Analysis of Transients in Overhead Telecommunication Subscriber Line Due to Nearby Lightning Return Stroke

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Abstract: A simple analysis of induced transients in an overhead telecommunication subscriber line due to nearby lightning return stroke to the ground is done considering a simple triangular pulse current as channel current. The field—transmission line coupling model is adopted from Agrawal et al.[1]. Results show that the front return stroke produces higher peak value of transients in comparison with the side return stroke, on the other hand side return stroke produces higher values of front steepness. The numerical results have a good agreement with the experimental data.

INTRODUCTION

The nearby lightning return stroke to the ground produces a strong electric and magnetic fields which, when illuminating the telecommunication subscriber lines, the lines act like a long interconnected antenna and acquire some induced overvoltages and overcurrents termed as transients. Transients are always threatening to the low voltage equipment in modern data communications, signalling and control systems. It is important to know the lightning induced characteristic so that an optimum protection measure for low voltage equipment can be taken. Theoretical development and analysis have been advanced to investigate the different characteristics of Lightning Induced Overvoltage (LIOV) on power and telecommunication lines [1-10]. In spite of some general agreement, quite different results have been reported concerning the intensity and wave shape of the induced voltages, which may be due to different approach in modeling the coupling between the electromagnetic field and conductors, consideration of channel current, and different approach of consideration in calculation process. The objective of this paper is to analyze some parametric effect of Overhead Telecommunication Subscriber Line (OTSL) and lightning upon LIOV in OTSL. The numerical analysis in this paper is done based on Agrawal et al. model [1]. The coupling differential equation of Agrawal model are solved with the use of finite difference numerical technique. The triangular current following the transmission line model [11] has been considered for channel current instead of considering modified transmission line [12] or traveling current source model [13].

The calculation of electric fields radiated from a straight vertical lightning channel considers the ground as an infinitely conducting plan. The voltage calculation considers the OTSL as lossless line.

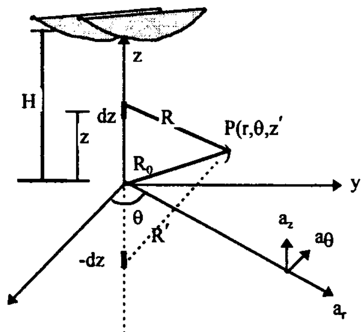

Figure 1. Geometry of a model nearby lightning used in the vertical and horizontal electric fields computations at a point above the ground.

CALCULATION OF ELECTRIC FIELD

The geometry to explain a model lightning phenomenon is shown in Fig. 1. Electric field radiated from lightning channel has two components, horizontal and vertical, which are both responsible for causing induced voltages in OTSL. The electric field at any point above the ground can be calculated by solving the time varying Maxwell's equations, which is executed in the previous works [14,15]. The equations for electric fields at point P(r,ϕ,z′) above the ground (Fig. 1), due to the effect of the dipole *dz* is expressed as follows:

$$d\overline{E}_z = \frac{dz}{4\pi\varepsilon_0}\times\Big[\frac{2(z-z')^2-r^2}{R^5}\int_0^t i(z',t-R/c)\,dt + \frac{2(z-z')^2-r^2}{cR^4}i(z',t-R/c) - \frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}\Big]\overline{a}_z \quad (1)$$

$$d\overline{E}_r = \frac{dz}{4\pi\varepsilon_0}\times\Big[\frac{3r(z-z')}{R^5}\int_0^t i(z',t-R/c)\,dt + \frac{3r(z-z')}{cR^4}i(z',t-R/c) + \frac{r(z-z')}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}\Big]\overline{a}_r \quad (2)$$

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where, $\bar{E}_r$ and $\bar{E}_z$ represent horizontal and vertical electric field intensity respectively, c is the velocity of light, μ_0 and ε_0 are the permeability and permitivity of free space, respectively. The geometric parameters R, z, r, and z' are defined in Fig. 1. Both Equations (1) and (2) contain three terms; electrostatic, induction, and radiation terms. The first one dominates at small distances, the last one dominates at far distances and the middle one behaves intermediate between electrostatic and induction terms. The effect of infinite conductivity of the ground can be included by considering an image dipole beneath the ground plane at the same distance as the dipole dz from the ground. The electric field produced due to the image dipole at point P(r,ϕ,z') is determined from equation (1) and (2) by substituting R' for R and -z for z. The total field at point P(r,ϕ,z') due to the dipole at point (0,0,z) is the sum of the dipole and image dipole fields. Electric field for the whole channel is determined from the integration of dipole field through out the channel.

CALCULATION OF INDUCED VOLTAGES

To calculate induced voltages on OTSL in this paper, use is made of the model proposed by Agrwal et al. [1], based on transmission line theory for field-to-transmission line coupling. According to this model horizontal and vertical electric fields are used as the forcing function to excite the telecommunication line (refer to Fig. 2). The expressions for coupling between fields to the line are as follows:

$$\frac{\partial}{\partial y}V^s(y,t) + L\frac{\partial}{\partial t}I(y,t) = E_y(y,h,t) \qquad (3)$$

$$\frac{\partial I(y,t)}{\partial y} + C\frac{\partial}{\partial t}V^s(y,t) = 0 \qquad (4)$$

where $I(y,t)$ is the line current, $V^s(y,t)$ is the scattered voltage, $E_y(y,h,t)$ is the horizontal component of electric field at height h in absence of the subscriber line, directed positive from left to right along the line. L and C are the per unit length inductance and capacitance of the telecommunication subscriber line respectively.

By using finite difference numerical technique, equations (3) and (4) can be expressed in the form of algebraic equations which are solved for scattered voltage and line current as follows:

$$V(y,t+\Delta t) = -\frac{\Delta t}{C\Delta y}\{I(y,t) - I(y-\Delta y,t)\} + V(y,t) \qquad (5)$$

$$I(y,t+\Delta t) = \frac{\Delta t}{L\Delta y}\{V(y,t+\Delta t) - V(y+\Delta y,t+\Delta t)\} + \frac{\Delta t}{L}\frac{E_y(y,t+\Delta t)+E_y(y,t)}{2} + I(y,t) \qquad (6)$$

where Δy is the position incremental and Δt is the time incremental of induced voltages and currents. The scattered voltages at the termination of the line is defined by the following equations:

$$V^s(y=0,t) = -I(y=0,t)r_0 - V^i(y=0,t) \qquad (7)$$

$$V^s(y=l,t) = -I(y=l,t)r_l - V^i(y=l,t) \qquad (8)$$

where r_0 and r_l are the terminating resistance at left and right end, respectively, of the OTSL.

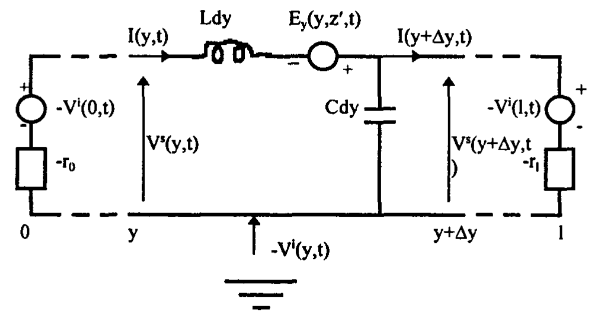

Figure 2. Differential equivalent coupling circuit for a single-wire lossless overhead telecommunication subscriber line

Equations (5) and (6) do not contain the total voltage which can be calculated by the following expression

$$V^T(y,t) = V^s(y,t) + V^i(y,t) \qquad (9)$$

where $V^i(y,t)$ is the incident voltage and

$$V^i(y,t) = -\int_0^h E_z(y,z,t)dz \approx -hE_z(y,h=0,t) \qquad (10)$$

here $E_z(y,z,t)$ is the incident or inducing vertical component of electric field directed positive towards the ground.

The equivalent circuit for the overhead telecommunication subscriber line above perfectly conducting ground, excited by non-uniform incident vertical and horizontal electric fields, follows the model given in equations (3) through (10) as shown in Fig. 2.

RESULTS AND DISCUSSIONS

Induced voltages due to nearby lightning as obtained by numerical analysis are presented and discussed theoretically in this section. A simple triangular pulse current as shown in Fig. 3 is considered for channel current. Typical values of return stroke and line parameters used in the calculation of induced voltages are as follows:

- Return stroke

$I_P = 10\ kA$, $t_f = 1.5\mu s$, and $t_e = 80\mu s$
velocity of return stroke 100 $m/\mu s$
Channel Height 4 km

- Overhead telecommunication line

length $= 1.8\ km$; height $= 5\ m$;
diameter $= 1.27\ mm$;
terminating resistance $= 600\ \Omega$

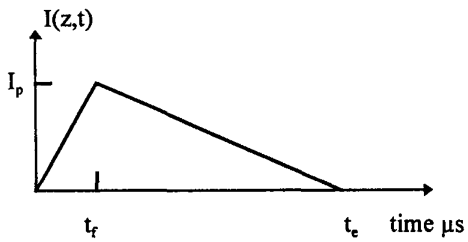

Figure 3. A typical triangular pulse current moving from ground to cloud through an upright lightning channel during lightning return stroke.

The description of the numerical results in this section uses two technical terms, front return stroke (FRS) and side return stroke (SRS), which can be defined with the help of Fig. 4. Strikes occurring at points M, A, B, H, I, and N are called SRS. On the other hand strikes at C, D, E, F, G, and Q are FRS. All the calculated voltages are taken at the left end termination of the OTSL and it is considered positive from line to ground.

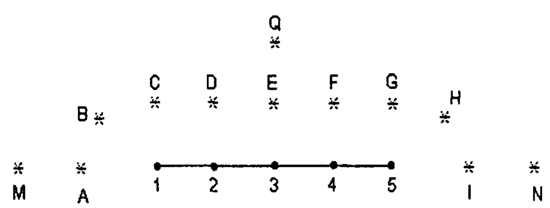

Figure 4. Relative positions of different lightning strike points from a OTSL. Points C, D, E, F, G, and Q are the FRS and points M, A, B, H, I, and N are the SRS.

The contribution of Horizontal Electric Field (HEF) and Vertical Electric Field (VEF) in producing induced voltages in telecommunication line, depending upon different strike distances during FRS as well as SRS, are presented in Fig. 5 to Fig. 10. In this case the FRS occurs along the direction of the perpendicular mid intersect of the line and the SRS occurs along the line extension to the left. The induced voltages are calculated for the strikes that occur at distances 0.5, 1.5, 2.5 km.. A look into the FRS induced voltages in Fig. 5, 7, and 9 show that both the HEF and VEF produce positive polarities of induced voltages. The HEF contribution to produce induced voltages dominates over VEF contribution when the strike distance is small. The HEF contribution becomes minor at far distances, where the induced effect is mostly contributed by the VEF. The SRS induced voltages are shown in Fig. 6, 8, and 10, where the VEF induced voltages are dominant over HEF induced voltages at all distances. In this case the HEF induced voltages are of negative polarities where as the VEF induced voltages remain of positive polarities as it is for FRS. The HEF induced voltages change their polarities because the active direction of HEF changes with the change of strike locations. The strike distance dependency of induced voltages can be explained with the help of distance dependence factors of HEF and VEF in equations (1) and (2). The distance dependence factors of VEF are R^{-1}, R^{-2}, and R^{-3} for radiation, induction and electrostatic field terms, respectively, where as the factors of HEF are R^{-2}, R^{-3}, and R^{-4} for radiation, induction and electrostatic field terms, respectively.

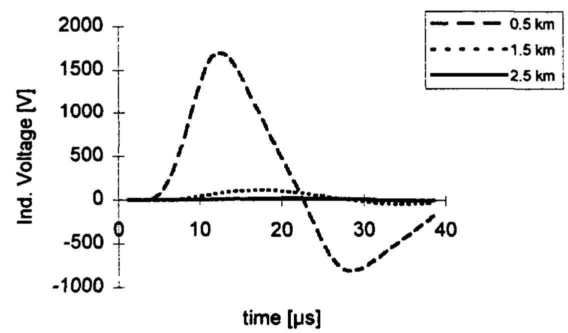

Figure 5. Induced voltages due to HEF to the left end of OTSL during FRS.

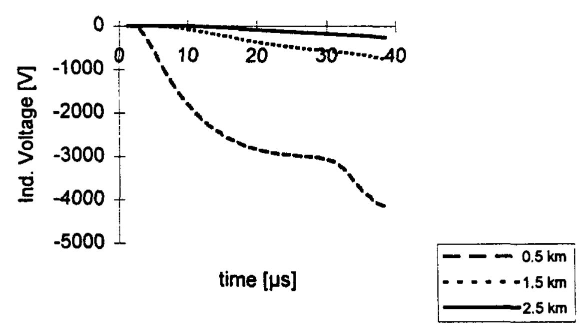

Figure 6. Induced voltages due to HEF to the left end of OTSL during SRS.

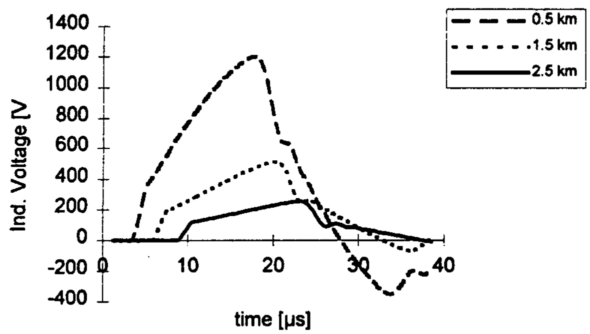

Figure 7. Induced voltages due to VEF to the left end of OTSL during FRS.

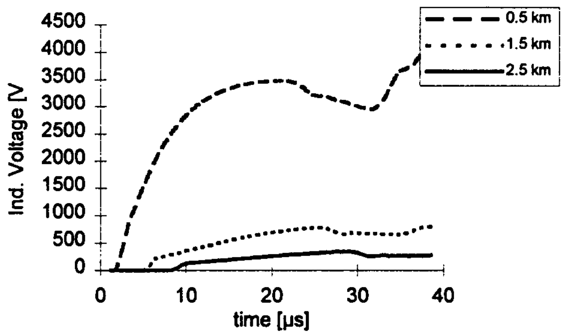

Figure 8. Induced voltages due to VEF to the left end of OTSL during SRS.

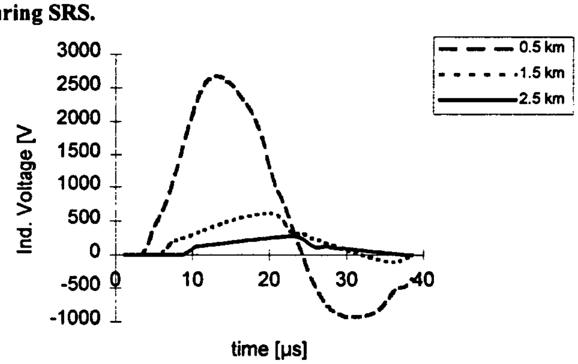

Figure 9. Total induced voltage to the left end termination of OTSL during FRS.

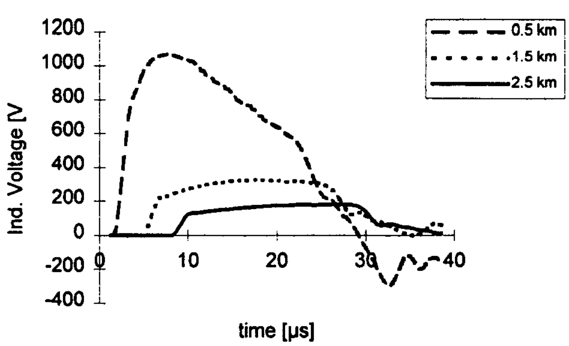

Figure 10. Total induced voltage to the left end termination of OTSL during SRS.

The effect of strike location on induced voltages is shown in Fig. 11 and the strike locations are defined in Fig. 4. The least distance between strike points and line is considered 0.5 km. From the observation of the plot it is found that the FRS produces higher values of induced voltages in peak compared with SRS. On the other hand SRS produces higher values in steepness compared with FRS. The value of peak induced voltages during FRS are mostly contributed by the electrostatic term of electric fields. Since the FRS produces additive effect of VEF and HEF, the peak value of induced voltages becomes higher. On the other hand the steepness of induced voltages is the contribution due to the fast rising radiation term of electric fields. The radiation term of VEF is dominant at the beginning of fields, while it is not dominant for HEF due to its distance dependent factor R^{-2} in equation (2). That is why SRS produces higher steepness of induced voltages.

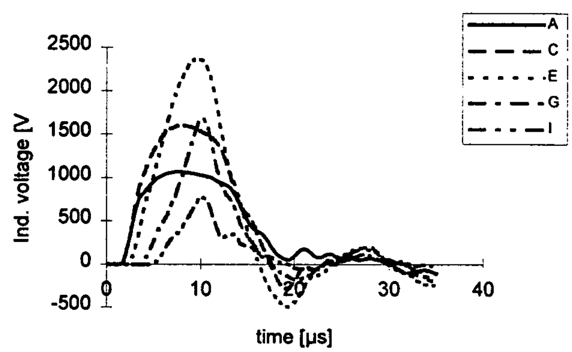

Figure 11. Calculated voltages at the left end of OTSL due to the strike locations shown in Fig. 4.

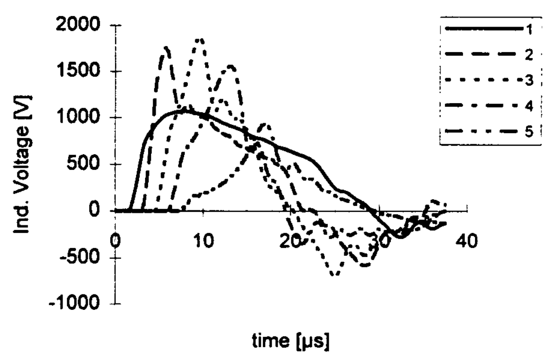

Figure 12. Induced voltage at the different points on OTSL due to the strike at 0.5 km along the line extension to the left. The points of voltage calculation are indicated in Fig. 4.

Induced voltages are calculated at different points on telecommunication line due to SRS at 0.5 km along the extension of the line to the left, the plots are presented in

Fig. 12 and the points (1, 2, 3, 4, and 5) of calculation are shown in Fig. 4. It is found that the maximum peak of induced voltage occurs at the mid point of the telecommunication line although the left end termination is near to the strike point. The maximum voltage on the middle may be the effect of the propagation of induced voltages through the telecommunication line.

The effect of lightning channel height on induced overvoltages on OTSL due to SRS at 0.5 km from the left is shown in Fig. 13. It is seen that there is no significant changes in induced voltages when the channel height is of 2 km or more but the wave shape of induced voltage changes considerably with lower value of channel height.

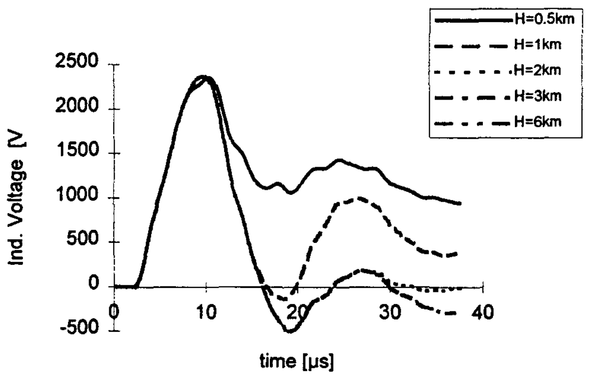

Figure 13. Effect of lightning channel height on induced voltages on OTSL during FRS at 0.5 km from the mid point of the line.

Several comparisons have been made between the numerical and experimental results. The maximum induced voltages recorded by our experimental setup of 1.8 km OTSL was around 2.5 kV. The clean wave forms of our recorded data show that the induced voltages start increasing towards the positive direction and reach its positive peak after which it start decreasing and drop to the negative values. In our simulation we have found the induced voltage around 2.7 kV using peak current of 10 kA and FRS distance of 0.5 km. The plot of calculated voltages also starts increasing towards the positive direction and reach its positive peak after which it start decreasing and drop to the negative values. The coordinates of actual lightning strike location were obtained from the Lightning Detection System (LDS) installed by the Tenaga National Research and Development (TNRD) unit. A comparison between numerical and experimental results is presented in Fig. 14, where the dotted line represents the simulation result and the solid line the experimental result. In our simulation we have considered the peak value channel current of 18 kA, strike distance of 0.5 km along the line extension from the left termination. On the other hand LDS records gives the peak channel current of 18 kA and strike location at around 1.5 km from the left. The calculated peak induced voltage is 1971 volts while the experimental recorded peak was 1775 volts. It is noted that LDS has some error in detecting exact lightning strike locations but we have consider it within acceptable limits.

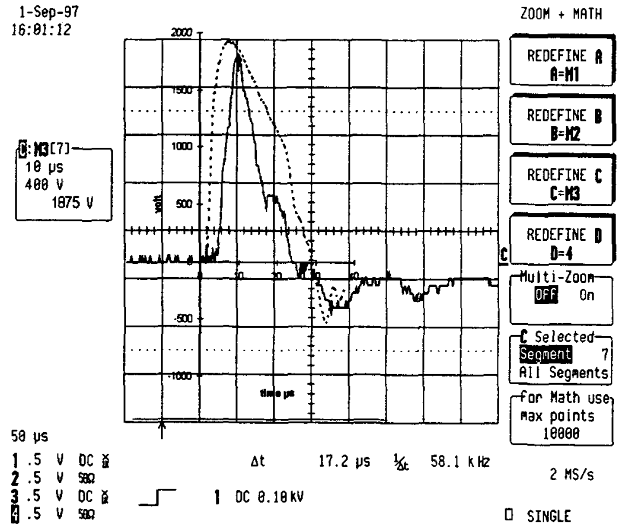

Figure 14. Comparison between experimental and numerical data as for the case of a SRS. Solid line presents experimental data and dotted line the numerical data. The strike point for calculation is at 0.5 km on the line extension to the left. According to Lightning detection system the actual lightning occurs at around 1.5 km on the line extension to the left from the end.

Conclusion

Numerical analysis of lightning induced transients on overhead telecommunication subscriber line has been carried out in this paper. The analysis shows that the consideration of infinite ground conductivity to calculate lightning induced transients in telecommunication subscriber line is reasonable when the strike location is at small distance from the line. Both the horizontal and vertical component of electric fields have significant effect on induced transients. HEF dominates during FRS while VEF dominates during SRS. The horizontal field contribution is greatly affected by the strike distance. The strike locations are of great concern to investigate the induced transients in telecommunication or power lines. The FRS produces higher value in peak, while SRS produces higher value in steepness. The induced voltages are different for different points on the line. The maximum induced transients always appear at the mid point of the line. The changes in channel height has also an effect on induced transients. Finally, the comparison of numerical and experimental results shows that the analysis in this paper is considered to be reliable.

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