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# LIGHTNING–INDUCED OVERVOLTAGES ON OVERHEAD LINES: MODELLING AND EXPERIMENTAL VALIDATION

**Abdenbi Mimouni — Zin E. Azzouz —Boualem Ghemri** *

The evaluation of induced overvoltages from indirect lightning has been for more years one of the most important problems in designing and coordinating the protection of overhead power lines. In this paper, we present the frequently coupling model used in the power lightning literature for the calculation of lightning induced overvoltages, the Agrawal approach. The algorithm applies to single conductor line above a perfectly conducting ground. The computation results are first validated by experimental results obtained using a reduced scale line model illuminated by the EMP simulator of the Swiss Federal Institute of Technology in Lausanne (SEMIRAMIS), and then are compared with the computation results obtained by the LIOV code (beta version).

Keywords: lightning induced overvoltages, FDTD, EMC

## 1 INTRODUCTION

Lightning induced overvoltages are nowadays a major issue in electromagnetic compatibility (EMC) and power quality domains. The need for a good quality in power supply along with the widespread use of sensitive devices connected to distribution lines makes the protection against lightning induced disturbances of primary importance. Lightning induced overvoltages are generally calculated in the following way:

1. The lightning return stroke electromagnetic field is calculated making use of return stroke current model which specifies the spatial-temporal distribution of the lightning current along the channel. This point has been and is still the object of several other papers; see for example [1], [2], [3], [4] and [5].

2. Secondly, the electromagnetic field is used to calculate the induced overvoltages, by means of a coupling model which describes the interaction between the field and the line conductors.

The two coupling models most frequently used in the power lightning literature for the calculation of lightning induced overvoltages, namely the model by Chowdhuri and Gross and the model by Agrawal, Price and Gurbaxani. The two models are compared and discussed in [6], it was showed that the Chowdhuri-Gross model is incomplete [6]. Only the Agrawal model and its equivalent formulations can be considered as rigorous within the limits of the adopted hypothesis (transmission line approximations) [7].

Lightning Electro Magnetic Pulse LEMP to transmission line coupling equation can be dealt with either in the frequency domain or in the time domain. A time domain approach allows handling in more straightforward way non-linearities which appear when considering corona effect, and/or when protective devices such as surge arresters are present. One of the popular approaches to solve the transmission line coupling equations in time domain is the Finite Difference Time Domain (FDTD) technique.

In this paper, we present an integration scheme of Agrawal *et al* transmission lines coupling equations based on the 1st order FDTD technique and give the relevant equations. The scheme is translated into a computer code which allows for the treatment of the coupling between an external electric field and a lossless wire above an ideal ground. The computation results are first validated by experimental results obtained using a reduced scale line model illuminated by the EMP simulator of the Swiss Federal Institute of Technology in Lausanne (SEMIRAMIS), and then are compared with the computation results obtained by the LIOV code (beta version).

## 2 COUPLING MODEL

In this section models for induced voltage calculations are presented. The basic assumptions are:

- The overhead line can be treated as loss-less.
- The electric electrical field is assumed to propagate unaffected by the ground.
- The Agrawal coupling model is used.
- The transmission line (TL) model is used for the lightning channel.
- The overhead line is matched with its characteristic impedance.

### 2.1 Agrawal *et al* Model:

Starting from Maxwell's equations and adopting the transmission line assumption, it is possible to derive a pair of equations describing the coupling of an external electromagnetic field and a single conductor line.

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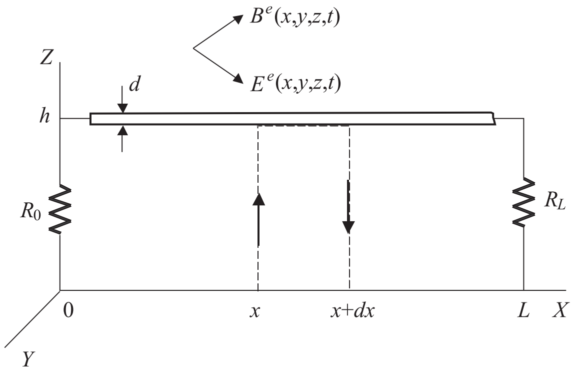

**Fig. 1.** Geometry for the calculation of overvoltages induced on an overhead power line by an indirect lightning return stroke.

These equations can be written in different equivalent formulations. The formulation we adopt in this paper is the one proposed by Agrawal et al. which, for the case of a lossless line, is given by (see Fig. 1 for the geometrical parameters):

$$\frac{\partial v^s(x,t)}{\partial x} + L\frac{\partial i(x,t)}{\partial t} = E_x^e(x,h,t)\,, \tag{1}$$

$$\frac{\partial i(x,t)}{\partial x} + C\frac{\partial v^s(x,t)}{\partial t} = j(x,t)\,, \tag{2}$$

where $L'$ and $C'$ are respectively the inductance and the capacitance per unit length of the line, $E_x^e(x,h,t)$ is the horizontal component of the incident electric field along the $x$ axis at the conductor height $h$; $v^s(x,t)$ is the scattered voltage, $i(x,t)$ is the induced current, and $j(x,t)$ is the equivalent current source pertinent to incident voltage $v^i(x,t)$ caused by the vertical component of exciting (or inducing) electric field $E_z^e(x,z,t)$

$$v^i(x,t) = -\int_0^h E_z^e(x,y,t)\mathrm{d}z\,,. \tag{3}$$

This can be under certain circumstances considered as unvarying in the height range $0 < z < h$.

The equivalent coupling circuit according to the Agrawal model is shown in Fig. 2.

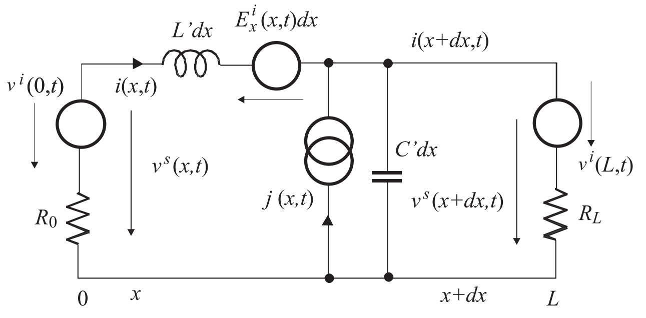

**Fig. 2.** Differential equivalent coupling circuit according to Agrawal *et al* for a lossless single wire overhead line.

## 2.2 FDTD METHOD

First, we proceed to make a schematic representation of the spatial discretization of the line (Fig. 3).

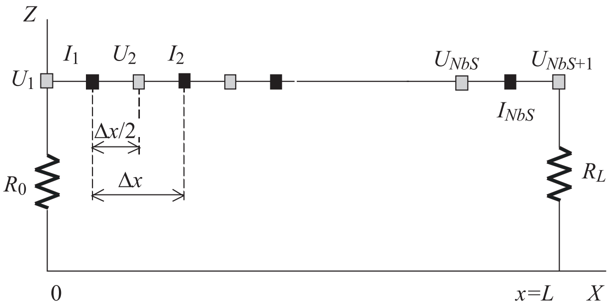

**Fig. 3.** Schematic representation of the spatial discretization along the line.

The current and the exciting horizontal electric field are calculated at the same points. The voltages are calculated at the medium points between two points of current. Therefore the current and the voltage are shifted by a half spatial step.

For the temporal discretization, the current is bring forward of half temporal step with regard to the voltage, see Fig. 4.

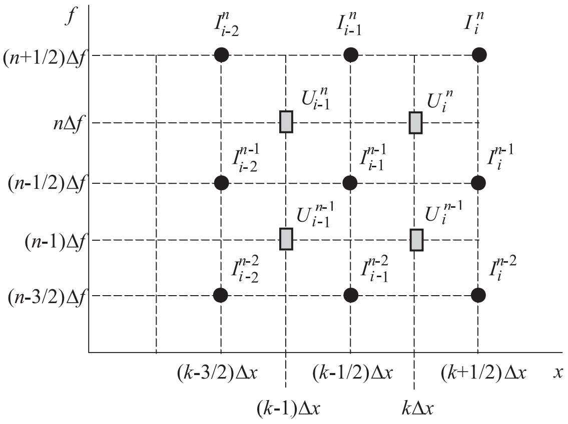

**Fig. 4.** Time and spatial discretization.

Stability condition:

Le temporal step and the spatial step must check the stability condition: $\Delta t.V_p < \Delta x$. Where $v_p = \sqrt{\frac{1}{LC}}$. If $\Delta t V_p = \Delta x$, The FDTD method give the best solution.

Equations:

The scattered voltage, calculated at the voltage nodes and at the instant $n\Delta t$:

$$U_k^n = v^s\big((k-1)\Delta x, n\Delta t\big)\,,\ 1 \le k \le K_{\max}+1\,.$$

The current, calculated at the current nodes ant at the instant $(n+0.5\Delta t)$:

$$I_k^n = I\big((k-0.5)\Delta x, (n+0.5)\Delta t\big)\,,\ 0 \le k \le K_{\max}\,.$$

The horizontal electric field, calculated at the current nodes and at the instant $n\Delta t$:

$$E_k^n = E_x\big((k-0.5)\Delta x, m\Delta t\big)\,,\ 1 \le k \le K_{\max}\,.$$

The current sources, calculated at the voltage nodes and at the instant $(n-0.5\Delta t)$, are null at all nodes of voltage, except at the two extremities of the line.

$$j_k^n = j\big((k-1)\Delta x, (n-0.5)\Delta t\big)\,,\ 1 \le k \le K_{\max}+1\,.$$

The two vertical electric fields, calculated at the two extremities of the line:

$$E_{z1}^n = E_z\big(0,(n{-}0.5)\Delta t\big) E_{z2}^n = E_z\big(N_{\max}\Delta x,(n{-}0.5)\Delta t\big).$$

First coupling equation:

$$\frac{\partial v^s(x,t)}{\partial x} + L\frac{\partial i(x,t)}{\partial t} = E_x^e(x,h,t)\,.$$

At the point $\big((k-0.5)\Delta x, n\Delta t\big)$:

$$\begin{aligned}\frac{\partial v^s(x,t)}{\partial x} &= \frac{U_{k+1}^n - U_k^n}{\Delta x}\,,\\ \frac{\partial i(x,t)}{\partial t} &= \frac{I_k^n - I_k^{n-1}}{\Delta t}\,,\\ E_x^e(x,h,t) &= E_k^n\,.\end{aligned}$$

We obtained:

$$I_k^n = \frac{\Delta t}{L}\Big(E_k^n - \frac{U_{k-1}^n - U_k^n}{\Delta x} + \frac{L}{\Delta t}I_k^{n-1}\Big),\qquad 1 \le k \le K_{\max}\,. \tag{4}$$

Second coupling equation:

$$\frac{\partial i(x,t)}{\partial x} + C\frac{\partial v^s(x,t)}{\partial t} = j(x,t)\,,$$

At the point $\big((k-1)\Delta x, (n-0.5)\Delta t\big)$:

$$\begin{aligned}\frac{\partial i(x,t)}{\partial x} &= \frac{I_k^{n-1} - I_{k-1}^{n-1}}{\Delta x}\,,\\ \frac{\partial v^s(x,t)}{\partial t} &= \frac{U_k^n - U_k^{n-1}}{\Delta t}\,,\\ j(x,t) &= j_k^n\,.\end{aligned}$$

We obtained for $2 \le k \le K_{\max}$:

$$U_k^n = \frac{\Delta t}{C}\Big(-\frac{I_k^{n-1} - I_{k-1}^{n-1}}{\delta x} + \frac{C}{\Delta t}U_k^{n-1}\Big)\,. \tag{5}$$

For $k=1$ and $k=k_{\max}$, we introduce the boundary conditions. For resistive terminations :

$$\begin{aligned}U_0^n &= -R_0 I_0^n + \int_0^h E_{z1}^n \mathrm{d}z\,,\\ U_{k\max}^n &= -R_L I_{k\max}^n + \int_0^h E_{z2}^n \mathrm{d}z\,.\end{aligned}$$

We introduce two fictive current nodes: at 0 and $k_{\max}+1$, we transform the two-poles: voltage source $hE_{z1}$ and $hE_{z2}$ created by the vertical electric field and $R_0$ and $R_L$ to equivalent two-poles containing the current sources, and further replace $C$ by $C/2$ (Capacitance in the half per unit length of the line).

$$\begin{aligned}j\big(0,(n-0.5)\Delta t\big) &= j_1^n = \frac{hE_{z1}^n}{R_0}\,,\\ j\big(L,(n-0.5)\Delta t\big) &= j_{k\max+1}^n = \frac{hE_{z2}^n}{R_L}\,.\end{aligned}$$

Finally we obtain

$$U_1^n = \Big(\frac{C}{2\Delta t} + \frac{1}{2R_0\delta x}\Big)^{-1}\Big(\frac{hE_{z1}^n}{R_0\Delta x} - \frac{I_1^{n-1}}{\Delta x} + \Big(\frac{C}{2\Delta t} - \frac{1}{2R_0\Delta x}\Big)U_1^{n-1}\Big)\,, \tag{6}$$

$$U_{k\max+1}^n = \Big(\frac{C}{2\Delta t} + \frac{1}{2R_L\Delta x}\Big)^{-1}\Big(\frac{hE_{z2}^n}{R_L\Delta x} + \frac{I_{k\max}^{n-1}}{\Delta x} + \Big(\frac{C}{2\Delta t} - \frac{1}{2R_L\Delta x}\Big)U_{k\max+1}^{n-1}\Big)\,. \tag{7}$$

## 3 SIMULATION RESULTS

### 3.1 Experimental validation

Our computation results of the Agrawal coupling model in the case of a lossless overhead line above an ideal ground are validated by experimentally test using reduced scale line model illuminated by the EMP simulator of the Swiss Federal Institute of Technology in Lausanne (SEMIRAMIS, for a detailed description of the simulator, see [8]).

The simulator is a bounded wave vertically-polarized type, with a working volume of 3 × 1 × 1 m (see Fig. 5).

To test a coupling model it is necessary to Know the incident electromagnetic field and the voltage or current induced by such field on a given line.

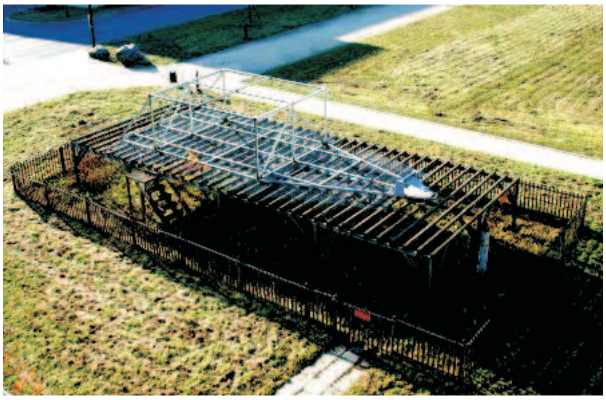

**Fig. 5.** SEMIRAMIS EMP simulator.

A measurement record of the wave form of the electric vertical field inside the working volume, performed in absence of the line, is presented in Fig. 6.

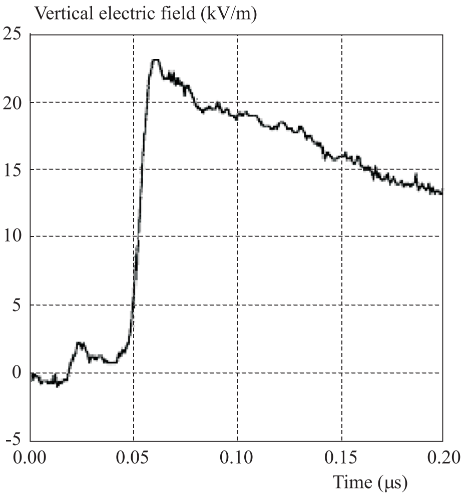

**Fig. 6.** Vertical electric field inside its working volume in absence of the line.

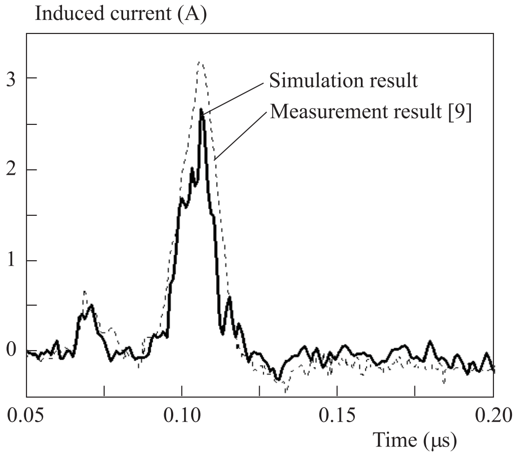

**Fig. 7.** Induced current on the overhead line: —○— Computational result of the current predicted by the Agrawal model. — Experimental test using a short line illuminated by a EMP simulator, adopted from [9].

*Line parameters:* Height $h = 20$ cm. Length $l = 2$ m. Diameter: $d = 1.4$ mm. $R_0 = 680\,\Omega$, $R_L = 680\,\Omega$.

*Simulation parameters:* $\Delta t = 1$ ns, $\Delta x = 0.4$ cm , $t_{\max} = 0.2\,\mu$s. Inductance and the capacitance per unit length of the line; $L = (\mu_0/(2*\pi))*ln(4*h/d)$; $C = \mu_0*\varepsilon_0/L$.

Figure 7 shows a comparison between the measured waveform of the induced current and the predicted one. It can be seen that our simulation allows us to obtain a good approximation of the original (experimental) waveform.

## 3.2 COMPARISON WITH THE COMPUTATION RESULTS OBTAINED BY LIOV

The LIOV (Lightning-Induced OverVoltage) code is a computer program developed in the framework of an international collaboration involving the Universities of Bologna (Department of Electrical Engineering), the Swiss Federal Institute of Technology (Power Systems Laboratory), and the University of Rome “La Sapienza” (Department of Electrical Engineering). It is based on the Agrawal formulation of the field-to-transmission line coupling equations, suitably adapted for the calculation of induced overvoltages when lightning strikes near a horizontal overhead transmission line. The LIOV code allows for the calculation of lightning-induced voltages along an overhead line as a function of lightning current wave shape (amplitude, front steepness, duration), return-stroke velocity, line geometry (height, length, number and position of conductors), stroke location with respect to the line, and value of termination impedances. In this section we compared our results with the free beta version of LIOV code for a single wire line above a perfectly conducting ground Available on Internet site [10].

We consider a 1 km long, 7.5 m high, single wire overhead line, matched at both ends, to avoid reflections which would render less simple the discussion of the results. The striking point is equidistant from the line terminations at a distance $y = 50$ m from the line centre. The lightning return stroke field is calculated using the transmission line (TL) model, since it is reported to give a reasonable agreement with measurements [11]; the relation between the initial field peak and the initial current peak is reasonably well predicted by the TL model, but after the first 10–15 $\mu$s this model is not valid any more[11].

An analytical expression adopted to represent the channel-base current $i(0,t)$, whose specific waveshape and amplitude can be determined experimentally, is the one proposed by Heidler [12], and frequently referred to as the "Heidler function"

$$i(0,t) = i_1(t) + i_2(t)\,, \tag{8}$$

$$i_1(t) = \frac{I_1}{\eta_1}\frac{(t/\tau_{11})^{n1}}{1+(t/\tau_{11})^{n1}}\exp\bigl(-t/\tau_{12}\bigr)\,, \tag{9}$$

$$i_2(t) = \frac{I_2}{\eta_2}\frac{(t/\tau_{21})^{n2}}{1+(t/\tau_{21})^{n2}}\exp(-t/\tau_{22})\,, \tag{10}$$

$$\eta_1 = \exp\bigl[-(\tau_{11}/\tau_{12})(n_1\tau_{12}/\tau_{11})^{1/n_1}\bigr], \tag{11}$$

$$\eta_2 = \exp\bigl[-(\tau_{21}/\tau_{22})(n_2\tau_{22}/\tau_{21})^{1/n_2}\bigr]. \tag{12}$$

**Table 1.** presents the parameters of the Heidler's functions corresponding to typical subsequent return strokes, according to the experimental data by Berger et al. [13].

| $I_1$ (KA) | $\tau_{11}(\mu\text{s})$ | $\tau_1 2(\mu\text{s})$ | $n_1$ | $I_2$ (KA) | $\tau_{21}(\mu\text{s})$ | $\tau_{22}(\mu\text{s})$ | $n_2$ |
|---|---|---|---|---|---|---|---|
| 10.7 | 0.25 | 2.5 | 2 | 6.5 | 2.1 | 230 | 2 |

*Line parameters:* Height: $h = 7.5$ m. Length: $l = 1000$ m. Diameter: $d = 1\times 10^{-2}$ m. $R_0 = 500\,\Omega$, $R_L = 500\,\Omega$.
*Simulation parameters:*

$$\Delta t = 3\times 10^{-8}\,\text{s},\ \Delta x = 10\ \text{m},\ t_{\max} = 6.75\,\mu\text{s}.$$

Figure 8 shows a comparison between the waveform of the induced voltage at the extremity of the line from the LIOV code and our computational result of the induced voltage. It can be seen that the agreement is very good for the first few microseconds. However, certain discrepancy can be observed for a later time in response.

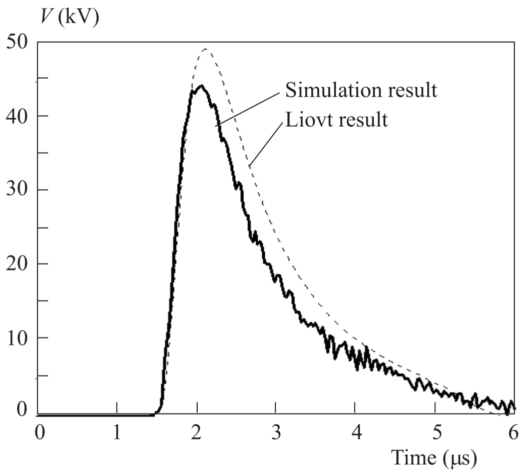

**Fig. 8.** Induced voltages on the overhead line.

## 4 CONCLUSION

In this paper, we have presented the Agrawal model transmission line coupling equations based on the 1st order FDTD technique. The computation results are validated by experimental results obtained using a reduced scale line model illuminated by the EMP simulator of the Swiss Federal Institute of Technology in Lausanne (SEMIRAMIS) and the computation results obtained by the LIOV code (beta version).

There is a good agreement in the first few microseconds. The disagreement is due to the simulation parameters employed to solving the two coupling equations (The choice of spatial ant temporal step, the line parameters). But, the comparison confirms the validity of the Agrawal model.

We have also shown that a coupling model can describe the electromagnetic field coupling to transmission lines in terms of different components of the electromagnetic field.

As perspective, we suggest the introduction of lossy ground effects, the effect of periodically grounded shielding wire and surge arresters on the lightning induced voltages.

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