The Effect of Lightning Parameters on Induced Voltages Caused by Nearby Lightning on Overhead Distribution Conducting Line.

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ABSTRACT

Lightning, being one of the causes of disturbances on electric power lines, was studied to determine how its parameters significantly influence induced voltages on overhead distribution lines**.** The geometrical configuration of the stroke as it interacted with the single phase line used is based on rectangular system of coordinate. Linearly rising return stroke model with infinite tail, in conjunction with Chowdhuri coupling method was adopted to simulate the induced voltages. A Maple 13 program was developed upon which lightning parameters- return-stroke peak current, I_p ; specific velocity, β; front duration, t_f ; and height of cloud charge center, h_c , were examined. The Peak Induced-Voltage (PIV) increased linearly with increasing I_p. The PIV decreased exponentially with increasing β. The same pattern of variation as the latter was observed between PIV and t_f. A power relationship was established between PIV and h_c. The β and the t_f of the return stroke current significantly affect the lightning-induced voltages.

(Keywords: distributed electrical systems, transmission lines, induced voltages, peak induced voltage, PIV)

INTRODUCTION

Lightning strikes generate transient voltage through direct stroke and indirect stroke. In case of direct stroke, the overhead conducting line is struck directly, leading to the flash over of the insulator string of the conductor or damage of the transformer connected to it. As for indirect stroke, lightning hits the ground several meters away from the line conductor, inducing overvoltage on the line. Chowdhuri (1989), Dermott et al. (1994), and Cinieri (1996) among others, have studied the induced voltages by lightning strokes on overhead conducting lines.

The computation of induced voltage on overhead lines due to a nearby lightning return stroke consists of the following steps: (a) modeling the lightning return stroke channel; (b) calculation of electromagnetic field generated by the lightning return stroke and (c) modeling of electromagnetic field coupling to overhead line, thus computing the induced voltage. The objective of this study is to bring to light the significant lightning parameters which affect the lightning induced voltages on overhead power lines. Using simulation, we examined the influence of lightning parameters on the lightning induced voltages on power distribution line as a measure of the severity of the disturbance they cause on power system. The parameters considered were: (i) return-stroke current peak, I_p, (ii) front time of the return-stroke current, t_f, (iii) return-stroke specific velocity, β, and (iv) cloud height, h_c.

RETURN STROKE CURRENT MODEL

The model of the lightning return stroke employed in the analysis of voltages induced by nearby lightning strokes is attributed to Schonland (1938). Shown in Figure 1 is the schematic diagram of the lightning channel. The return stroke progresses upwards with a velocity, v, neutralizing the charge lowered by the preceding stepped leader. The lightning channel then consists of a vertical column; the lower part, containing current, is rapidly expanding upwards, and the upper part, containing the residual charge of the preceding stepped leader, is diminishing rapidly. The total electric field *Ei,* created by the lightning channel is given by:

$$E_i = -\nabla\phi - \frac{\partial A}{\partial t} = E_{ei} + E_{mi} \quad \textbf{(1)}$$

where ϕ is the electrostatic potential created by the residual charge of the preceding stepped leader in the upper part of the channel, and *A* is the vector potential created by the current of the return stroke in the lower part of the channel. The electromagnetic fields in space produced by the lightning channel consists of two sources: the upper part of the column produces the electrostatic component and the lower part produces the magnetic component. (Chowdhuri, 2004).

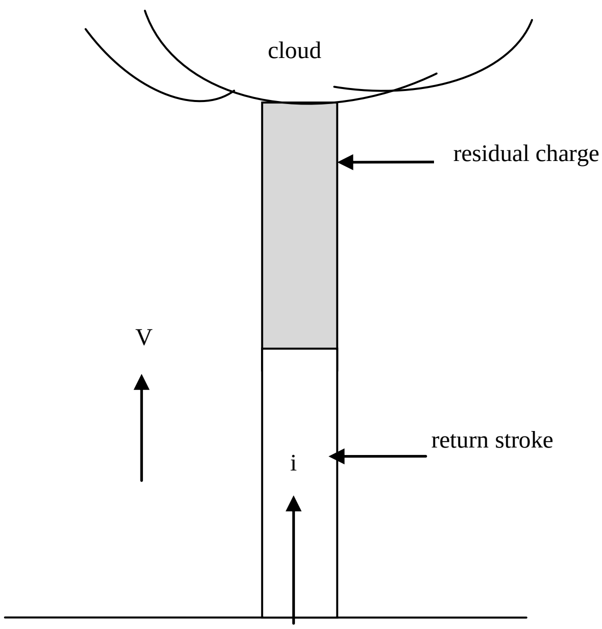

Figure 1: Lightning Channel.

It should be noted that the effects of the stepped leader are considered to be negligible in the induction process because of the low velocity of the downward-moving stepped leader. Although the upper part of the return stroke channel in Figure 1 contains the residual charge from the preceding stepped leader, its influence can be significant because of its rapid rate of change.

The vector potential *A* for the model (Figure 1*)* is given by:

$$A(r,t) = \frac{\mu_0}{4\pi}\int_0^{z'} \frac{I_0\,(r',t-(r-r')\sqrt{\varepsilon_0\mu_0})}{r-r'}\,dr' \quad \textbf{(2)}$$

and

$$\phi(r,t) = \frac{1}{4\pi\varepsilon_0}\int_{z'}^{h_c} \frac{q_0\,(r',t-(r-r')\sqrt{\varepsilon_0\mu_0})}{r-r'}\,dr' \quad \textbf{(3)}$$

where *r* and *r'* are the field and source points, respectively, I_0, is the return-stroke current, , q_0 is the charge density per unit length of the lightning channel, $h_c$is the cloud height and *z'* is the instantaneous height of the current wavefront.

ASSUMPTIONS OF THE ANALYSIS

Analysis and computations of the lightning-induced are performed with the following assumptions:

1. Only the electrostatic and the magnetic components induced by the return stroke current and the residual charges on the upper part of the return stroke are considered.

2. Charge distribution along the leader stroke is uniform.

3. The return-stroke current is rectangular and it has a finite speed *v,* that is less than the speed of light ($\beta = v/c < 1$, where *c* is the speed of light). However, the result with the rectangular current wave can be transformed to that with currents of any other waveshape by the convolution integral (Duhamel's theorem).

4. The stroke channel is vertical, where the upper part consists of a column of residual charge that is neutralized by the rapid upward movement of return-stroke current in the lower part of the channel (Figure 1).

5. Overhead lines are loss free and the earth is perfectly conducting.

INDUCTION OF RETURN-STROKE ELECTROMAGNETIC FIELDS TO OVERHEAD SINGLE PHASE-LINES

The geometrical configuration of the stroke and lines is based on the rectangular system of coordinates where the origin of the system is the point where lightning strikes the surface of the earth (Figure 2) The phase line considered is located at a distance y_0 (m) from the origin, having a mean height of *h* (m) above ground and running along the *x*-direction. The origin of time (*t* = 0) is assumed to be the instant when the return stroke starts at the earth level.

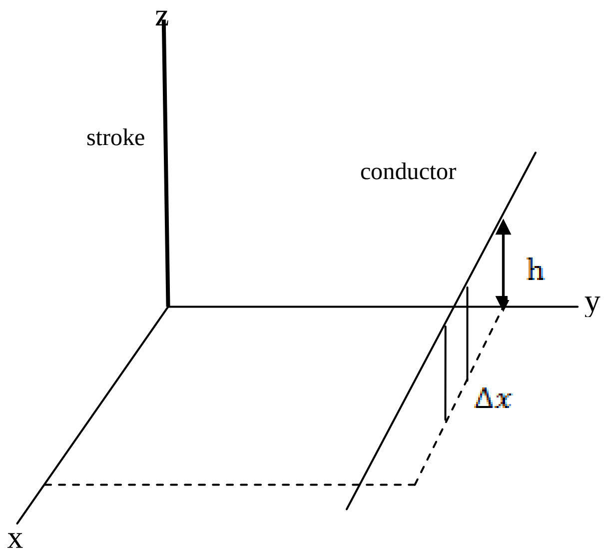

Figure 2: Geometry Used for the Calculation of Lightning Induced Voltages on a Single Phase Line.

The Schonland model of the return stroke (Figure 1) was assumed. The two transmission-line equations of the equivalent circuit for lightning-induced voltage on single-conductor overhead line (Figure 3) are given by:

$$-\frac{\partial V}{\partial x} = L\frac{\partial I}{\partial t}$$
$$-\frac{\partial I}{\partial x} = C\frac{\partial}{\partial t}(V - V_i) \qquad \textbf{(4)}$$

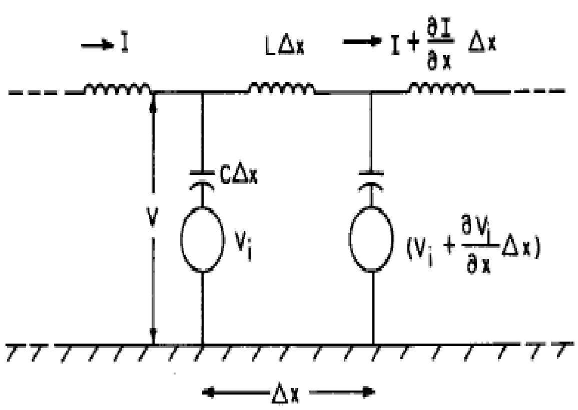

Figure 3: Equivalent Circuit for Computing Lightning-Induced Voltage on Single-Conductor Overhead Line.

Differentiating Equation 4 and eliminating current I:

$$\frac{\partial^2 v}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 v}{\partial t^2} = \frac{1}{c^2}\frac{\partial^2 v_i}{\partial t^2} = F(x,t) \qquad \textbf{(5)}$$

where v(x, t) is the induced voltage at a point *x* on the overhead line, *c* is the velocity of light in free space and v_i (x, *t)* is the inducing voltage which would have existed without the presence of the overhead line and defined as:

$$v_i = -\int_0^h E_i . dz = \int_0^h \left(\nabla\phi + \frac{\partial A}{\partial t}\right). dz = \int_0^h (E_{ei} + E_{mi}). dz = v_{ei} + v_{mi} \qquad \textbf{(6)}$$

E, has been defined in Equations 1, 2, and 3. E, in Equation 5 contains both the electrostatic component ($\nabla\phi$) from the charge above the current column and the magnetic component ($\partial A / \partial t$) due to the current column of Figure 1.

Equation 5 is an inhomogeneous wave equation for the induced voltage along the overhead line. It is valid for any charge distribution along the leader channel and any waveshape of the return-stroke current. Its solution can be obtained by assuming F(x,t) to be the superposition of impulses that involves the definition of Green's function.

PROCEDURE OF CALCULATION OF LIGHTNING INDUCED VOLTAGES WITH MAPLE 13

The procedure for calculation of lightning induced voltages is stated thus:

1. Second order partial differential wave equation was generated in terms of induced voltage, $v(x,t)$ and inducing voltage $v_i(x,t)$ (Equation 5).
2. The initial conditions $v(x,0)$ and $\frac{d}{dt}v(x,0)$ were set at zero.
3. The Laplace transform Equations of 1 and 2 above were determined in terms of V(x, s).
4. The Wronskian was evaluated in terms of the basic vectors $\varphi_{1(x,s)=e^{-sx}}$ and $\varphi_{2(x,s)=e^{sx}}$.
5. Second order Green's function was evaluated.
6. Particular solution was determined.
7. The general solution of the transformed induced voltage was determined on substituting the boundary conditions.
8. The solution is the inverse Laplace of V(x, s)

Varying each lightning parameter in turns, and keeping all other parameters constant, the lightning induced voltage as a function of time is determined in each case.

RESULTS AND DISCUSSION

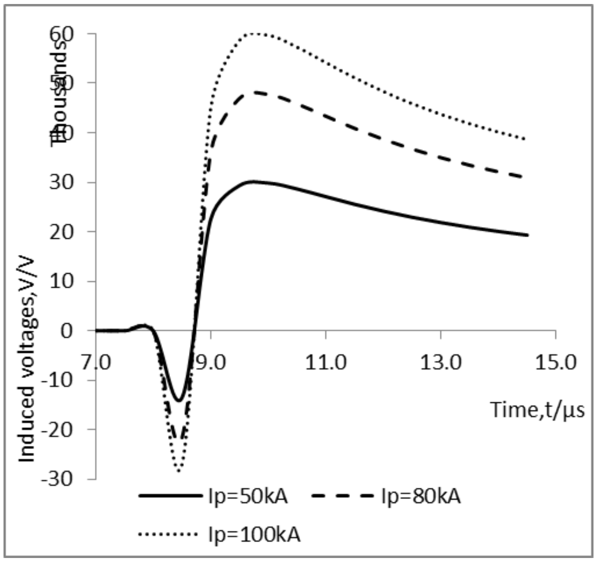

Figure 4: Variation of Induced Voltages with Return Stroke Peak Current (h=10m,tf=5μs, β=0.3, y_0=100m ;x=1000m, h_c=3km).

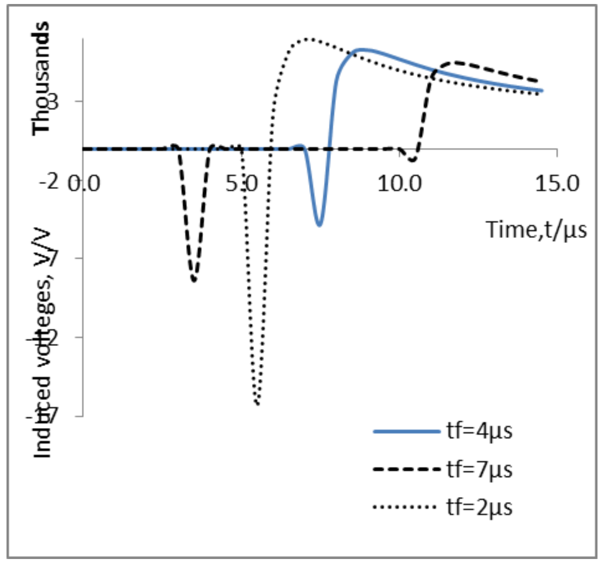

Figure 6: Variation of Induced Voltages with Return Stroke Front Time (h=10m, β=0.3, I_p=10kA , y_0=100m ;x=1000m , ,h_c=3km).

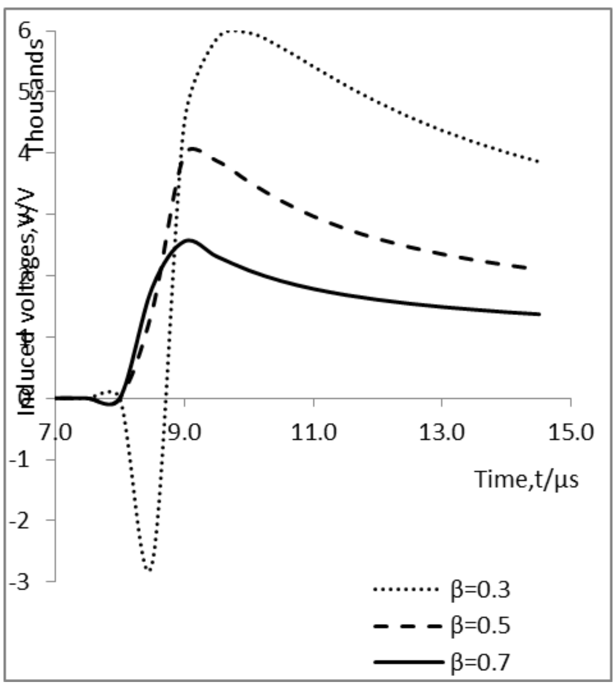

Figure 5: Variation of Induced Voltages with Return Stroke Specific Velocity (h=10m ,tf =5μs,I_p=10kA , y_0=100m ;x=1000m , ,h_c=3km).

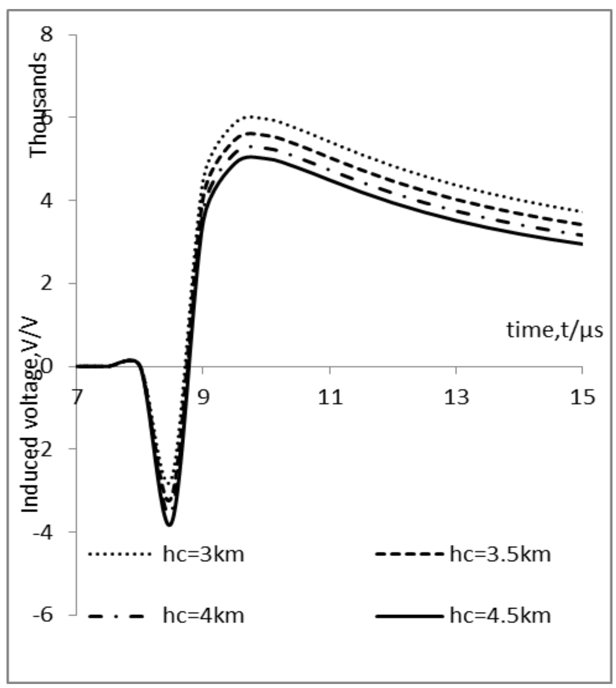

Figure 7: Variation of Induced Voltages with Height of Cloud (h=10m ,tf =5μs,I_p=10kA, y_0=100m ;x=1000m , , β=0.3).

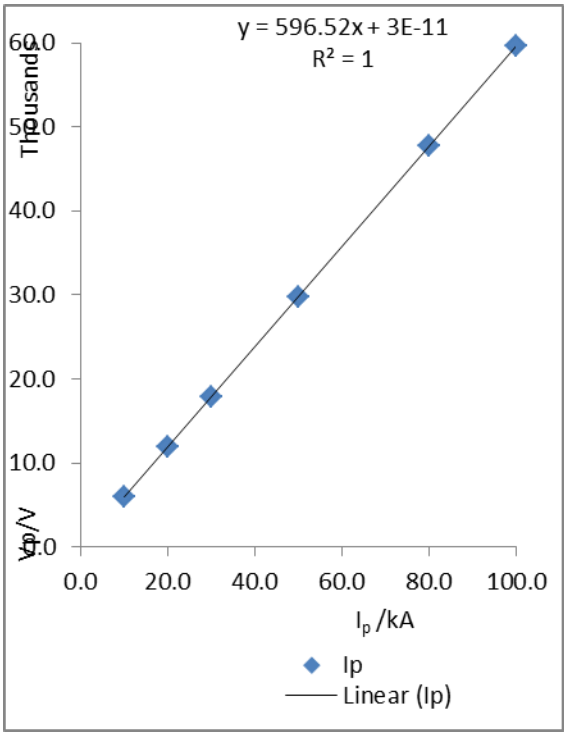

Figure 8: Trend Line of Variation of Peak Induced Voltages with Return Stroke Peak Current.

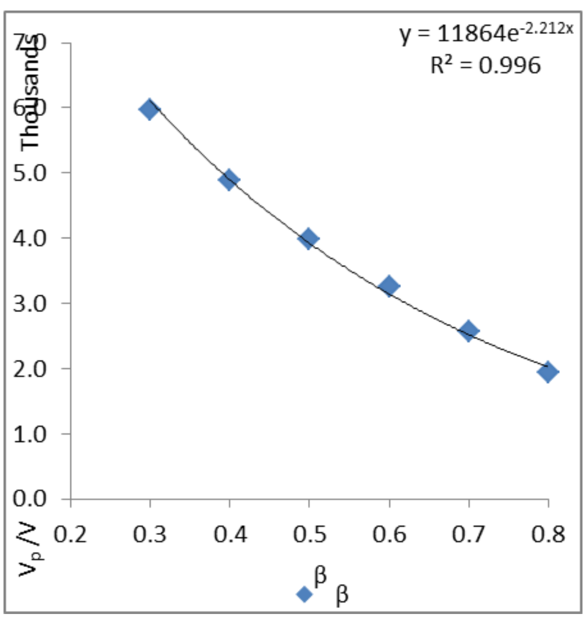

Figure 9: Trend Line of Variation of Peak Induced Voltages with Return Stroke Specific Velocity.

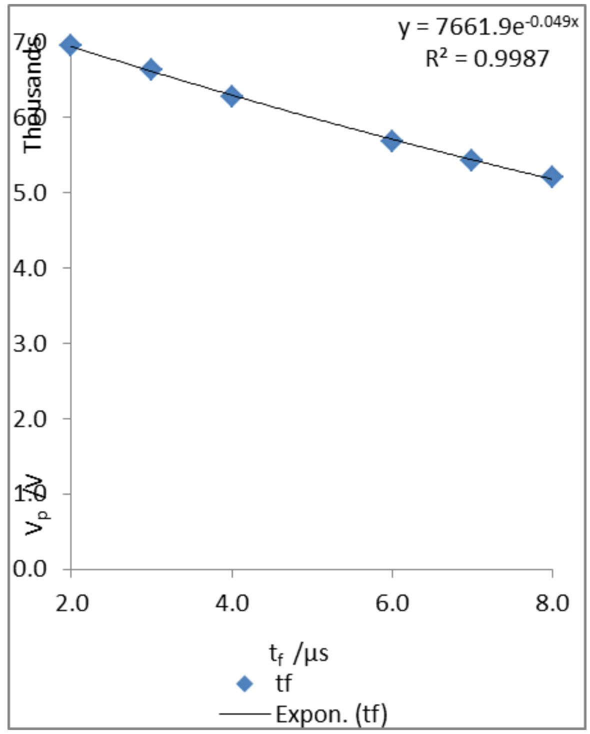

Figure 10: Trend Line of Variation of Peak Induced Voltages with Return Stroke Front Time.

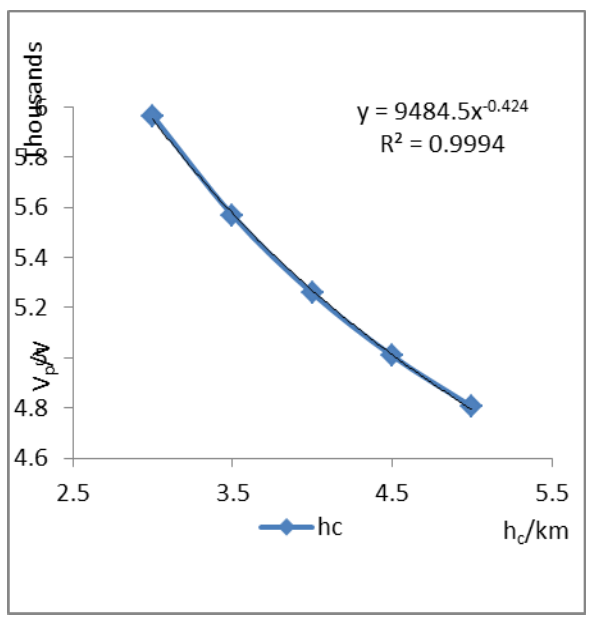

Figure 11: Trend Line of Variation of Peak induced voltages with height of cloud

The wave shape of the lightning induced voltage varies with varying lightning parameters (Figures 4-7). The peak induced voltage increased linearly with increasing peak return stroke current, I_p (Figures 4 and 8) . Peak induced voltage decreased exponentially with increasing specific velocity, β (Figures 5 and 9). The same pattern of variation as in latter, was observed between peak induced voltage and return stroke front time, t_f (Figures 6 and 10). A power relationship was established between peak induced voltage and height of cloud charge center, h_c (Figures 6 and 11).

CONCLUSION

The results revealed that significant voltages could be induced on power lines due to nearby lightning strokes. The specific velocity and the front time of the return stroke current significantly affect the lightning-induced voltages on overhead conductor lines.

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