COMPUTATION OF LIGHTNING INDUCED VOLTAGES ON TELECOMMUNICATION SUBSCRIBER LINES

P. Durai Kannu
Dept. of Electrical Engg,
Karnataka Regional Engineering College,
Surathkal-574157.

M. Joy Thomas
Dept. of High Voltage Engg,
Indian Institute of Science,
Bangalore-560012.

Abstract— **The electric and magnetic fields produced by a lightning stroke in the vicinity of a telecommunication line can illuminate the line and it can acquire induced over voltages which may be detrimental to the equipments connected to the telecommunication line. The magnitude and waveshape of the electromagnetic fields produced by lightning as well as the induced voltage on telecommunication line are influenced by the finite conductivity of the ground. In this paper, the induced transient voltages on an overhead telecommunication subscriber line due to a nearby lightning stroke to the ground are computed. From the results it is seen that the induced voltage is bipolar for all the observation points except at the line midpoint for the lightning striking point location chosen in this study. It is also observed that the finite ground conductivity decreases the magnitude of the induced voltage at the line terminations where as it increases the induced voltage as the line mid point is approached. The results obtained in this study will be useful in evolving a suitable lightning protection scheme for the rural telephone exchanges which are interconnected using overhead lines instead of underground cables as in the case of urban exchanges. At the same time these rural telephone exchanges have become more vulnerable to transient over voltages as they are being converted into digital ones with their susceptibility levels for transient over voltages being much lower than the old electromechanical exchanges.**

1. Introduction

Overhead conductors are still being used particularly in rural areas for telephone communication. These are situated wholly or partially in severe lightning prone areas. Such lines are affected by lightning return strokes and other atmospheric electric phenomena which may occur in the vicinity of the line. A lightning stroke to the ground produces intense transient electric and magnetic fields. If the lightning stroke is in the vicinity of a telecommunication line, these fields will illuminate the telecommunication subscriber lines and the lines can acquire induced over voltages and currents in a wide frequency range as they behave as very long interconnected antenna. These high energy surges due to lightning discharges can produce temporary upsets or permanent damages to the electronic equipments in modern data communication, signalling and control systems which are connected at the ends of a telecommunication line. A knowledge of these effects and of their incidence and magnitude is essential for an understanding of the protective measures required for overhead telecommunication lines and associated terminal equipments.

Induced voltages on overhead conductors due to a nearby lightning stroke are generally calculated in the following way

1. The lightning return-stroke electromagnetic field is calculated making use of a return-stroke current model which specifies the spatial-temporal distribution of the current along the lightning channel.
2. The electromagnetic fields thus obtained are used to calculate the induced overvoltages by means of a coupling model which describes the interaction between the field and the conductors.

In this paper, the induced transient voltages on an overhead telecommunication subscriber line due to a nearby lightning stroke to the ground are computed for a lightning stroke current of 10 kA. The lightning striking point is taken as 50 m from the mid point of a 1 km long telecommunication line.

2. EM Fields due to Lightning Return Stroke

The lightning return stroke current has been assumed be a double exponential waveform and modified transmission line(MTL) model[1] has been used to describe the current along the vertical lightning channel. The return stroke current at ground level is expressed as[2]

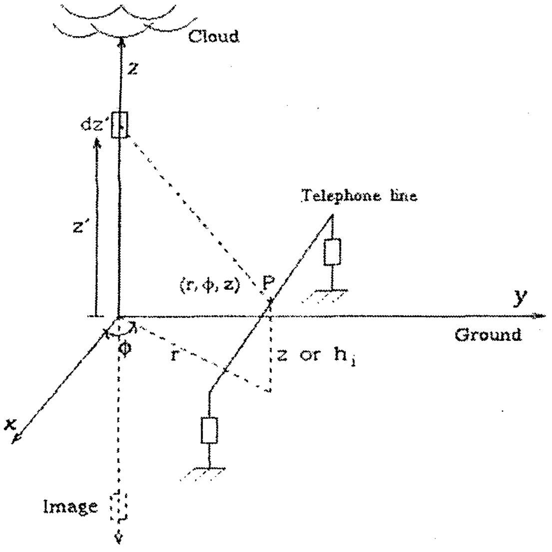

Fig. 1. Geometry showing the lightning return stroke channel and the telephone line.

$$i(0,t) = I_0(e^{-\alpha t} - e^{-\beta t}) \qquad (1)$$

According to the MTL model, the lightning current at a height of z' is given by the expression

$$i(z',t) = e^{(-z'/\lambda)} i(0, t - z'/v) \qquad (2)$$

where v is the velocity of the return stroke and λ, the return stroke current decay constant.

The electric field which excites the line due to lightning is resolved in to (i) vertical electric field and (ii) horizontal electric field. Both the above fields are the source terms for induced voltage calculation. By assuming that the ground is a perfect conductor the vertical electric field $dE_z(r,z,t)$ and horizontal electric field $dE_r(r,z,t)$ due to an infinitesimal lightning curent element of length dz' at height z' carrying current $i(z',t)$ can be calculated at a general point $P(r,\phi,z)$ by the following equations[1,3]. Figure 1. shows the geometry for the calculation of the fields.

$$\begin{aligned} dE_z(r,z,t) = {} & \frac{dz'}{4\pi\epsilon_0} \\ & [\frac{2(z-z')^2 - r^2}{R^5} e^{(-z'/\lambda)} \int_0^t i(0, \tau - z'/v - R/c) d\tau \\ & + \frac{2(z-z')^2 - r^2}{cR^4} e^{(-z'/\lambda)} i(0, t - z'/v - R/c) \\ & - \frac{r^2}{c^2 R^3} e^{(-z'/\lambda)} \frac{\partial}{\partial t} i(0, t - z'/v - R/c)] \qquad (3) \end{aligned}$$

$$\begin{aligned} dE_r(r,z,t) = {} & \frac{dz'}{4\pi\epsilon_0} \\ & [\frac{3r(z-z')}{R^5} e^{(-z'/\lambda)} \int_0^t i(0, \tau - z'/v - R/c) d\tau \\ & + \frac{3r(z-z')}{cR^4} e^{(-z'/\lambda)} i(0, t - z'/v - R/c) \\ & + \frac{r(z-z')}{c^2 R^3} e^{(-z'/\lambda)} \frac{\partial}{\partial t} i(0, t - z'/v - R/c)] \qquad (4) \end{aligned}$$

It is reported that the vertical electric field is not very much influened by the finite ground conductivity, where as the horizontal electric field is modified significantly by the finite conductivity of the ground[1]. Hence the vertical elecric field is calculated assuming the ground as a perfect conductor. For the computation of the horizontal electric field with finite ground conductivity, Cooray-Rubinstein formula[4] has been used. This requires the azimuthal component of magnetic field produced by lightning, which is given as

$$\begin{aligned} dH_\phi(r,z,t) = {} & \frac{dz'}{4\pi} \\ & [\frac{r}{cR^2} e^{(-z'/\lambda)} \frac{\partial}{\partial t} i(0, t - z'/v - R/c) \\ & + \frac{r}{R^3} e^{(-z'/\lambda)} i(0, t - z'/v - R/c)] \qquad (5) \end{aligned}$$

where μ_0 and σ_g are the permeability of free space and conductivity of the ground respectively.

The horizontal electric field including the ground conductivity $E_{rg}(r,z,t)$ is given as[4]

$$\begin{aligned} & E_{rg}(z=h,r) = \\ & \quad E_r(z=h,r) - H_\phi(z=0,r) \frac{\sqrt{\mu_0}}{\sqrt{\epsilon + \sigma_g / j\omega}} \qquad (6) \end{aligned}$$

where $E_r(z=h,r)$ is the Fourier-transform of the horizontal electric field at height h,

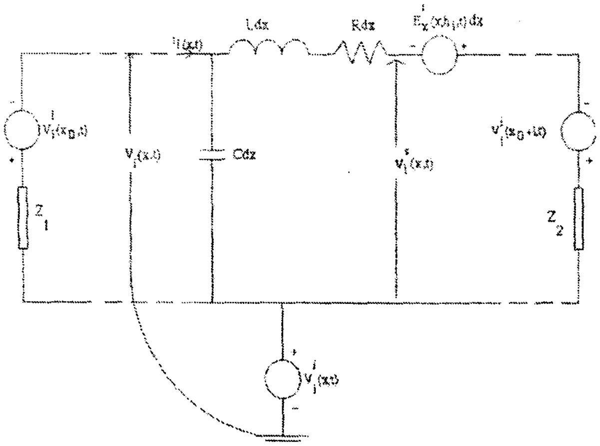

Fig. 2. Equivalent circuit of an overhead line excited by an external electromagnetic field.

$H_\phi(z = 0, r)$ is the Fourier-transform of the azimuthal(ie., horizontal) component of the magnetic field at ground level. μ_0 is the permeability of air, ϵ and σ_g are the permittivity and conductivity of the ground respectively.

3. Coupling to Multiconductor Lines

The induced voltages are calculated using the coupling model in time domain proposed by Agrawal et.al[5]. The coupling equations incorporating the effect of finite ground conductivity on the surge propagation along the line are given as follows[6]

$$\frac{\partial}{\partial x}[v_i^s(x,t)] + [R_{ij}][i_i(x,t)] + [L_{ij}]\frac{\partial}{\partial t}[i_i(x,t)]$$

$$+ \int_0^t [\xi_{ij}(t-\tau)]\frac{\partial}{\partial \tau}[i_i(x,\tau)]d\tau = [E_x^i(x,h_i,t)] \quad (7)$$

$$\frac{\partial}{\partial x}[i_i(x,t)]+[G_{ij}][v_i^s(x,t)]+[C_{ij}]\frac{\partial}{\partial t}[v_i^s(x,t)] = 0 \quad (8)$$

where $[E_x^i(x,h_i,t)]$ is the horizontal electric field along the conductor at the conductor height h_i.

$v_i^s(x,t)$ is the scattered voltage.

$[L_{ij}]$, $[C_{ij}]$, $[R_{ij}]$ and $[G_{ij}]$ are the per unit length inductance, capacitance, resistance and conductance matrices respectively.

$[\xi_{ij}]$ is the transient ground resistance, which is equal to the inverse Fourier transform of $[Z_{g_{ij}}/j\omega]$. $[Z_{g_{ij}}]$ is the ground impedance per unit length.

According to this coupling model the equivalent circuit for a single over head telecommunication line is shown in figure 2.

The voltage at the end of the line is determined by the boundary conditions and the current at the two ends of the line, viz., $i(x_0, t)$ and $i(x_0 + l, t)$, where l is the length of the overhead line. The boundary conditions for the scattered voltage are

$$v_i^s(x_0,t) = -[Z_1][i_i(x_0,t)] + \int_0^{h_i} E_z^i(x_0,z,t)dz \quad (9)$$

$$v_i^s(x_0+l,t) = [Z_2][i_i(x_0+l,t)] + \int_0^{h_i} E_z^i(x_0+l,z,t)d \quad (10)$$

where E_z^i is the vertical electric field at the i^{th} conductor. $[Z_1]$ and $[Z_2]$ are the terminating impedence matrices.

4. Results and Discussion

The induced voltage on a multiconductor overhead telecommunication subscriber line has been computed by the above described method. The configuration of the line is shown in figure 3. The length of the line is taken as 1 km and each of the line conductors shown in figure 3, has a diameter of 1.0 mm. The location of lightning is at a distance of 50 m away from the conductor 1 and equidistant from the line ends. The geometry of lightning location is shown in figure 4. The lines at end 'A' are terminated by the surge impedance of the lines and at the end 'F', the lines are terminated by the surge impedance of the cable which is taken as 170 Ω [7].

Figure 5. shows the induced voltage, on conductor 1 at point 'F'. The figure shows the induced voltage for two cases, viz., (a) when ground is considered as a perfect conductor and (b) when ground is assumed to have a finite conductivity. From figure 5, it is seen that the ground conductivity reduces the peak value of the induced voltage from 4 kV to 3 kV, but there is a negative peak in the initial portion of the waveform which reaches almost 5 kV.

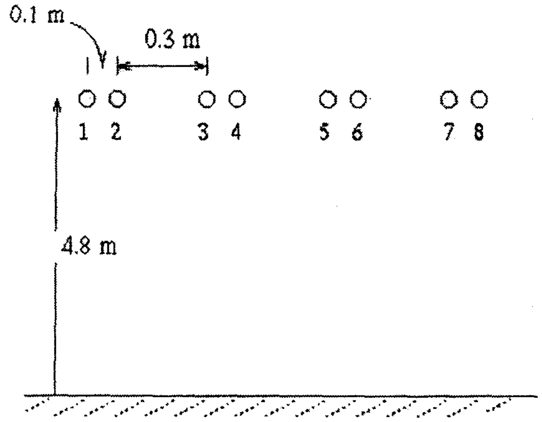

Fig. 3. Telephone line configuration.

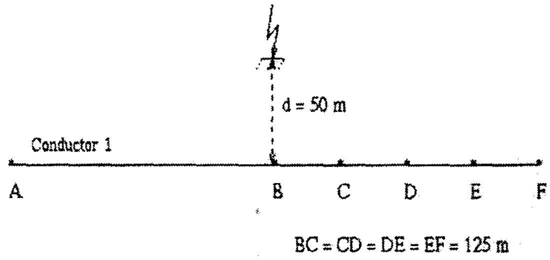

Fig. 4. Sketch showing the lightning stroke location w.r.t the induced voltage observation points on the line.

Figure 6. shows the induced voltage at different points on the conductor 1. These induced voltages are calculated assuming a finite ground conductivity, σ_g of 0.001 S/m and ϵ_r of 10. It can be seen from figure 6, that the induced voltage at the line mid point (ie., at 'B') has no initial negative peak where as at all the other points an initial negative peak is observed. This can be explained from the horizontal electric field waveforms which are shown in figures 7(a) and 7(b).

The calculated horizontal electric field at a height of 4.8 m from the ground and at distances of 500 m and 50 m from the lightning channel are shown in figures 7(a) and 7(b) respectively. When ground conductivity is included, the horizontal electric field goes negative initially, and this gets reduced as we approach the midpoint of the line, ie., 50 m from the lightning striking location. At the line mid point, the component of horizontal electric field along the direction of the line is zero for the lightning location chosen. Moreover, at such distances, ie., for distances close to 50 m, the horizontal electric field has a negligible negative peak as compared to the positive value as can be seen from figures 7(a) and (b). Hence there is no initial negative peak observed in the induced voltage at the line mid point where as at all the other points, there is an initial negative peak as can be seen from figure 6.

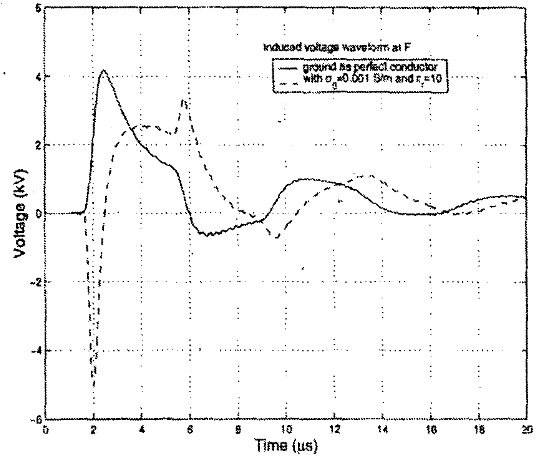

Fig. 5. Induced voltage on conductor 1, at the line termination(at point 'F').

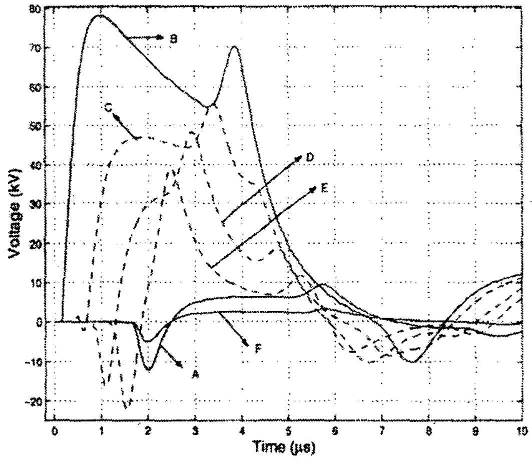

Fig. 6. Induced voltage on conductor 1, at different points assuming ground parameters $\sigma_g = 0.001$ S/m and $\epsilon_r = 10.0$.

Figure 6. also shows that the induced voltages at observation points closer to the junction of the overhead line with the cable(C, D and E) are less than that at the midpoint of the line. The induced voltage at the junction of the line with the cable (ie., at 'F') has the lowest positive peak which is 3 kV only. But the negative peak is more than that of the positive peak and is about 5 kV. This is in contrast to the case of a long power distribution line terminated by the surge impedance of the line, where the negative peak of the induced voltage is much lower than the positive peak at the line terminations[8]. Now this induced voltage as it reaches the telephone exchange may get magnified depending on the input impedance of the telephone exchange. This can inturn cause a permanent damage or temporary upset to the internal electronic circuitry unless suitable surge suppressive devices are provided at the entry point of the cable to the telephone exchange.

5. Conclusion

The induced voltage on a telecommunication subscriber line due to a nearby lightning stroke has been computed. From the results it is seen that the induced voltage is bipolar at all the observation points other than the midpoint. The finite ground conductivity decreases the magnitude of the induced voltage at line termination where as it increases the induced voltage as the line midpoint is approached. The results obtained in this study will be useful in evolving a suitable lightning protection scheme for rural telephone exchanges which are interconnectrd using overhead lines.

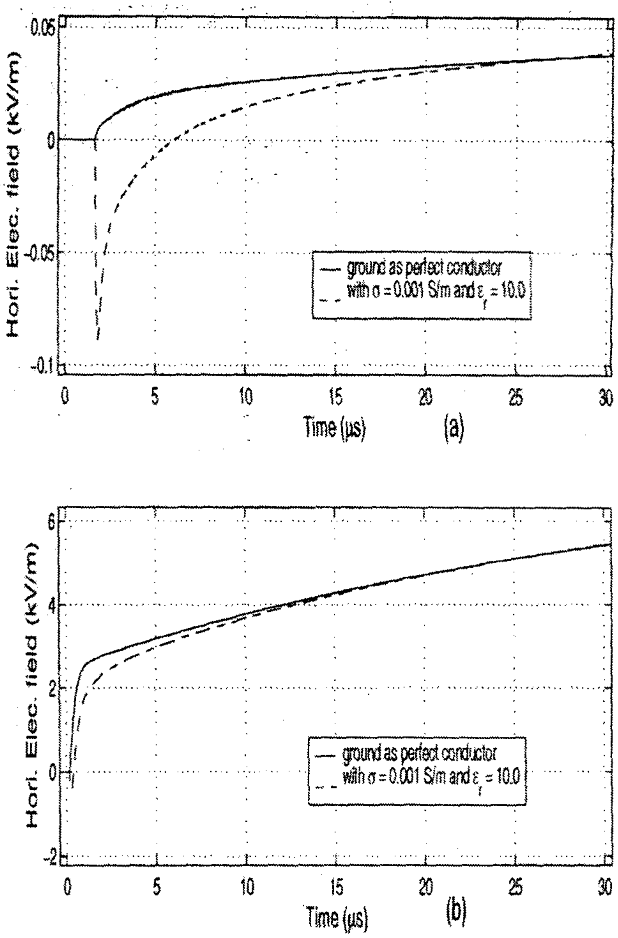

Fig. 7. Horizontal electric field (a) at d = 500 m and height of 4.8 m (b) at d = 50 m and height of 4.8 m

References

[1] C.A.Nucci, F.Rachidi, M.V.Ianoz and C.Mazzetti, "Lightning - Induced Voltages on Overhead Lines", IEEE Trans.Electromagnetic Compatibility, Vol.35, No.1, pp 75-85, Februray 1993.

[2] A.Zeddam and P.Degauque, "Current and Voltage Induced on Telecomunications Cable by a Lightning return Stroke", in Lightning Electromagnetics, R. L Gardner, Ed, New York, Hemisphere, pp 377-400, 1990.

[3] M.J.Master and M.A.Uman, "Lightning Induced Voltages On Power Lines: Theory", IEEE Transactions on Power Apparatus and Systems, Vol.PAS-103, No.9, pp 2502-2515, September 1984.

[4] M.Rubinstein, "An Approximate Formula for the Calculation of the Horizontal Electric Field from Lightning at Close, Intermediate, and Long Range", IEEE Trans.Electromagnetic Compatibility, Vol.38, No.3, pp 531-535, August 1996.

[5] A.K. Agrawal, H.J. Price and S.H. Gurbaxani, "Transient Response of Multiconductor Transmission Lines Excited by a Nonuniform Electromagnetic Field", IEEE Trans.Electromagnetic Compatibility, Vol.EMC.22, No.2, pp 119-129, May 1980.

[6] F.Rachidi, C.A.Nucci, M.Ianoz and C.Mazzetti, "Influence of a lossy Ground on Lightning-Induced Voltages on Overhead Lines", IEEE Trans.Electromagnetic Compatibility, Vol.38, No.3, pp 250-264, August 1999.

[7] "Telecommunications Engineer's Reference Book", Fraidoon Mazda (Editer), Focal Press, 1998.

[8] P. Durai kannu and Joy Thomas M. "Influence of Ground Conductivity on the over Voltages Induced on Overhead Power Distribution Lines due to an Indirect Lightning Stroke", IEEE, International symposium on EMC, Vol-2, pp 949-954, Washington, DC, 2000.