(0,t) = \frac{i_0}{\eta} \frac{\left(\frac{t}{t_1}\right)^n}{1+\left(\frac{t}{t_1}\right)^n} \exp\left(\frac{-t}{t_2}\right) \quad (1)$$

Where

i_0 is the amplitudes of the channel base current,
t_1 is the front time constants,

t_2 is the decay- time constants,
n is the exponents (2~10),

$\eta = \exp\left[-\left({}^{t_1}/_{t_2}\right)\left(n \times \frac{t_2}{t_1}\right)^{\frac{1}{n}}\right]$.

On the other hand, the behavior of current at different heights above ground surface can be expressed by current models. In this study, the current model is based on the MTLE (Modified Transmission line with Exponential Decay model)[14] as expressed by equations (2) whereas the current at different heights along lightning channel can be expressed by the value of current at channel base and the value of particular attenuation height dependent factor. Noted that, the value of height dependent factor in MTLE current model is dependent on a constant parameter (λ) that is typically set between 1-2km[4, 14].

$$i(z',t) = \begin{cases} i(0, t - z'/v)\exp(-z'/\lambda), & z' \le vt \\ 0, & z' > vt \end{cases} \qquad (2)$$

Where:

z' is the instantaneous height along lightning channel ,
λ is the decay constant which allows the current to reduce its amplitude with height,
v is the return stroke current velocity along lightning channel

It should be mentioned that the return stroke velocity is usually assumed constant value in the range between c/2 to 2c/3 (c is speed of light in free space). However in reality return stroke velocity is a height dependent variable [15-17]. In this study, the values of v and λ are set to 1×10^8 m/s and 1500m, respectively.

■3.0 LIGHTNING VERTICAL ELECTRIC FIELD

The vertical electric fields associated with lightning channel for a perfect ground conductivity condition can be evaluated by equation (3) below whereas the geometry of problem is shown in Figure 1 [2]. Noted that the third part of F_i term (in equation 3) is the radiation component of vertical electric field that is effective on the initial peak at different radial distances with respect to lightning channel and also total field at far distances with respect to lightning channel[2, 18].

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

Where:

k is division factor (>=2)

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

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

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

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

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

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

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

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

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

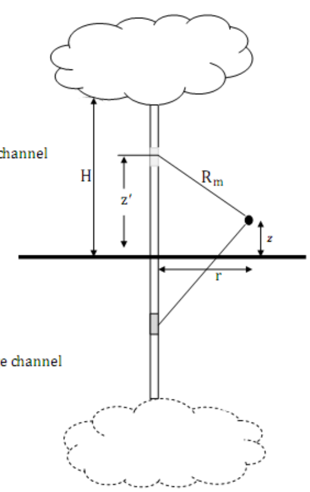


Figure 1 The geometry of problem

It should be mention that the values of electromagnetic fields components at time equal to or less than $\frac{\sqrt{r^2+z^2}}{c}$ are zero. On the other hand the values of vertical electric fields on non perfect ground conductivity can be obtained from equation (4) below [18];

$$E_z^{NPG}(0,r,t) = \int_0^t E_z(0,r,t-\tau)S_f(0,r,\tau)d\tau \qquad (4)$$

Where:

E_z^{NPG} is the vertical electric field in non perfect ground conductivity condition,

E_z is the vertical electric field in perfect ground conductivity condition that can be evaluated by equation (3),

ε_r is the relative dielectric constant,

σ is the ground conductivity typically in the range 5.5×10^{-6} to 5.5×10^{-2} S/m for non perfect ground.

$$S_f(0,r,t) = \frac{d\{1-\exp(\frac{-t^2}{4\zeta^2})+2\alpha(\varepsilon_r+1)\frac{J(x)}{t}\}}{dt},$$

$$\zeta = \sqrt{\frac{r}{2\mu_0\sigma c^3}},$$

$$\alpha = \frac{1}{2\mu_0\sigma c^2},$$

$$x = \frac{t}{2\zeta},$$

$$J(x) = x^2(1-x^2).$$

4.0 RESULTS AND DISCUSSION

In order to consider on the effect of time from the peak values of vertical electric field a sample of current based on equation (1) is applied in this study whereas the current parameters are tabulated in Table 1 as follow;

Table 1 Current parameters based on equation (1)

I_0(kA)	t_1(μs)	t_2(μs)	n
11.3	0.072	30	2

On the other hand, the channel base current wave shape is illustrated in Figure 2 as follow;

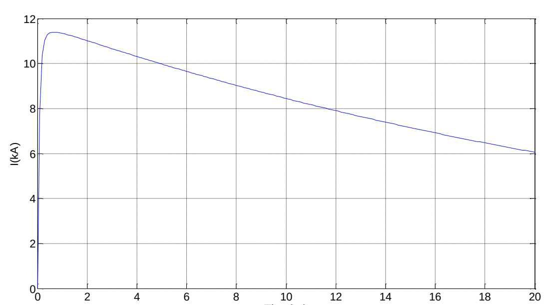


Figure 2 Simulated channel base current based on current parameters from Table 1

Therefore, by entering six different current wave shapes with different time fronts as shown in Figure 3 into field expressions (equations 3 and 4) the vertical electric fields in a non perfect ground conductivity condition are demonstrated in Figure 4.

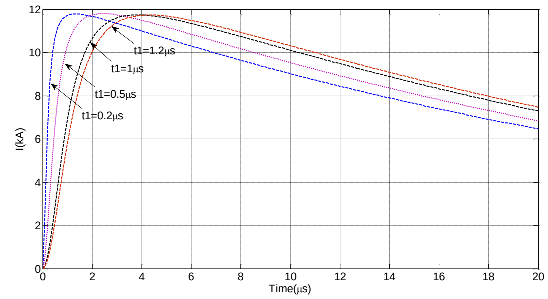


Figure 3 Return stroke currents with different front times

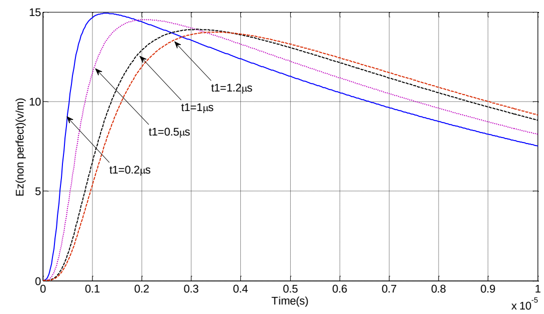


Figure 4 Comparison between the simulated vertical electric fields in non perfect ground conductivity condition (r=15km, z=0, σ=0.001, $\varepsilon_r = 10$)

Figure 4 shows that the front time of evaluated vertical electric fields have a direct relationship with the corresponding current time front in Figure 3 whereas the current time front is more effective on the values of $\frac{\partial i}{\partial t}$ and $\frac{\partial^2 i}{\partial t^2}$ in F_i term of equation (3)[19,20]. On the other hand, the effect of ground conductivity parameter on the values of vertical electric field is shown in Figure 5. Figure 5 illustrates that by increasing the value of ground conductivity, the front time and also the field peak are decreased.

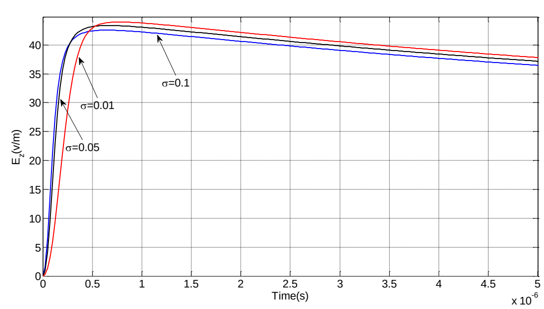


Figure 5 Comparison between the simulated vertical electric fields in different non perfect ground conductivity conditions (r=5km, z=0, $\varepsilon_r = 10$)

Figure 6 and Figure 7 illustrates comparison between the simulated vertical electric field at perfect ground and non perfect ground conductivity conditions. The simulated field due to non perfect ground conductivity has higher value of front time and lower value of field peak compared to the corresponding simulated field in perfect ground condition.

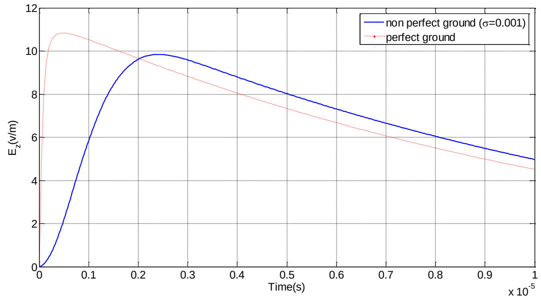


Figure 6 Comparison between the simulated vertical electric fields in perfect and non perfect ground conductivity conditions (r=20km, z=0, σ=0.001, $\varepsilon_r = 10$)

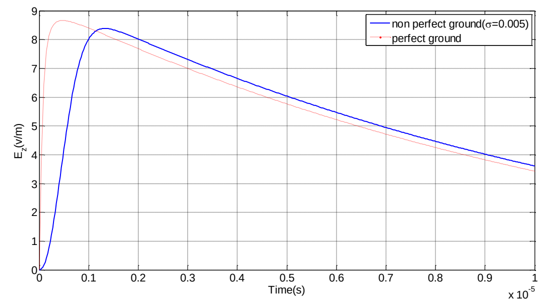


Figure 7 Comparison between the simulated vertical electric fields in perfect and non perfect ground conductivity conditions (r=25km, z=0, σ=0.005, $\varepsilon_r = 10$)

Likewise, the simulated vertical electric fields at perfect ground and another non perfect ground conductivity condition are compared together whereas it confirms that the time front of vertical electric field under non perfect conductivity condition is higher than the corresponding simulated field for perfect ground. Moreover, the field peak is decreased in non perfect case compared to simulated field that is obtained from perfect ground. The results show that the ground conductivity can be considered as an effective parameter that can change the values of time front and peak of vertical electric field associated with lightning channel. Moreover, the results illustrate that the current time front has a direct relationship with the corresponding simulated vertical electric field at non perfect ground case.

■5.0 CONCLUSION

In this paper, the vertical electric field due to lightning channel in perfect and non perfect ground conductivity conditions are considered and the effect of ground conductivity parameter on the peak value and time front of field is considered and the results are discussed accordingly. Likewise, the relation between the front time of current and the field time front is considered. The results showed, the ground conductivity can effectively reduce the field peak and increase the front time of field compared with perfect ground condition.

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