Presentation of an approach based on EMTP for the calculation of lightning induced overvoltages

A. Xémard[1], P. Baraton[1], B. Bressac[1], N. Qako[2], J. Mahseredjian[2], G. Simard[2], J. Ribeiro[3], R. Tarafi[3], A. Zeddam[3]

(1) Electricité de France R&D, (2) Hydro-Québec/IREQ, (3) France Télécom R&D

Abstract **– LIPS (Lightning Impact on Power Systems) is a toolbox based on EMTP (DCG version) and devoted to the calculation of the failure rate of apparatus due to lightning. This software covers direct and induced lightning. It has been developed in a partnership project between France Telecom, Hydro-Québec and Électricité de France. The induced lightning module calculates overvoltages due to a lightning flash nearby the electrical system. It is based on the following computational steps:**

1) **For each overhead line and underground cable of the electrical system, two equivalent current sources are calculated in the frequency domain, representing the illumination of the conductors by external electrical field due to lightning. These sources are evaluated in the frequency domain, taking into account the variation of the parameters of lines and cables with frequency. The conductivity of the ground is taken as finite. The modal theory is applied in the case of multi-conductor cable or line.**
2) **The equivalent sources are converted into time-domain and then included in an EMTP representation of the system allowing a time-domain transient computation.**

After providing theoretical background this paper will present this approach and follow by comparisons between induced overvoltages calculated by LIPS and results from the literature.

Keywords – induced lightning, coupling, traveling wave theory, EMTP.

I. INTRODUCTION

The aim of this paper is to describe an approach compatible with EMTP [4] and based on the line theory to model the coupling between a lightning return stroke and a multi-conductor line. The first part of the paper gives the theoretical background. It covers the evaluation of the electrical field and the calculation of the coupling between the electrical field and the line. The second part of the paper presents some comparisons between results obtained by applying the approach described here (calculation of sources in the frequency domain and then calculation of over-current in the time domain using EMTP) and results obtained applying a frequency domain approach [5].

It is worth to mention other publication related to various aspects of the presented subject: [12]-[16].

II. NOTATIONS

λ	spatial attenuation along the lightning channel
μ	velocity of the return stroke along the channel
a	propagation function of the line
E_i	incident electric field; the field which would exist without the line and which is due to the lightning return stroke
E_x^i	horizontal component of the incident electric field
E_z^i	vertical component of the incident electric field
$i(x,s)$	current circulating along the line
s	Laplace operator
$u_i(x,s)$	incident voltage
$u_s(x,s)$	scattered voltage: voltage which is related only to the current circulating along the line
$u(x,s)$	total voltage induced along the line
x	abscissa along the line from the origin
$Z(s)$	impedance of the line per unit length
Y	admittance of the line per unit length
Z_c	surge impedance of the line

III. THEORETICAL BACKGROUND

A. Calculation of the lightning return stroke EM field

Lightning return stroke representation

The first step of induced voltage calculation is the evaluation of the lightning return stroke electromagnetic field. This evaluation requires an assumption regarding the spatial-temporal distribution of the lightning current along the channel. Numerous models have been proposed for this representation [5][6]. The one adopted in LIPS is the MTL (Modified Transmission Line) model proposed by Rakov [7]. The lightning current is assumed to attenuate when propagating upward along a vertical channel, according to the following formula:

$$i(z,t) = \mathrm{e}^{(-z/\lambda)}\, i(0, t - z/\mu) \qquad (1)$$

This equation also refers to the model presented in [1] and validated in [2] and [3]. It can be also labeled as the MTLE model, to distinguish from the MTLL model [7].

EM field above ground evaluation

The calculation of the vertical and horizontal components of the EM field above ground is performed in the frequency domain, considering the finite value of the conductivity of the ground. In LIPS the so-called integral of Sommerfeld is approximated using [8]. This approximation has a wider domain of validity than other approximations (Rubinstein, Wavetilt) [6] which have been proposed. The vertical field does not depend on the height above ground.

Evaluation of EM field in the soil

This field can also be evaluated from the integrals of Sommerfeld, but P.R.Bannister [9] has shown that the horizontal component of the electric field in the ground can be calculated by multiplying the electric field calculated in the air (height=0) with the term of propagation in the ground $e^{-\gamma d}$ considering an exponential decrease of field versus depth d. The vertical component of the electric field is negligible.

B. Calculation of the coupling between EM field and a horizontal line

Different models have been proposed and used for the representation of line coupling with the lightning impulse [5][11]. In the approach presented in this paper the coupling is represented using the so-called Agrawal model [10], which is based on the line theory and considers that the excitation of the line is due to the horizontal and vertical components of the incident electric field.

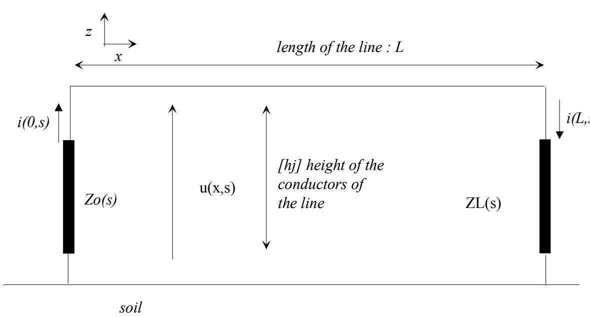


Figure 1: Representation of the line

The scattered voltage is obtained by solving the following set of equations :

$$\frac{\partial u_s(x,s)}{\partial x} + Z(s)i(x,s) = E_x^i(x,h_j,s) \tag{2}$$

$$\frac{\partial i(x,s)}{\partial x} + Yu_s(x,s) = 0 \tag{3}$$

The conditions at the line terminals are given by :

$$u_s(0,s) = -Z_0(s)i(0,s) + \int_0^{h_j} E_z^i(0,z,s)dz \tag{4}$$

$$u_s(L,s) = +Z_L(s)i(L,s) + \int_0^{h_j} E_z^i(L,z,s)dz \tag{5}$$

Where Z_0 and Z_L are the equivalent impedances at both terminals of the line. In the case of a multi-conductor line they are matrices.

The total voltage is the sum of the scattered voltage and of the voltage due to the incident field :

$$u(x,s) = u_s(x,s) + u_i(x,s) = u_s(x,s) - \int_0^{h_j} E_i(z,s)dz \tag{6}$$

VI Presentation of the approach used in LIPS

A. Calculation of the lightning electric field

The horizontal and vertical components of the electric field are calculated in the frequency domain, based on the Norton approximation and considering a Dirac for the lightning return stroke current. This approach allows evaluating the field for any lightning stroke current form by a simple convolution operation. The calculation of the electric field is time consuming therefore it is performed in advance and stored for a given set of frequencies and distances from the lightning channel. An interpolation procedure is applied to limit the number of samples calculated. In [5] it is shown that by multiplying the field by e^{-jkR}, (where R is the distance between the intersection of the lightning channel and the ground) and the point of observation, the obtained field changes smoothly with frequency.

B. Principle of the model of coupling

During transient simulations, the illumination of the line by the external EM field is represented by two current sources F_0 and F_l located at the terminals of the line (see Figure 2). These two sources depend on the incident electric field and on the characteristics of the line. They do not depend on the other parts of the electrical system. Therefore they may be evaluated before making the calculation of the transient occurring on the whole electrical system and included in the EMTP representation afterwards.

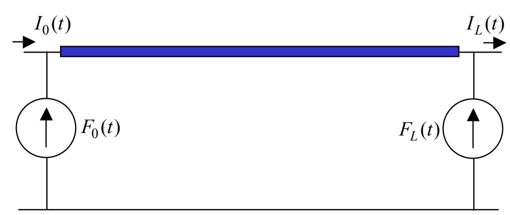


Figure 2: Model of illuminated line

C. Calculation of the equivalent sources

The equivalent sources are deduced from the overvoltages obtained at both terminals of the line when the line illuminated by the incident electric field E_i is matched. The whole calculation is performed in the frequency domain. If $U(0)$ and $U(l)$ are the voltages at the terminals of the matched line, then $F_0(s)$ and $F_l(s)$ are evaluated from the following set equations :

$$Z_cF_0(s) + Z_ca(s)e^{-\tau s}F_l(s) = 2U(0) \tag{7}$$

$$Z_cF_l(s) + Z_ca(s)e^{-\tau s}F_0(s) = 2U(l) \tag{8}$$

A Fast Fourier transform is performed afterwards in order to determine F_0 and F_l in the time-domain. The Appendix explains how $U(0)$ and $U(l)$ are evaluated.

D. Transient simulation

The sources calculated for each illuminated horizontal line or cable are included in an EMTP representation of the system.

The coupling with vertical conductors is represented by lumped voltage sources with values given by:

$$E = h\, E_i^{vertical} \tag{9}$$

where h is the length of the vertical conductor.

V Comparison of LIPS results with literature

In this section comparisons are made between the results found by LIPS for the calculation of the induced current on an overhead line and results presented in [5] which are based on a frequency domain approach. The work presented in [5] is based on the Norton approach when calculating the electrical field, and takes into account the frequency dependence of the line.

The value of the induced current is calculated at both terminals of a single-conductor line, of length 200m. The line is 6m high and matched at both ends.

The electrical field is calculated considering a bi-exponential return stroke current and a Transmission Line Model (TLM) of propagation of the lightning current along the channel:

$$I(t,0) = I_0(e^{-\alpha_1 t} - e^{-\alpha_2 t})$$

$$I(t,x) = I(t - h/v, 0)$$

with:

$I_0 = 15\text{kA}$

$v = 1.1\text{e}08\text{m/s}$

$\alpha_1 = 3\text{e}04\text{s}^{-1}$

$\alpha_2 = 3\text{e}07\text{s}^{-1}$

Two distances d between the point of impact of the lightning stroke and the line are considered : d=200m and d=1km. The studied configuration is shown in Figure 3. The following cases are studied.

<u>Case 1</u>

The point of impact is A. The line is 200m long and matched, d=1000m. The soil resistivity is equal to 100 Ωm. Figure 4 presents results found by LIPS and compared to results given in [5].

<u>Case 2</u>

The point of impact is C. The line is 200m long and matched, d=1000m. The resistivity of the soil is equal to 100Ωm. Figure 5 presents results found by LIPS and compared to results given in [5].

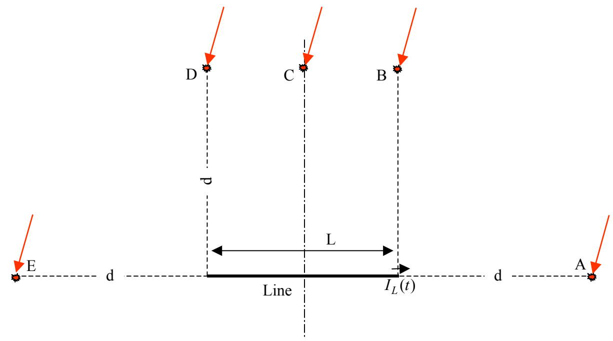
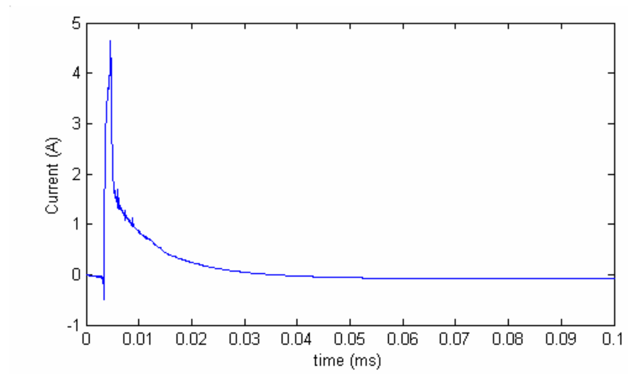
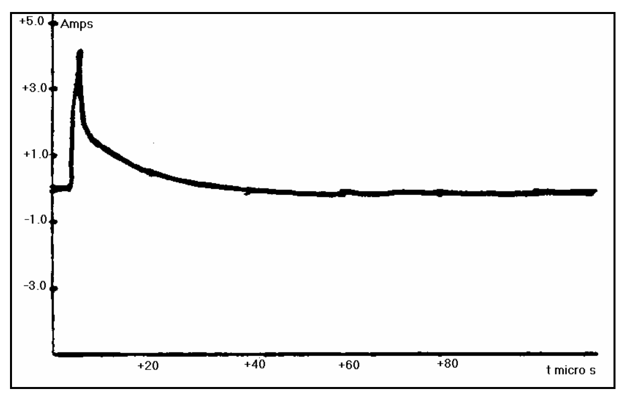


Figure 3: Representation of the induced line and lightning impact points



(a) LIPS



(b) Results from [5]

Figure 4: Currant $I_L(t)$, the point of impact is A, Case 1

<u>Case 3</u>

The point of impact is E. The line is 200m long and matched, d=1000m. The soil resistivity is equal to 100Ωm. Figure 6 presents results found by LIPS and compared to results given in [5].

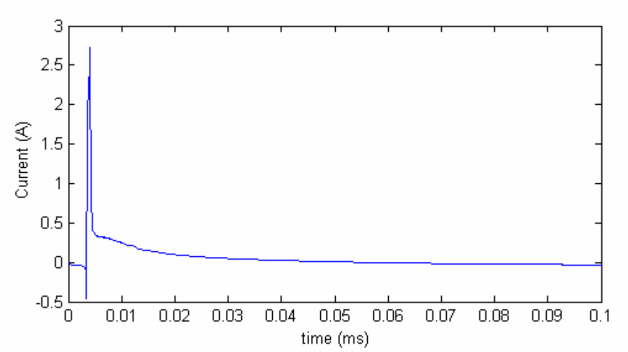
<u>Case 4</u>

The point of impact is A. The line is 200m long and matched, d=200 m. The soil resistivity is equal to 10000Ωm. Figure 7 presents results found by LIPS and compared to results given in [5].

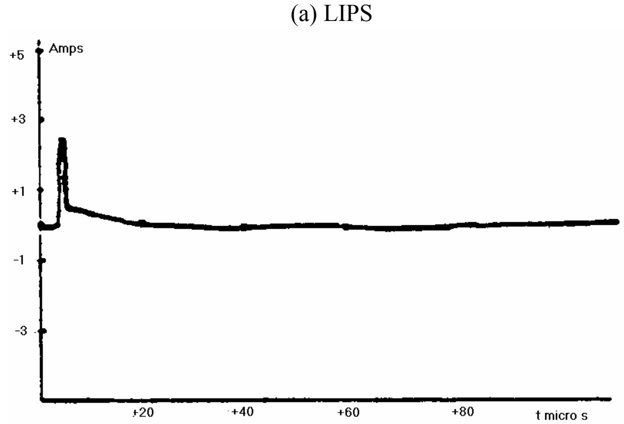
The current in case 4 is higher than in case 1 because of the lower value of d and higher value of soil resistivity which leads to an increase of the coupling.

LIPS is based on the calculation of lightning representation sources in the frequency domain and usage of these sources in EMTP for the simulation in time-domain.

It is apparent from these figures that the simulation results found by LIPS are able to match the results given in [5] which are obtained by applying a frequency domain approach.

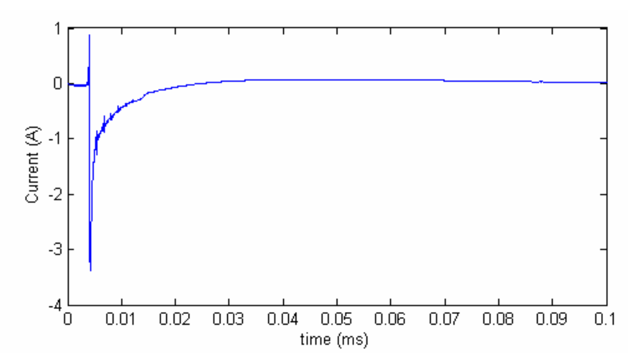


(a) LIPS

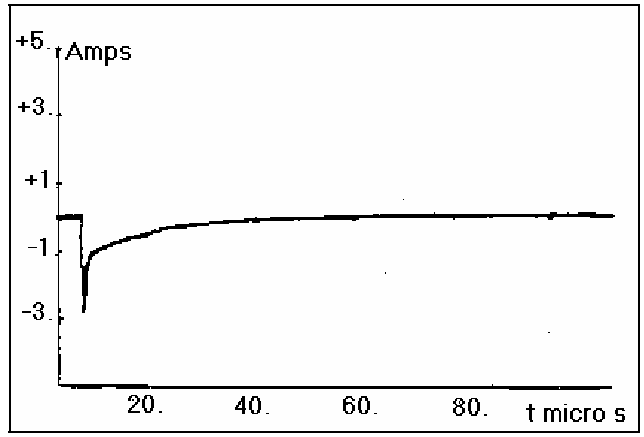


(b) Results from [5]

Figure 5: Current $I_L(t)$, the point of impact is C, Case 2

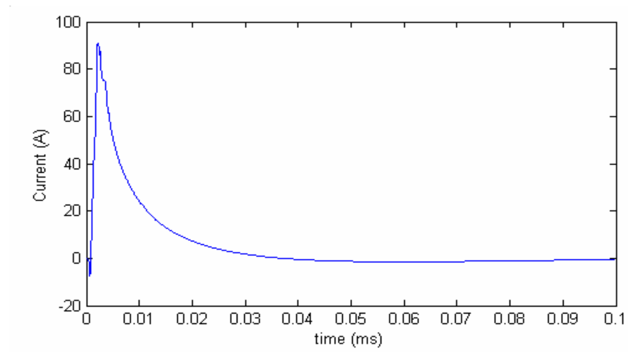


(a) LIPS result

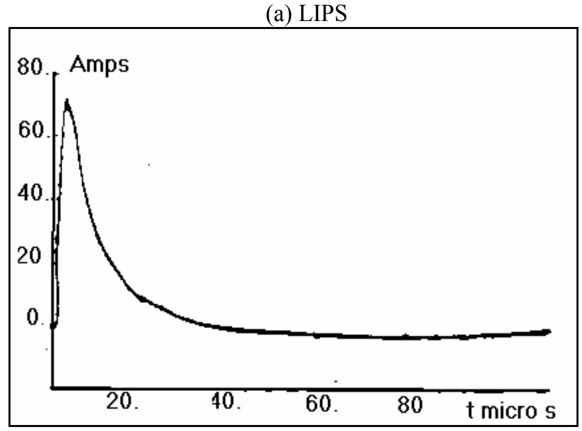


(b) Results from [5]

Figure 6: Current $I_L(t)$, the point of impact is E, Case 3



(a) LIPS



(b) Results from [5]

Figure 7: Current $I_L(t)$, the point of impact is A, Case 4

VI CONCLUSIONS

The paper has presented the theoretical principles of the module used in LIPS to perform the calculation of overvoltages due to induced lightning. The approach is based on the preliminary calculation of current sources representing the induced effect of lightning. It provides an efficient combination of a precise representation of the coupling phenomenon and a detailed modeling of the electrical system based on EMTP. The approach has been validated by comparing the results of LIPS with the results obtained using a frequency domain approach.

APPENDIX EVALUATION OF VOLTAGES AT BOTH ENDS OF A MATCHED LINE DUE TO AN INCIDENT ELECTRIC FIELD

From equations 2 and 3 it is deduced that:

$$\frac{\partial^2 i}{\partial^2 x} - Y(s)Z(s)i = -Y(s)E_x^i(s) \tag{10}$$

At both terminals of the line we have the two following equations :

$$\frac{\partial i(0,s)}{\partial x} = Y(s)Z_c i(0,s) - Y(s)\int_0^{h_j} E_z^i(0,z,s)dz \tag{11}$$

$$\frac{\partial i(L,s)}{\partial x} = -Y(s)Z_{cph} i(L,s) - Y(s)\int_0^{h_j} E_z^i(L,z,s)dz \tag{12}$$

Equation (10) is solved directly in the frequency domain, applying the modal theory and using equations (11) and (12) as boundary conditions.

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