Lightning Induced Overvoltages on Multiconductor Overhead Lines

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Abstract - **The calculation of voltages induced by indirect lightning on multiconductor overhead lines has been the subject of several studies. In this paper a multi-phase transmission line model is presented, which allows taking into account external exciting fields illuminating the line. These fields are computed by using the coupling model by Agrawal et al and the representative voltage sources distributed along the line are derived. The shielding effect, due to mutual coupling among the conductors of a three-phase line and between the ground wires and the phase conductors, is studied. Results obtained by computer simulation are compared with those published by other authors, and a good agreement is found. Although the models dealt with in the paper apply to any type of power lines (transmission or distribution), particular attention is given to low voltage distribution lines, for which lightning induced overvoltages have a greater importance.**

Keywords: Induced Overvoltages, Multiconductor Lines, Coupling, Lightning Stroke, Shielding Effect.

I. INTRODUCTION

The electromagnetic fields generated by lightning return strokes, interact with overhead power lines inducing overvoltages that may lead to the flashover of the insulator strings. Several authors [1-3] refer that, contrary to the case of overhead transmission lines, most outages on overhead distribution lines are caused by lightning strokes to nearby ground.

The overvoltages induced by lightning strokes on overhead lines have been studied deeply in the literature [1-11]. Although there is some agreement on the general basis of the problem, a variety of models exist for the return stroke, the coupling between this and the line, and the line itself. The results reported in several studies are often in disagreement with each other.

As the work reported in this paper deals exclusively with transmission line modelling, the authors assumed the return stroke current used in [9], and employ the "LEMP" programme [10] for computing the fields that illuminate the line when a lightning stroke hits nearby ground.

Once the illuminating fields are computed, and in order to evaluate the induced overvoltages, a transmission line model allowing to include in the wave propagation equation the effect of the illuminating field is required. The model presented in this paper corresponds to the generalisation to multi-phase of the multi-purpose transmission line model presented in [12] applied the case distributed sources. The external exciting fields illuminating the line are computed by using the coupling model by Agrawal et al. [13].

The line model is used to evaluate the voltages induced on two multiconductor lines with different configurations. These lines are the same as in [6, 9, 11] so that the computed values can be used to validate the line model proposed in this paper.

It is important to quantify the reduction on the induced voltage amplitudes due to the presence of the other phase conductors of the multiconductor lines, and the shielding effect due to the presence of ground wires grounded at the line terminations. Two studies are done with this purpose.

II. TRANSMISSION LINE MODEL

A. Coupling Model

Agrawal et al. [13] derived the equations describing, in the time domain, the coupling between an external electromagnetic field and a multiconductor line. Starting from Maxwell's equations and considering transverse magnetic propagation, the following pair of expressions are proposed for the case of a lossless line,

$$\frac{\partial}{\partial x}\left[u_i^s(x)\right]+\left[L'_{ij}\right]\frac{\partial}{\partial t}\left[i_i(x)\right]=\left[E_x^i(x,h_i)\right] \qquad (1)$$

$$\frac{\partial}{\partial x}\left[i_i(x)\right]+\left[C'_{ij}\right]\frac{\partial}{\partial t}\left[u_i^s(x)\right]=0 \qquad (2)$$

where:

- $\left[L'_{ij}\right]$ is the inductance matrix per unit length of the line;
- $\left[C'_{ij}\right]$ is the capacitance matrix per unit length of the line;
- $\left[E_x^i(x,h_i)\right]$ is the horizontal component of the incident electric field at conductor *i* height, h_i;
- $\left[i_i(x)\right]$ is the line current, and
- $\left[u_i^s(x)\right]$ is the scattered voltage.

In order to obtain the total voltage, it is necessary to add to the scattered voltage the voltage of the incident field between the reference and the *i*th conductor:

$$\begin{aligned}[u_i(x)] &= [u_i^s(x)] - \left[\int_0^{h_i} E_z^i(x,z)\,dz\right] \\ &\cong [u_i^s(x)] - [h_i E_z^i(x,0)]\end{aligned} \tag{3}$$

where:

- $[E_z^i(x,0)]$ is the vertical component of the incident electric field, considered unvarying in the height range $0<z<h_i$.

All the time dependencies from voltage, current and electric field vectors were omitted for simplifying reasons.

Finally there are two expressions (one for each line terminal) representing the boundary conditions in terms of scattered voltage:

$$[u_i^s(x=0)] = -[R_0][i_i(x=0)] + [h_i E_z^i(x=0,0)] \tag{4}$$

$$[u_i^s(x=L)] = [R_L][i_i(x=L)] + [h_i E_z^i(x=L,0)] \tag{5}$$

where $[R_0]$ and $[R_L]$ are the matrices of the line terminations.

B. Numerical Solution

The algorithm used to solve (1) and (2) is based on a finite-differences approximation to the partial derivatives, which has proven itself to be adequate to represent overhead transmission lines in electromagnetic transients calculation in the time domain.

Considering the transmission line divided into *N* incremental segments, the partial differential equations are represented by the following set of *2(N+1)* equations in the time variable:

$$\begin{aligned}&h_0(u_0, i_0, u'_0, i'_0) = 0 \\ &a_j = [u_{j+1}] - [u_j] + [\Delta u_{j+1}(i_j, i'_j)] = 0 \quad j = 0,\dots,N-1 \\ &b_j = [i_j] - [i_{j-1}] + [\Delta i_j(u_j, u'_j)] = 0 \qquad j = 1,\dots,N \\ &h_N(u_N, i_N, u'_N, i'_N) = 0\end{aligned} \tag{6}$$

where *u'* and *i'* denote the time derivatives of *u* and *i*. The functions Δu_j and Δi_j represent the longitudinal voltage drop and the transverse current on segment *j* of the line, and may contain in their expressions the non-uniformity of the line parameters. The boundary conditions are given by the implicit functions h_0 and h_N. The segment equations are also kept in their general implicit form to keep the algorithm independent from the particular line parameter modelling techniques to be use in applications.

In this particular case we have:

$$h_0 = [u_i^s(0,t)] + [R_0][i_i(0,t)] + [h_i E_z^i(0,0,t)], \tag{7}$$

$$[\Delta u_{j+1}] = \Delta x [L'_{ij}] \frac{\partial}{\partial t}[i_i(j,t)], \tag{8}$$

$$[\Delta i_j] = \Delta x [C'_{ij}] \frac{\partial}{\partial t}[u_i^s(j,t)], \tag{9}$$

$$h_N = [u_i^s(N,t)] + [R_N][i_i(N,t)] + [h_i E_z^i(N,0,t)], \tag{10}$$

where Δx is the length of the line segments.

The time equations are solved using a multi-step linear integration formula. The Gear's 2nd order method was chosen for the present application. The very nature of the travelling wave problem implies that the system matrix has a band-diagonal structure, thus allowing fast recursive formulas to be used in evaluating its solution.

Typically, the discretization of wave propagation equations gives rise to system's supporting lightly damped oscillating modes at a high frequency determined by the spatial step-size. Using Gear's 2nd order method [12] these can be smoothed out by the time integration algorithm by making an adequate choice of the space and time steps.

Trapezoidal integration has proven inadequate for this purpose [14], while Gear's 2nd order method introduce an increasing damping for higher frequencies. However, accuracy is usually impaired by the introduction of damping. Gear's 2nd order, for a given bandwidth and a constant time-step, remains accurate enough over a wide range of frequencies. Therefore, it is the most suitable integration method to be used for the numerical filtering of the spurious oscillations introduced by the space discretization of the transmission line equations.

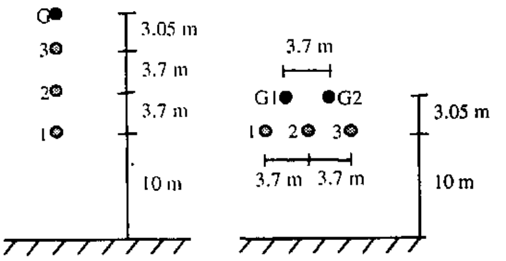
Evaluation of the transmission line parameters is made by independent routines of any suitable type, which may implement simple equivalent circuits, as well as suitable physical models. The above described line model allows considering any variation law of the line parameters. It also is adequate to include non-linear (such as corona) as well as frequency dependent parameters.

The boundary conditions may be evaluated by dedicated routines or by a general-purpose program, such as an EMTP.

III. VOLTAGES INDUCED ON THREE PHASE VERSUS SINGLE PHASE POWER LINES

Lets consider two lines (Fig. 1.a and Fig. 1.b) previously used in other studies [6, 9, 11] on the subject, the first one having vertical configuration and the second one horizontal configuration. The radius of the phase conductors on each line is 9.14 mm and that of the ground wires is 3.96 mm. As in [9], all the phase conductors are terminated on a resistance equal to its characteristic impedance determined in the absence of other conductors and that both lines are 1 km long.

The "LEMP" program [10] is used to calculate the electric fields. The channel base return stroke current has a peak value of 12 kA and a maximum time-derivative of 40 kA/μs as in [9]. The return stroke velocity is assumed to be 1.3 x 10^8 m/s. And the stroke location is 50 m from the line center and equidistant from the line terminals.



(a) (b)

Fig. 1. The two overhead lines in study: (a) vertical configuration, (b) horizontal configuration.

To begin with, let us consider that the lines do not have ground wires, and calculate the induced voltages at the lines extremities. As in [9], in order to determinate the shielding effect due to the presence of the other conductors, we compare these induced voltages with those calculated considering a single conductor situated at same height. In Fig. 2. and Fig, 3. we show the induced voltages calculated for each line configuration and in Fig. 4. the induced voltages calculated considering a single conductor line at the same height of the phase conductors. In Table I we give the ratio between the induced voltage amplitudes on each conductor and those calculated for the case of a single conductor line.

Table I shows a reduction in the voltage amplitudes of 12-25% due to the presence of other conductors in multiconductor lines of finite length. The calculated values are in agreement with those reported in [9] (there is just a small variation of about 1% in the case of the vertical line conductor 3). This results show that the transmission line model is adequate to use in the analysis of induced overvoltages on multiphase overhead power lines.

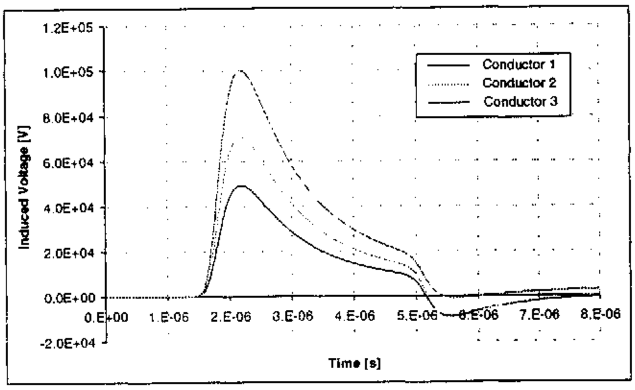


Fig. 2. Voltages induced on the three phase conductors of the vertical configuration line, without the ground wire.

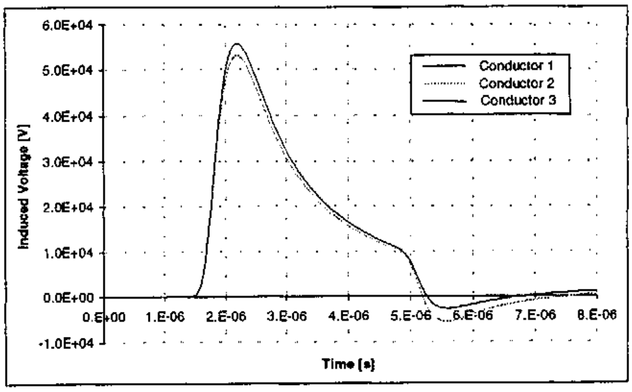


Fig. 3. Voltages induced on the three phase conductors of the horizontal configuration line, without the ground wires.

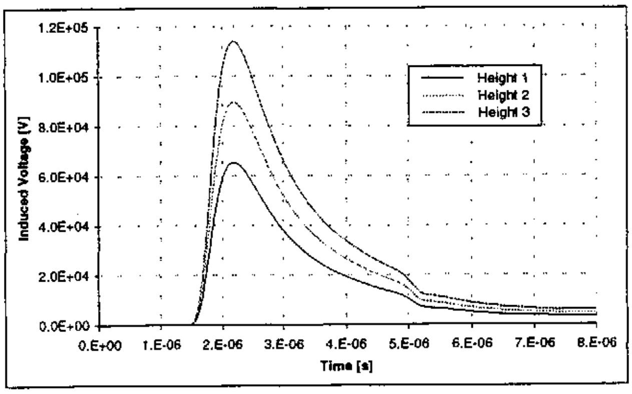


Fig. 4. Voltages induced on a single conductor at a height of 10.0, 13.7 and 17.4 m.

Table I

Ratio between the induced voltage amplitudes on a line conductor V_i and those corresponding to a single conductor at the same height $V(h_i)$.

Ratio	Vertical line	Horizontal line
$V_1/V(h_1)$	0.75	0.85
$V_2/V(h_2)$	0.79	0.81
$V_3/V(h_3)$	0.88	0.85

IV. SHIELDING EFFECT FROM GROUND WIRES

Now, in order to evaluate the shielding effect due to the presence of ground wires let us consider that the ground wires are present in both line configurations (as in Fig. 1.). The vertical configuration line has a ground wire 3.05 m above the uppermost conductor, and the horizontal configuration line has two symmetrical ground wires 3.05 m above the phase conductors and 3.7 m apart from each other. All the ground wires are solidly grounded at the line extremities.

In Fig. 5. and Fig. 6. we show the voltages induced on the vertical and horizontal configuration lines respectively. In Table II we give the ratio between the induced voltage amplitudes on each conductor considering and disregarding the presence of ground wires for the two line configurations.

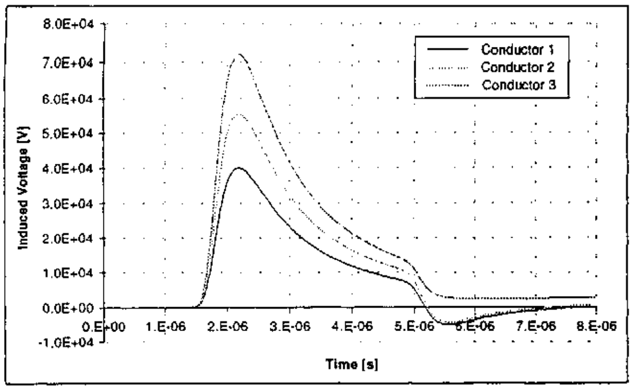


Fig. 5. Voltages induced on the three phase conductors of the vertical configuration line, with the ground wire.

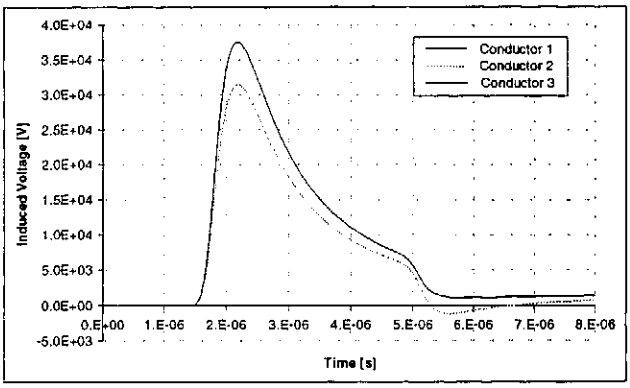


Fig. 6. Voltages induced on the three phase conductors of the horizontal configuration line, with the ground wires.

Table II

Ratio between the induced voltage amplitudes on a line conductor with (V_{ig}) or without (V_i) the ground wires.

Ratio	Vertical line	Horizontal line
V_{1g}/V_1	0.81	0.67
V_{2g}/V_2	0.78	0.59
V_{3g}/V_3	0.72	0.67

As it can be seen from Table II, the presence of ground wires significantly reduces the amplitudes of the induced overvoltages in the phase conductors in the vicinity of the grounding point. This reduction can be as high as 41% in the case of the horizontal line and 28% for the uppermost conductor of the vertical line.

Once again the results presented in Table II are in agreement with those published in [9], confirming the previous conclusion that the transmission line model developed by the authors is adequate.

V. CONCLUSIONS

A multiphase line model for transmission lines illuminated by LEMP was developed and successfully implemented. It is based on a finite-differences algorithm to solve the wave equations for any space and time variation of the external exciting fields illuminating the line. The model is used to calculate the lightning induced voltages on two 1 km-long distribution lines with different configurations.

For a given lightning return stroke striking the vicinity of the line, two studies were made. The first study gave the reduction in the amplitudes of the induced voltages on multiconductor lines of finite length, when compared to those obtained considering single wire lines at the same height of each phase conductor. A reduction of 12-25% was calculated for the two line configurations. In the second study, the shielding effect due to the presence of ground wires was evaluated. This shielding, in the case of the horizontal line, that has two ground wires, can produce a reduction as high as 41% on the induced voltage amplitudes. On the vertical line, having just one ground wire, only 28% of reduction is obtained for the conductor closest to the ground wire.

All the results are in perfect agreement with those reported in [9] for the same lightning current and line configurations. For the case of the shielding from ground wires, the results are also in agreement (same order of magnitude for the reduction caused by the shielding effect) with those published by other authors [4, 7, 8], in spite of the differences on the system components modelling.

VI. ACKNOWLEDGEMENTS

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