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The behavior of radiation component of lightning electric versus current time front changes

Abstract .*The electromagnetic fields associated with a lightning channel can have an effect on power lines by creating induced voltages on the power networks. The shape of a channel base current especially up to the first value has a great effect on the radiation components of electromagnetic fields, while the electromagnetic fields due to lightning can be evaluated by considering the different field components. This study considers the behavior of the radiation component of the electric field versus current time front changes as the radiation component is a critical component of the electric field. The results show that the radiation component has a greater effect on the total field at far distances from the lightning channel while this effect will be larger for close and intermediate distances from the lightning channel only during the initial time periods. Furthermore, the results illustrate that the current time front has an inverse relationship with the radiation component of an electric field at different distances from the lighting channel.*

Streszczenie. *W artykule przedstawiono analizę wpływu zmian czoła fali prądowej, wyładowania atmosferycznego na poziom emitowanego promieniowania pola elektrycznego i oddziaływanie tego pola na linie energetyczne. Zbadano także zawartość promieniowania pola elektrycznego w całkowitym wytworzonym polu w zależność od odległości od wyładowania. (**Wpływ zmian czoła fali prądowej wyładowania atmosferycznego na promieniowanie pola elektrycznego**)*

Keywords: Lightning, electric field, return stroke current
Słowa kluczowe: Pole elektryczne wyładowania atmosferycznego, udar powrotny prądu

Introduction

The electromagnetic fields associated with a lightning channel can have a great effect on power lines by creating lightning induced voltages on the line[1]. Several studies have been undertaken to evaluate the electromagnetic fields due to a lightning channel using the widely used assumptions expressed as follows[2, 3]:

i. The lightning channel is vertical.
ii. The branch effects are ignored.
iii. The ground conductivity is assumed to be perfect.

The electromagnetic fields are evaluated by setting a channel base current function and a current model to represent the current wave shape at different heights along a lightning channel. The electric fields due to the lightning can be classified into three components i.e. the electrostatic, the induction and the radiation components while the lightning magnetic fields can be considered as consisting of two components i.e. the magnostatic and the radiation components [4, 5]. The electromagnetic field measurements show that the radiation components of the electromagnetic fields have a greater effect at the initial peak of the total fields at different distances from the lightning channel [4, 5]. In addition, the radiation component has more effect on the total electromagnetic fields at far distances from the lightning channel [4]. On the other hand, the radiation part is dependent on the derivative of the lightning current with respect to time which in turn is dependent on the current front time. Therefore, based on a realistic current function, the relation between the current front time and radiation field components will be considered. Furthermore, the effect of the radiation electric field on the total electric field at different distances from the lightning channel will be examined.

Return stroke current

The lightning current can be considered in two areas i.e. the channel base current and the current at different heights along the lightning channel. The channel base current can be simulated by current functions while the current wave shape at different heights can be described by current models. In this study, the current function is based on the improvement of Dindorefer and Uman (DU) on the Heidler function to provide a good agreement between the measured current and the simulated channel base current as illustrated in Figure.1 using typical current parameters that are expressed in Table.1. The DU function is given by equation (1) as follows [6-8]:

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

where

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

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

Table.1. Typical current parameters [9]

Case	i_{01} (kA)	i_{02} (kA)	τ_{11} (µs)	τ_{12} (µs)	τ_{21} (µs)	τ_{22} (µs)	n_1	n_2
1	8.5	3.2	0.12	14	14	95	2	2

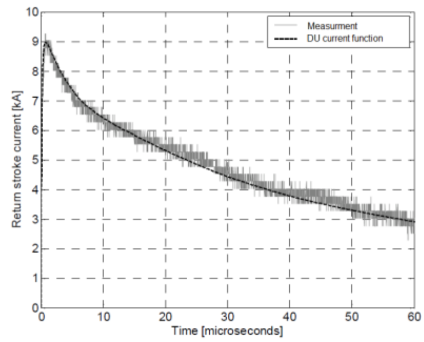

Fig.1.Comparison between the measured and simulated return stroke currents[9]

On the other hand, the current wave shape at different heights along a lightning channel can be expressed by the engineering current models. The general form of the engineering current models can be expressed by equation (2) as follows [6, 8]:

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

Furthermore, the return stroke velocity along a lightning channel can be entered into the current model by using an average value of the return stroke front velocities along channel whereby it is typically between c/2 to 2c/3 (c is equal to the speed of light in free space) [10].

Lightning Electromagnetic fields

The electromagnetic fields associated with a lightning channel can be evaluated by equations (3) to (7) assuming the geometry of the problem as shown in Figure.2[11, 12].

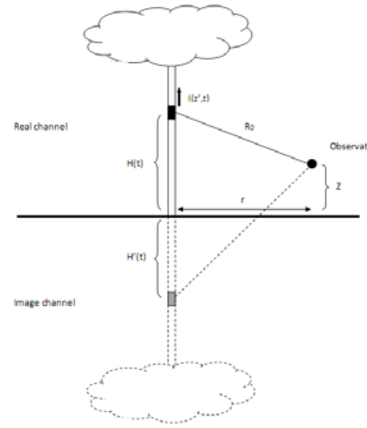

Fig. 2.The geometry of problem

(3) $$\vec{E}_r(r,z,t)=\left(\frac{1}{4\pi\varepsilon_0}\right)\int_{H'(t)}^{H(t)}\left(\frac{3r(z-z')}{R_0^{5}}\int_0^t i\left(z',\tau-\frac{R_0}{c}\right)d\tau+\frac{3r(z-z')}{cR_0^{4}}\,i\left(z',t-\frac{R_0}{c}\right)+\frac{r(z-z')}{c^2R_0^{3}}\frac{\partial i\left(z',t-\frac{R_0}{c}\right)}{\partial t}\right)dz'$$

(4) $$\vec{E}_z(r,z,t)=\left(\frac{1}{4\pi\varepsilon_0}\right)\int_{H'(t)}^{H(t)}\left(\frac{2(z-z')^2-r^2}{R_0^{5}}\int_0^t i\left(z',\tau-\frac{R_0}{c}\right)d\tau+\frac{2(z-z')^2-r^2}{cR_0^{4}}\,i\left(z',t-\frac{R_0}{c}\right)-\frac{r^2}{c^2R_0^{3}}\frac{\partial i\left(z',t-\frac{R_0}{c}\right)}{\partial t}\right)dz'$$

(5) $$\vec{B}_\varphi(r,z,t)=\left(\frac{\mu_0}{4\pi}\right)\int_{H'(t)}^{H(t)}\left(\frac{r}{R_0^{3}}\,i\left(z',t-\frac{R_0}{c}\right)+\frac{r}{cR_0^{2}}\frac{\partial i\left(z',t-\frac{R_0}{c}\right)}{\partial t}\right)dz'$$

(6) $$H(t)=\beta\chi^2\{-(\beta z-ct)-M_1\}$$

(7) $$H'(t)=\beta\chi^2\{-(\beta z+ct)+M_2\}$$

The first, second and third terms of equations (3) and (4) present the electrostatic, induction and radiation components which have more effect on the total field at close, intermediate and far distances from the lightning channel, respectively. On the other hand, the magnetic flux density can be split into magnostatic and radiation components corresponding to the first and second terms of equation (5), respectively. Moreover, the radiation components have a greater effect on the initial peak of the corresponding total electromagnetic fields at different distances from the lightning channel especially during the initial time periods. Therefore, based on equations (4) and (5), the radiation components of the vertical electric field and the magnetic flux density on the surface of the ground can be estimated by equations (8) and (9) respectively as follows [13]:

(8) $$\vec{E}_z^{\,radiation}(r,z=0,t)=\left(\frac{1}{2\pi\varepsilon_0}\right)\int_0^{H(t)}-\frac{r^2}{c^2(r^2+z'^2)^{3/2}}\frac{\partial i\left(z',t-\frac{\sqrt{r^2+z'^2}}{c}\right)}{\partial t}dz'$$

(9) $$\vec{B}_\varphi^{\,radiation}(r,z=0,t)=\left(\frac{\mu_0}{2\pi}\right)\int_0^{H(t)}\frac{r}{c(r^2+z'^2)}\frac{\partial i\left(z',t-\frac{\sqrt{r^2+z'^2}}{c}\right)}{\partial t}dz'$$

Equations (8) and (9) indicate that the radiation components of the electromagnetic fields are dependent on the derivative of current with respect to time. Figure.3 shows a typical wave shape of di/dt where the initial parameters are obtained from Table 1. Also, in order to consider the front time effect on the vertical electric field, the channel base current from Table 1 is extended to two others channel based currents with higher values of front time compared to the original current in Table 1 whereas the current parameters are listed in Table.2.

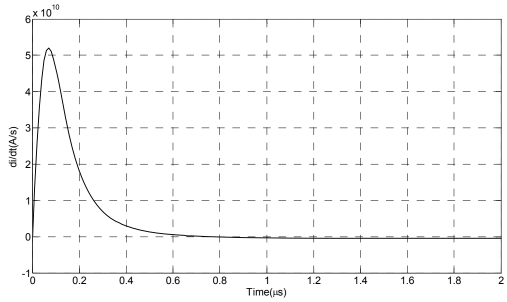

Fig.3.Derivative of current to time based onTable.1

Table.2.The initial parameters of extended currents

Case	i_{01} (kA)	i_{02} (kA)	τ_{11} (μs)	τ_{12} (μs)	τ_{21} (μs)	τ_{22} (μs)	n_1	n_2
2	8.374	3.768	0.243	12.47	14.99	81.69	2	2
3	8.320	4.289	0.3798	10.28	16.16	67.61	2	2

Likewise, Figure 4 illustrates a comparison between channel base currents with different front times (t_{ft}) using the initial parameters obtained from Tables 1 and 2 ($t_{ft}^{(case1)} < t_{ft}^{(case2)} < t_{ft}^{(case3)}$). Furthermore, it shows, they have an almost similar behavior at the peak values and the current shape after the peak.

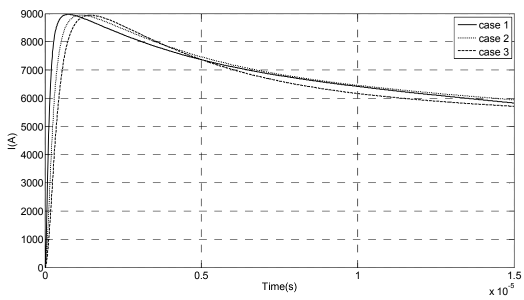

Fig.4.Comparison between different currents

Therefore, based on equation (2), the MTLE current model with a typical value of λ equal to 2000 m is selected for this study and the corresponding attenuation factor can be found from equation (11) [8, 14]. Moreover, the return stroke velocity is set at 1.5×10^8 m/s as it is usually entered into calculations in the range between c/2 to 2c/3[10].

(11) $$P(z')=e^{-z'/\lambda}$$

Figure.5 shows the radiation component of vertical electric fields due to three current cases at different distances with respect to channel when the observation point is set on the ground surface. It illustrates, by increasing the front time in the return stroke currents, radiation components are decreased because radiation part is directly dependent on di/dt and time front has a greater effect on the di/dt values as demonstrated in Figure.6. On the other hand, the front times of radiation components have a direct relationship with current time fronts. In addition, by increasing of radial distance with respect to channel, the radiation fields are reduced as shown in Figure.5. Figure.7 shows the radiation fields due to three current cases at a close distance from a lightning channel (at r=50m and z=0). It confirms the relation between the radiation field and the time front that is expressed for far distances from a lightning channel.

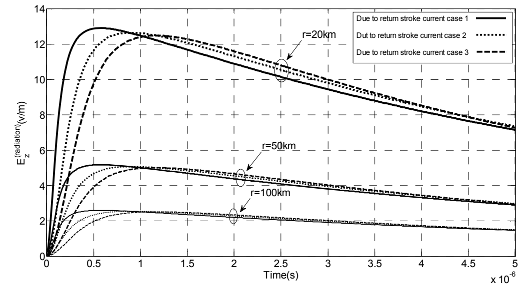

Fig. 5.Radiation component of vertical electric fields

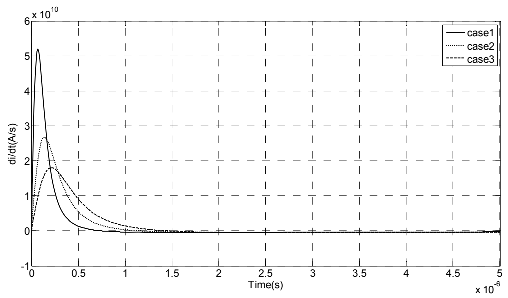

Fig. 6.Comparison between $\frac{di}{dt}$ for different cases

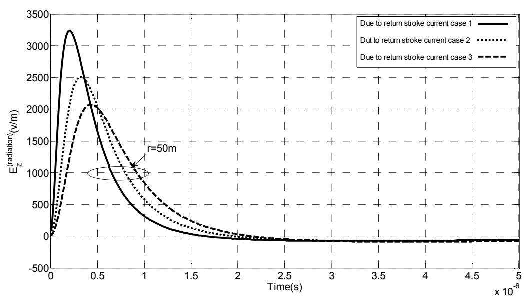

Fig. 7.Radiation component of vertical electric fields

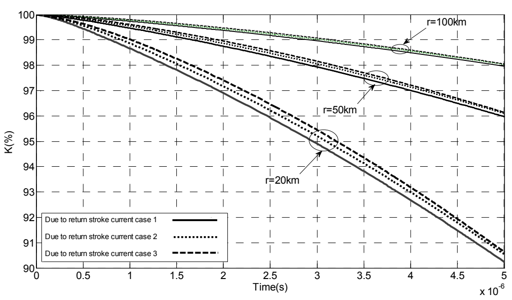

Figure.8. the K factor behavior at z=0

In order to consider the effect of the radiation component on the total vertical electric fields at different distances from a lightning channel, an indicator factor is introduced as expressed by equation (12) with a maximum value of K of 100% for the full effect of the radiation component on the total vertical electric field.

(12) $$K = 100 + 100 \times \frac{E_z^{(radiation)} - E_z^{(total)}}{E_z^{(total)}}$$

Figure.8 shows the behavior of K at far distances from lightning channel while the radiation fields have a greater effect on the total fields during initial time periods compared to subsequent times. Also, it illustrates that the values of the K factor due to the applied currents are in the ranges100~98,100~96 and 100~90.5 for 100 km, 50 km and 20 km, respectively during the first 5 μs. Furthermore, it demonstrates a direct relationship between the K factor and current time front and also by increasing of radial distance, the effect of radiation component on the total electric field is increased. Likewise, Figure 8 indicates that by assuming the total electric field with radiation components at far distances from the lightning channel some percentage of electric field will be neglected while these neglected values of electric field are reduced by increasing the radial distance from the lightning channel. In addition, the effect of the radiation component on the total electric field is considered at close and intermediate distances from the lightning channel as shown in Figure.9 whereas z=0. It illustrates that the K factor has higher values during the initial time periods compared to later times. Moreover, it demonstrates that by decreasing distance from channel, the interval time periods of the effect of the radiation component on the total field will be reduced. Also, Figure.9 confirms the direct relationship between the K factor and the front time of the channel base current that is expressed for far distances from channel.

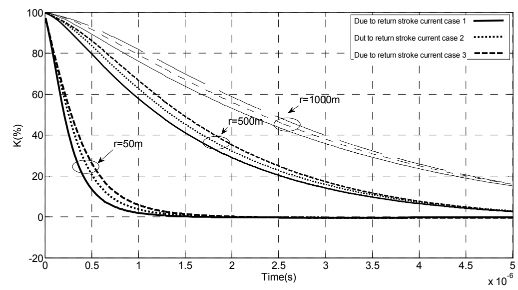

Fig .9. the K factor behavior at closed distances

Also, Figures.8 and 9 show that by increasing the time front of currents, the effect of the radiation component on the corresponding total field is increased.

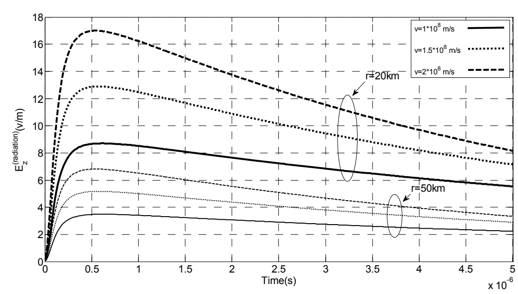

Fig. 10.the velocity effect on radiation components

Figure.10 illustrates the velocity effect on the radiation fields at two different distances from the lightning channel when the channel base current is obtained from Table 1. It demonstrates that the radiation fields increase when the return stroke velocity is increased. Moreover, Figure.11 shows the effect of the return stroke velocity on the K factor at two different distances from the lightning channel. It demonstrates that the K factor has an inverse relationship with the value of return stroke velocity.

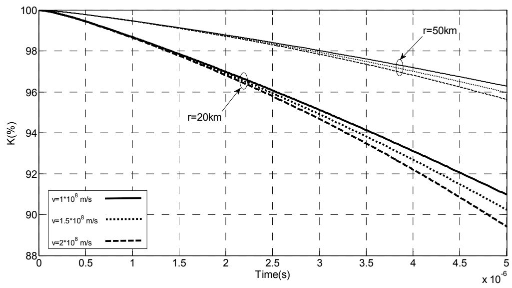

Fig. 11. The velocity effect on K parameter

Conclusion

In this study, the electromagnetic fields due to a lightning channel are considered. Also, the effect of the current time front on the radiation component of electric field at different distances from the lightning channel has been studied. The results illustrate that the radiation component of an electric field has more effect on the total electric field at far distances from the lightning channel while by increasing the distance from the lightning channel this effect will be increased. In addition, the current time front has an inverse relationship with the radiation component of an electric field. Therefore, the channel base currents with lower values of current front time have higher values of radiation field components compared to the channel base currents with higher values of time front under similar conditions in terms of current peak and shape of the current after the peak. Also, the results for the close and intermediate distance from a lightning channel show that the radiation component has more effect on the total field just in the initial time periods. Furthermore, the radiation component behavior versus the change in the return stroke velocity is considered and it is found that they have a direct relationship.

Nomenclature

$\vec{E}_z(r,z,t)$	vertical electric field
$\vec{E}_r(r,z,t)$	horizontal electric field
$\vec{B}_\varphi(r,z,t)$	magnetic flux density
z'	temporary charge height along channel
λ	decay constant
I (z',t)	return stroke current at height of z'
I (0,t)	return stroke current at channel base
P (z')	attenuation height depend factor
v_f	return stoke front velocity
v	return stroke current velocity
c	speed of light in free space
$i_{01}/\ i_{02}$	amplitude of the channel base current
$\tau_{11}\ /\tau_{12}$	front time constants
τ_{21}/τ_{22}	decay- time constants
$n_1/\ n_2$	exponent (2~10)
β	v/c
$R_0(z')$	$\sqrt{r^2+(z-z')^2}$
M_1	$\sqrt{(\beta ct-z)^2+(\frac{r}{X})^2}$
M_2	$\sqrt{(\beta ct+z)^2+(\frac{r}{X})^2}$

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