LIGHTNING ELECTROMAGNETIC FIELDS AROUND TRANSMISSION LINES USING FDTD

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Abstract: For proper design of the transmission and distribution insulation systems, it is necessary to fully clarify the lightning phenomena characteristics. In this paper, two typical power transmission lines (500 kV and 220 kV) are modeled to compute the lightning electromagnetic fields around the transmission lines. The lightning electromagnetic fields around the different power lines are calculated using the finite difference time domain (FDTD) method with Maxwell's equations. Two selected zones are used to capture the electromagnetic fields while lightning strike. The first zone is around the insulators and the second is at the ground level underneath the power line at 1 m above ground and at the power line right of way (ROW). The correlation between the induced magnetic and electric fields is verified in the free space inside the two selected zones. The induced electromagnetic fields at different positions of each power line phases are evaluated. The obtained results show that while lightning strikes the conductor, the waveforms of electromagnetic field obtained at the selected monitoring points are the same as the lightning current's waveform. The amplitude of the electromagnetic field intensities exhibits a stabile linear relationship with the lightning currents as the free air intrinsic impedance.

1- INTRODUCTION

Characteristics of electric and magnetic fields produced by lightning discharges are being the core of the recent research areas worldwide. Indeed, the lightning phenomenon is still full of mystery parameters that should be tackled adequately [1]. Lightning strikes to the overhead power transmission lines are the major accidental reason of their outage of service or insulation damage. Recently, the lightning strikes produce over-imposed electromagnetic waves on the overhead power transmission lines. Subsequently, these electromagnetic waves have probable potential and direct influences on the insulation levels design process [2, 3]. The effects of presence of the strike object on the radiated electric and magnetic fields depend essentially on the height and the shape of object and the distance of observation points as well [4-6]. The lightning current waveform is a microsecond-scale waveforms that are probably formed in a shape of downward negative lightning. Meanwhile, it is of an order of millisecond-scale waveforms for subsequent stokes [7]. In the absence of structure with high height level, the most of positive lightning is initiated by a positively charged downward leader. The highest directly measured current for positive lightning with charge transfer of few100 C is about 320 kA [8]. The measured current parameters of the positive and negative first strokes are considered in common weighted statistics. The damages caused by lightning have no significant dependability on the direction of the current flow [9, 10]. Lightning strikes have been observed for about three decades over the Canadian National Tower to simultaneously capture the lightning parameters and return-stroke current derivative at about 475 m above ground (using a Rogowski coil and broadband active sensors). A good linear correlation between the magnetic field wave and that of the current is detected [11]. For modeling electromagnetic return-stroke, Maxwell's equations are solved to yield the distribution of current along the lightning channel using numerical techniques, such as the method of moments (MOM) or the finite-difference method [12-15]. These approaches are the Cooray formula, Exact evaluation of the field equation numerically and numerical solution of Maxwell's equation using Finite Difference Time Domain (FDTD). The solution using exact numerically and the FDTD are virtually identical. It is also shown that the Cooray formula has good accuracy for the underground fields, especially for their early time response. In this paper, the 3-D finite-difference time-domain (FDTD) for solving Maxwell's equations is tackled to calculate the lightning magnetic and electric fields during lightning conditions around two typical 500 kV and 220 kV overhead transmission lines. Moreover, the field equation is solved by exact solution analytically to verify how far the convergence of the two methods. To represent the lightning electromagnetic fields, many Matlab M-Script files have been developed based on the three dimensional techniques field calculation using the FDTD technique. The electromagnetic fields are calculated at different points around the simulated towers and at the Right Of Way (ROW) of each line. The lightning current is simulated based on the summation of the two Heidler's functions and its derivative in order to evaluate its suitability to simulate the lightning return-stroke current and its derivative, respectively. The lightning magnetic and electric fields at the selected points around the towers are calculated.

2- TRANSMISSION LINES AND LIGHTNING CURRENT SIMULATION.

2.1 System configurations

Two power lines of 500 kV and 220 kV are simulated to calculate the lightning electromagnetic fields. The power line conductors of each phase are simulated as a series of connected current segments to closely fit the geometry of the catenary shape based on Biot-Savart low in three dimensions and using FDTD Method [16-17]. Two different positions for calculating the lightning electromagnetic fields are selected at the ground level of (1 m, 4m and 7 m from ground) and at 1m from the power line conductors. Moreover the electromagnetic fields are calculated over the entire area underneath the power line along two different directions (lateral and longitudinal). Figure 1 shows the main configurations of the two simulated lines. The lightning is assumed to strike the power line conductors of each line and the ground conductors as well to demonstrate the effects of ground conductors.

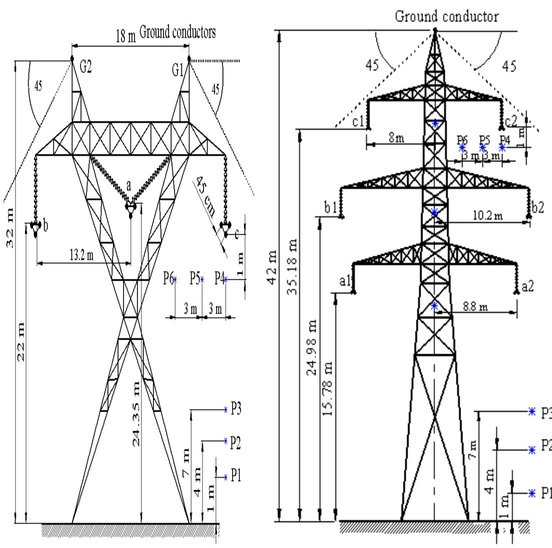

Figure1: 500 kV and 220 kV tower with ground conductors.

2.2 Lightning current simulation

For the developed charges cloud to ground or ground to cloud with different polarities, there are four different lightning strikes. These types depend on the cloud polarity to the ground ("positive or negative cloud" to "negative or positive" ground). Recent researches regarding the lightning current simulation for the first and subsequent return stroke tackled the more appropriate analytical expression of the sum of so-called Heidler's functions [18-19].

$$\mathrm{i}(0,\mathrm{t}) = \left(\frac{\mathrm{I}_{01}}{\eta_1}\left(\frac{\left(\frac{\mathrm{t}}{\tau_{11}}\right)^{\mathrm{n}}}{1+\left(\frac{\mathrm{t}}{\tau_{11}}\right)^{\mathrm{n}}}\right)\exp\left(-\frac{\mathrm{t}}{\tau_{12}}\right)\right) + \left(\frac{\mathrm{I}_{02}}{\eta_2}\left(\frac{\left(\frac{\mathrm{t}}{\tau_{21}}\right)^{\mathrm{n}}}{1+\left(\frac{\mathrm{t}}{\tau_{21}}\right)^{\mathrm{n}}}\right)\exp\left(-\frac{\mathrm{t}}{\tau_{22}}\right)\right) \qquad (1)$$

$$\eta = \exp\left[-\left(\frac{\tau_{i1}}{\tau_{i2}}\right)\left(n\left(\frac{\tau_{i2}}{\tau_{i1}}\right)\right)^{\frac{1}{n}}\right] \qquad (2)$$

Where:
I_{01}: *is the* amplitude parameter of the front current
I_{02}: *is the* amplitude parameter of the decay current
τ_{i1} - front time constant (i=1,2)
τ_{i2} - decay time constant (i=1,2)
η : is the amplitude correction factor
n : is exponent (2 … 10)

Assuming the highest protection level [20] then Table 1 gives the parameters of the simulated double-exponential lightning currents.

Table1: Main parameters of the simulated lightning currents.

Simulated Stroke	**I_1 (kA)**	**t_f μS**	**t_t μS**	**τ_1 μS**	**τ_2 μS**	**η**
Positive First	200	10	350	470.1	4064	0.951
Negative First	100	1	200	284.3	373.9	0.990
Negative subs.	50	0.25	100	143.1	92.4	0.995

3- LIGHTNING ELECTROMAGNETIC FIELDS CALCULATION

3.1 Using exact field equations (analytically)

Two simultaneous steps have to be tackled to evaluate the lightning electromagnetic fields. The first step is to calculate the currents on the conductors due to lightning. The second step is to calculate the radiated electromagnetic fields around the conductors due to the travelling current waveform. The lightning transient electromagnetic fields can be evaluated numerically or analytically [21] by assuming the line or conductor to be a cylinder with very small radius with respect to the wavelength. This is because the effective reflection is usually proportional to the target electrical size coupled with the frequency. Frequency should be in microwave frequency range of greater than 100 MHz to considered effective reflection. Figure 2 shows a line segment of length L along z direction from the origin and P(x,y,z) is an arbitrary point in space around the conductor [22]. For the electromagnetic field potential vector $\vec{A}_z(t)$ for a filament along the z- axis is presented while the X and Y components of the potential vector can be neglected [17]. The z component $A_z(t)$ created by current i(ξ ,t) flowing in the line at the point P can be expressed as:

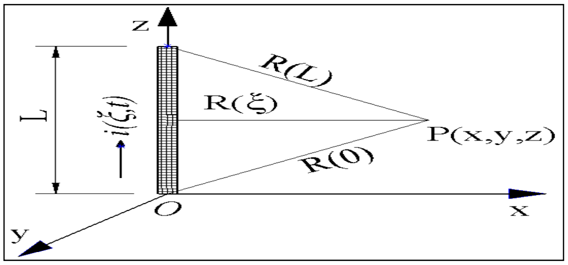

Figure 2: Simple presentation of the current segment.

$$A_z(t) = \frac{\mu_o}{4\pi}\int_0^L i(\xi, t - R(\xi)/c)/R(\xi)d\xi \tag{3}$$

$$i(\xi, t - \frac{R(\xi)}{c}) = i_g(t - \frac{\xi + R(\xi)}{c}) + i_f(t - \frac{-\xi + R(\xi)}{c}) \tag{4}$$

where:

- ξ : arbitrary point on the conductors
- C : speed of the light in free space (3x 10^8 m/s)
- i_g : the current wave travelling in the forward direction
- i_f : the current wave travelling in the backward direction.

the magnetic field can be evaluated by;

$$H_x(t) = \frac{1}{\mu_\circ}\frac{\partial A_z(t)}{\partial y};\ H_y(t) = -\frac{1}{\mu_\circ}\frac{\partial A_z(t)}{\partial x};\ H_z(t) = 0 \tag{5}$$

After determining the transient magnetic field, the transient electric field $\vec{E}(t)$ is calculated by integrating the curl of $\vec{H}(t)$ to get the three components of the electric field as follows:

$$\begin{aligned} E_x(t) &= \frac{1}{\varepsilon_\circ}\int_0^t \frac{\partial H_y(t)}{\partial z}dt \\ E_y(t) &= \frac{1}{\varepsilon_\circ}\int_0^t \frac{\partial H_x(t)}{\partial z}dt \\ E_z(t) &= \frac{1}{\varepsilon_\circ}\int_0^t \left[\frac{\partial H_y(t)}{\partial x} - \frac{\partial H_x(t)}{\partial y}\right]dt \end{aligned} \tag{6}$$

3.2 Using FDTD Method

Maxwell's equations for a driving sources and lossy dielectric materials can be presented as in Equation 7 and Equation 8. Expanding these two main equations over Yee cell in space with time domain [22-24] yields the main relations of electromagnetic fields in both space and time domain.

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu}\nabla X\vec{E} - \frac{\sigma}{\mu}\vec{H} \tag{7}$$

$$\frac{\partial \vec{E}}{\partial t} + \frac{\sigma}{\varepsilon}\vec{E} = \frac{1}{\varepsilon}\nabla X\vec{H} \tag{8}$$

Expanding E and H over the Yee cell in space and time domain yields to six sub-equations. These six equations present the main standard form of the develop FDTD algorithm used to monitor and capture the effects of the distribution of both magnetic and electric field and their duality effects.

4- LIGHTNING ELECTROMAGNETIC FIELDS RESULTS

4.1 For Normal Conditions

The maximum lightning electromagnetic fields at different points under 500 kV and 220 kV (with the configurations shown in Figure 1 for normal operation with each power line loaded by 1 kA are tabulated in Table 2. The calculation is performed analytically and numerically to validate the accuracy of the FDTD algorithm. The percentage error is found to be less than 1 % for 500 kV and less than 2 % for 220 kV power line. The maximum induced magnetic field is about 222 A/m while the maximum electric field value is about 83 kV/m at point No. 4 under 500 kV power line under normal operation. The maximum induced magnetic field is about 191 A/m while the maximum electric field value is about 72 kV/m at point No. 4 under 220 kV power line under normal operation. The electromagnetic field profiles under 220 kV power lines are presented in Figure 3 for normal operation at 1 m above ground through an area between mid-span of two subsequent line spans of one complete span with the tower positioned in the center of the electromagnetic field profiles. For 500 kV power line the maximum magnetic field is about 17 A/m at mid-span while the maximum electric field value is about 10 kV/m at mid-span position. Meanwhile, for 220 kV power line the maximum magnetic field is about 23 A/m at mid-span while the maximum electric field value is about 13 kV/m at mid-span position.

Table 2: Maximum induced electromagnetic field values for normal operation of 500 kV and 220 kV lines.

500 kV	**Magnetic field (A/m)**			**Electric field (kV/m)**		
	analytically	**numerically**	**% error**	**analytically**	**numerically**	**% error**
P1	7.216	7.232	0.22	2.72	2.73	0.37
P2	8.968	8.992	0.27	3.37	3.39	0.59
P3	11.45	11.48	0.21	4.31	4.33	0.46
P4	222.4	222.8	0.18	83.91	83.97	0.072
P5	77.12	77.52	0.52	29.18	29.21	0.1
P6	51.76	51.79	0.05	19.49	19.52	0.15
220 kV	**Magnetic field (A/m)**			**Electric field (kV/m)**		
	analytically	**numerically**	**% error**	**analytically**	**numerically**	**% error**
P1	11.92	12.08	1.32	4.51	4.54	0.66
P2	13.86	13.87	0.12	5.21	5.23	0.38
P3	16.89	16.93	0.24	6.34	6.38	0.63
P4	191.4	191.5	0.09	72.1	72.18	0.11
P5	64.72	64.89	0.27	24.36	24.45	0.37
P6	40.67	40.69	0.06	15.31	15.34	0.20

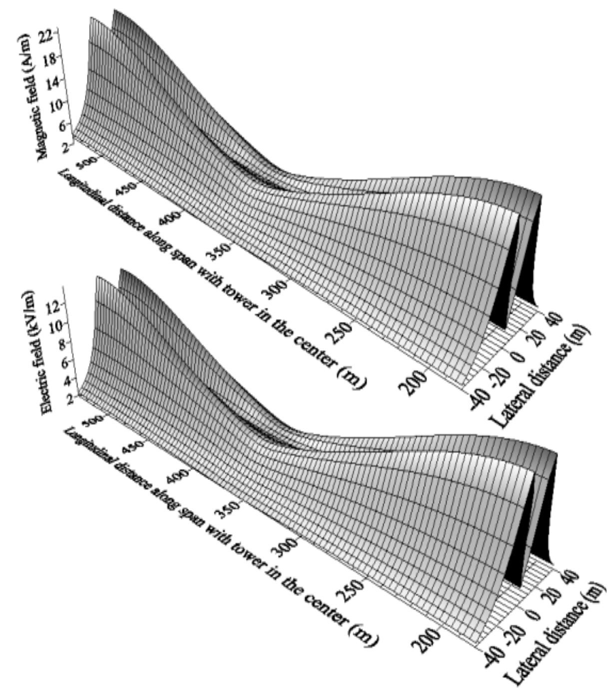

Figure 3: Magnetic and electric field profiles around the 220 kV power transmission lines under normal conditions

4.2 For Lightning Conditions

it is assumed that, lightning strikes phase C of 500 kV power line and phase C (circuit - C2) of 220 kV power line with a peak lightning current of 100 kA. The maximum induced electromagnetic field values at the monitoring points under 500 kV and 220 kV are tabulated in Table 3. For 500 kV the maximum induced magnetic field value is about 22.4 kA/m while the maximum induced electric field is about 8.45 MV/m and are obtained at the closest point to the striking point (P4). For 220 kV the maximum induced magnetic field value is about 22 kA/m while the maximum induced electric field is about 8.3 MV/m and are obtained at the closest point to the striking point (P4). Figure 4 illustrates the time-varying lightning electromagnetic field under 500 kV power line at 1 m above ground during the period of lightning strikes. The electromagnetic field profiles are presented along lateral direction (x- direction) with simulation time of 500μS. Obviously, the lightning electromagnetic fields have profiles similar to the waveforms of the lightning currents. The electromagnetic field profiles at 1 m above ground during 500μS with a peak striking current value of 100 kA for the 500 kV power lines are presented in Figure 4. For 500 kV electromagnetic field profiles, the maximum induced magnetic field value is about 1 kA/m while the maximum induced electric field is about 376 kV/m. For 220 kV the maximum induced magnetic field value is about 615 A/m while the maximum induced electric field is about 230 kV/m. To monitor the electromagnetic field profiles around the insulator surfaces during lightning a capture zone is selected. This zone is extended along area of (from 10 m to 16 m laterally) and (from 18 m to 26 m vertically) for 500 kV. While for 220 kV the selected zone is extended along area of (from 6 m to 10 m laterally) and (from 33 m to 37 m vertically).

Table 3: Maximum electromagnetic field values under lightning for 500 kV and 220 kV power lines.

Points		P1	P2	P3	P4	P5	P6
500 kV	(A/m)	1026	1201	1446	22430	6498	3338
	(kV/m)	386	452	544	8451	2448	1257
220 kV	(A/m)	612	664	735	22027	6499	3334
	(kV/m)	227	250	277	8299	2449	1256

Figure 5 presents the induced magnetic and electric fields around the insulators of 220 kV line with 100 kA striking current. For 220 kV power line the maximum induced magnetic field value is about 59 kA/m and the induced electric field value is about 36 MV/m For 500 kV power line Meanwhile, for 500 kV line, the maximum induced magnetic field value is about 57.3 kA/m and the induced electric field value is about 34 MV/m. The induced electromagnetic field values for lightning striking at different phases and ground conductors for both 500 kV and 220 kV power transmission lines on front of tower position and on front of mid-span at 1 m above ground level are tabulated in Table 4.

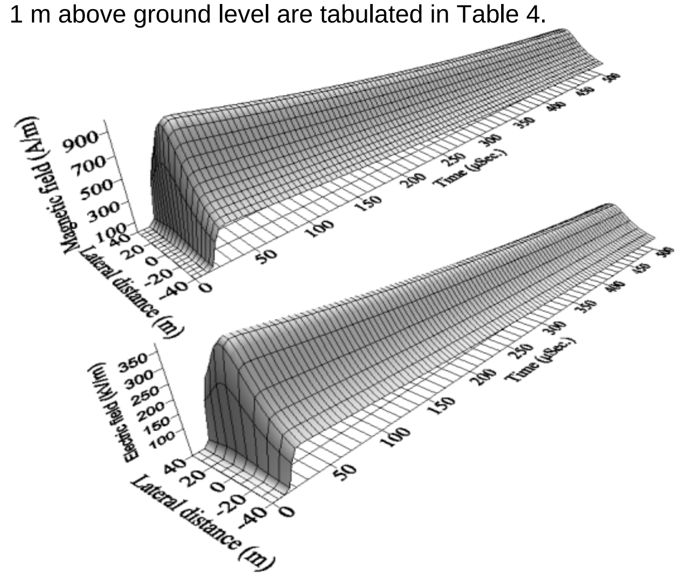

Figure 4: Lightning electromagnetic field profiles under the 500 kV power transmission lines at 1 m above ground.

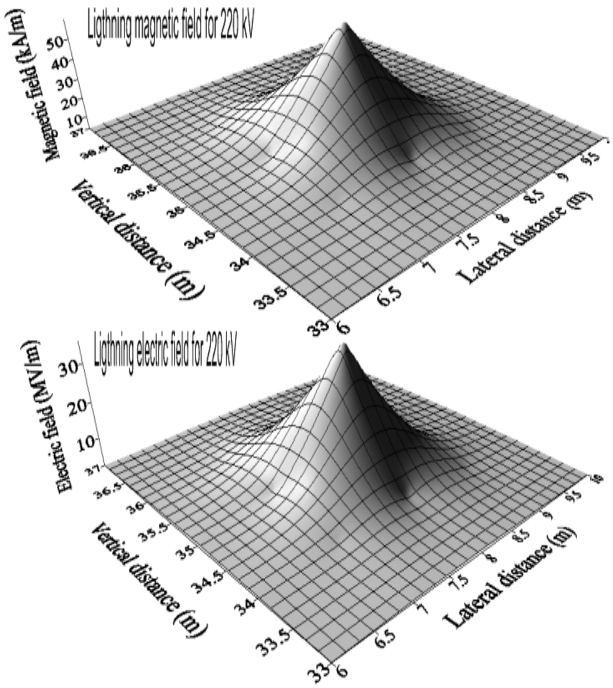

Figure 5: Lightning field profiles around the insulator of the 220 kV power Line

Table 4: Lightning induced electromagnetic field values for 500 kV and 220 kV power lines for different striking points.

Lightning electromagnetic fields at (ROW) for 500 kV power line				
Striking point	On front of tower		On front of mid-span	
	(A/m)	(kV/m)	(A/m)	(kV/m)
Phase A	604.9	227.9	688.1	259.2
Phase B	463.6	174.7	486.2	183.2
Phase C	882.7	332.6	1222.2	460.5
G1	644.6	242.8	1006.1	379.1
G2	464.0	174.8	539.6	203.3
Lightning electromagnetic fields at (ROW) for 220 kV power line				
Striking point	On front of tower		On front of mid-span	
	(A/m)	(kV/m)	(A/m)	(kV/m)
Phase A1	634.4	239.03	676.7	254.9
Phase A2	1140.2	429.6	1557.8	586.9
Phase B1	532.97	200.83	575.52	216.85
Phase B2	828.6	312.2	1101.23	414.9
Phase C1	473.8	178.5	518.5	195.4
Phase C2	570.01	214.8	678.2	255.5
G. cond.	453.8	170.9	506.76	190.9

Figure 6 presents the induced current at different position of the phases and the two ground conductors for striking position of phase C of 500 kV. The maximum value of striking current is -100 kA. The peak values of the induced current over the different position depend mainly on the relative distances between the striking point and the monitoring points. The maximum value of the induced current is about 23 kA on the ground conductor G1 while for Phase A the maximum value of induced current is about 20 kA.

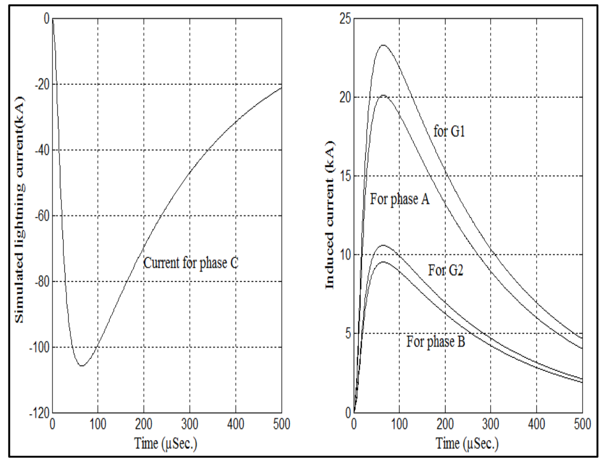

Figure 6: Lightning current and induced currents on different phase and ground conductors for 500 kV power transmission lines.

5- CONCLUSIONS

The obtained results indicate that the FDTD can be used to model and simulate the lightning electromagnetic fields around 500 kV and 220 kV power transmission lines. Comparing the obtained results from the FDTD model and analytical solutions shows that a small deviation less than 2%. Simulation results show that lightning electromagnetic field at the selected points depends mainly on the relative position of the striking point. The results of lightning electromagnetic fields could be used for electromagnetic compatibility studies and insulation coordination and as powerful in early design stage of the power transmission lines. Comparing the obtained results with previous work and standards exhibits a great convenience with minor deviation. The lightning electromagnetic fields at ROW of the two lines are evaluated at different positions to be a guide for environmental studies. The maximum values of the lightning electromagnetic fields around the insulator are 57.4 kA/m and 35 MV/m. these values are dependent upon the peak value of the striking lightning currents.

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