Modelling with EMTP of Overhead Lines illuminated by an External Electromagnetic Field

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1 Introduction

Today, one of the major causes for concern on the part of companies supplying electricity is the protection of low-voltage networks against surges due to electromagnetic coupling (chiefly lightning), as their clients' equipment is becoming increasingly sensitive to the quality of the electricity. Coupling phenomena have formed the subject of numerous studies which have led to the development of purpose-designed theoretical models and computational aids for voltage faults and eddy currents induced on the lines. EMTP is normally used for analyzing service quality and it was necessary to add models ensuring the ready representation of the coupling of an electromagnetic wave on to a line. This paper describes and analyzes two of the coupling models developed by EDF. Other papers have already been published [1], [2].

2 Electromagnetic Coupling with the Line

If we take a line length L consisting of a conductor, located at height h above conductive ground and illuminated by an external electromagnetic field (Figure 1):

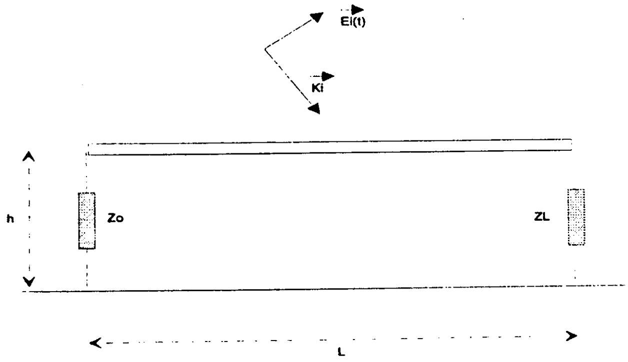

Figure 1 - Illuminated Line

The exciting electromagnetic field (E^e, B^e) is the result of the sum of the incident fields (E^i, B^i) and the fields reflected by the ground (E^r, B^r) in the absence of the overhead line. The total electromagnetic field (E^t, B^t) is defined as the sum of the exciting fields (E^e, B^e) and the fields diffracted by the conductor (E^d,B^d). Using Maxwell equations and approximations of the transmission line theory, we can find the equations describing the coupling of the exciting electromagnetic fields on to the line.
There are a number of formulae which can be used to equate the physical phenomenon of electromagnetic coupling (Rachidi, Agrawal, Taylor). These different formulae have been compared and found to be equivalent [3]. The choice done here is the formula described by AGRAWAL [4], which only uses as a source term the exciting electric field horizontal and tangential to the line.

On this principle, the layout of the disturbed line is made up of a series of elementary cells representing a segment of length Δx and consisting of a source term (the exciting electric field), the impedance (Z) and the admittance (Y) per unit length.

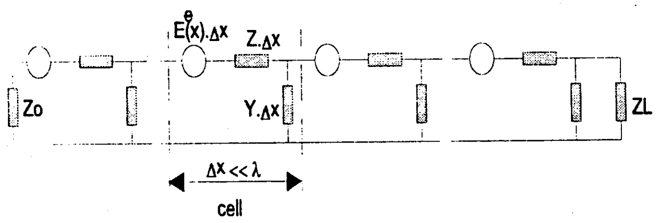

Figure 2 - Modelling of the Disturbed Line according to Agrawal's Formula

The equations are expressed in terms of diffracted voltage Vd which is due solely to the current circulating in the line and which is defined as follows:

$$V^d(x) = \int_0^h E_z^d(x).dz \tag{1}$$

The system of differential equations of the currents and voltages on the line is then:

$$\begin{cases} \dfrac{dV^d(x)}{dx} + Z.I(x) = E_x^e(x,h) \\ \\ \dfrac{dI(x)}{dx} + Y.V^d(x) = 0 \end{cases} \qquad (2)$$

The total voltage is obtained by adding to the calculated diffracted voltage, resolving the system of equations [equ 2], the voltage due to the exciting vertical electric field.

$$V^t(x) = V^d(x) + \int_0^h E_z^e(x,z).dz \qquad (3)$$

Conditions in respect of the limits expressed in terms of diffracted voltage and total current values, having regard to coupling of the electric field vertical to both terminals are expressed as follows:

$$\begin{cases} V^d(o) = -Z_A.I(o) + \int_0^h E_z^e(o,z).dz \\ \\ V^d(L) = -Z_B.I(L) + \int_0^h E_z^e(L,z).dz \end{cases} \qquad (4)$$

In the case of lines consisting of several conductors, the coupling equations can be generalized by replacing Z and Y respectively by the matrices of impedance and admittance per unit length. V^d and I^d are then diffracted voltage and line current vectors.

Remarks

The line theory does not allow for the coupling of wires vertical to the horizontal conductor. The antenna theory is the only approach capable of dealing with the problem accurately. If the line is long enough, we can forget the verticals connections. That said, conductor length should not be overlooked, because the absence of conductors could hide a number of resonance phenomena.

3 Line Models illuminated by EMTP

3.1 Coupling modelling via voltage sources distributed along the line.

The line is then segmented into several sections, and between two successive sections, a voltage source (V) is placed, corresponding to the applied exciting field integrated over the length of the segment (Δx).

$$V(x) = E_x^e(x).\Delta x \qquad (5)$$

Because of the nodal representation used in EMTP, each voltage source is modelled on the basis of two sources of current placed between the earth and the line (infinite impedance), and very low impedance (r) connecting the two nodes supplied (Figure 3).

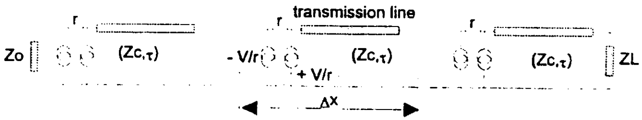

Figure 3 - Line illuminated by the Direct Input of Source Terms into EMTP (Model 1)

3.2 Coupling modelling by an equivalent quadrupole.

The calculation involves two successive stages:

- Coupling resolution on the straight line,
- Input into EMTP of a quadrupole equivalent to the whole of the disturbed line.

3.2.1 Coupling resolution and calculation of two equivalent source terms

The purpose here is to determine two source terms Fo(t) and FL(t) which combine the different phenomena distributed over the line.

The source terms are determined on the basis of currents Io(t) and IL(t) induced at the line terminals when it is matched (Figure 4) :

$$\begin{aligned} F_o(t) &= 2.I_o(t) \\ F_L(t) &= 2.I_L(t) \end{aligned} \qquad (6)$$

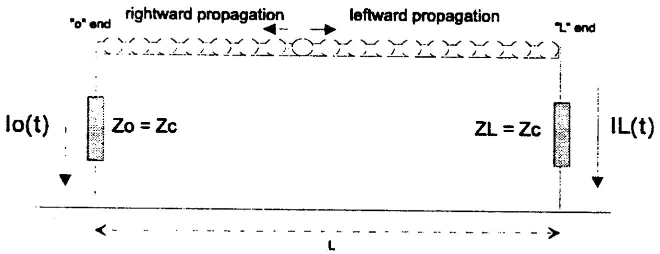

Figure 4 - Determination of Currents Io(t) and IL(t) for a Line Modified by an FDTD Method .

With this configuration (Zo=ZL=Zc), Io(t) is the resultant of all the contributing factors induced on the line and which propagate towards terminal "o". Similarly, IL(t) combines all the induced contributing factors which propagate towards terminal "L". Here, Io(t) and IL(t) are calculated directly in the time domain using a finite differences method (FDTD). In particular, this enables the line to be rendered discrete very precisely [5]. Io(t) and IL(t) can also be determined using a frequency method [6] combined with an inverse Fourier transform.

3.2.2 Quadrupole equivalent to the disturbed line with EMTP

The EMTP equivalent layout of the whole of the disturbed line is shown in Figure 5.

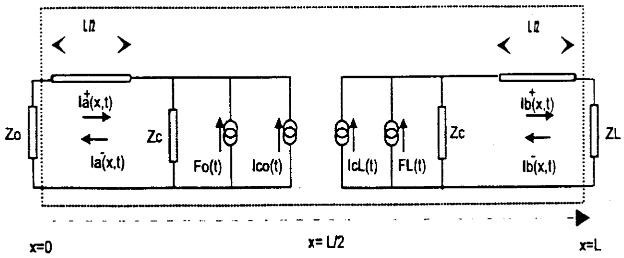

Figure 5 - EMTP Diagram equivalent to the whole of the Disturbed Line

This includes the following :

- Sources of current Fo(t) and FL(t) as previously calculated,
- Two EMTP transmission lines of length L/2 matched at x=L/2 in order to avoid reflections,
- Two current generators Ico(t) and IcL(t) ensuring electrical continuity between the two half lines and controlled by TACS,
- Two units located on each side in x=L/2, configured for measuring currents propagating to the positive x's (half line dimensioned "o" : $I_a^+(x=L/2,t)$) and to the negative x's (half line dimensioned "L" : $I_b^-(x=L/2,t)$). These currents are then used in Ico(t) and IcL(t):

$$I_{co}(t) = 2.I_a^+(L/2,t-dt)$$
$$I_{cL}(t) = 2.I_b^-(L/2,t-dt) \qquad (7)$$

The diagram in the dotted box forms a quadrupole equivalent to the whole of the disturbed line, whatever its length.

Remark :
The time increment used by the TACS may be transparent in respect of propagation using two transmission lines of length:

$$L' = (L - v.dt)/2 \qquad (8)$$

4 Simulation Results

4.1 Single-conductor line

4.1.1 Application 1: straight line
The EMTP results obtained by the two models described in §3 are compared with those in [4]. We take a line of length L = 5m located above perfectly conductive ground which finishes at one terminal with a capacitive load of 100pF (voltage Ua) and is

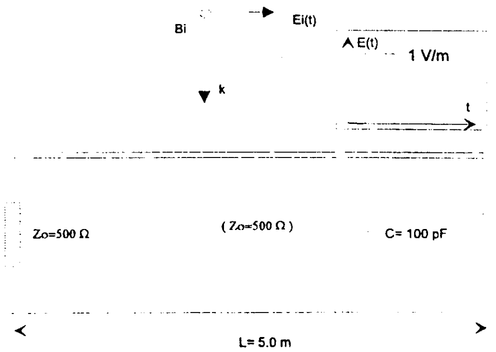

Figure 6 - The Configuration Considered

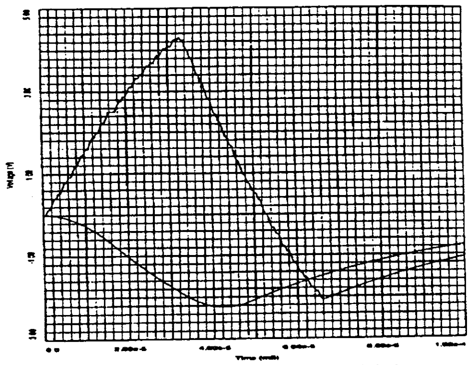

Figure 7 - EMTP (Model 1) Voltage Values at Line Terminals (line divided into 20 sections)

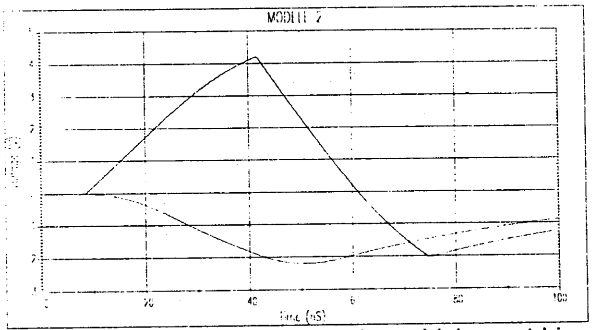

Figure 8 - EMTP (Model 2) Voltage Values at Line Terminals

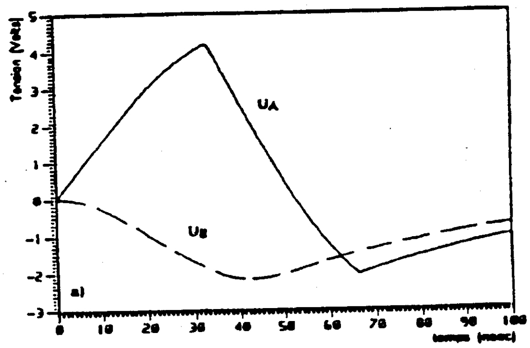

Figure 9 - Voltage Values at Line Terminals determined by the Transmission Line Matrix (TLM) Method [5]

matched at the other terminal (500Ω) (voltage Ub). The line is illuminated on simultaneous input by a plane wave represented by a square-wave pulse lasting 33ns, amplitude 1 V/m tangential to the line (Figure 6).

4.1.2 Application 2: angled line

A line of length L=10m is located at a height of h=10cm above perfectly conductive ground. It is matched with one of the terminals (Point A : ZA = Zo= 320Ω) and left in open circuit at the other terminal (point C Zc=∞). In L=6m (Point B) the line changes direction at an angle of 120° whilst remaining parallel to the ground (Figure 10).

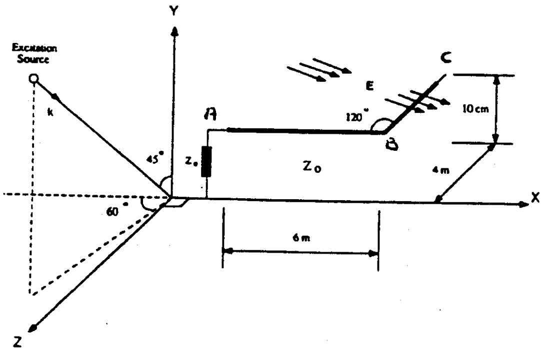

Figure 10 - Example of Angled Line

The line is illuminated by a biexponential pulse :

$$E^i(t) = E_o\left[e^{-t/T_1} - e^{-t/T_2}\right] \qquad (9)$$

where:

$$E_o = 50\ kV/m$$
$$T_1 = 250\ ns$$
$$T_2 = 2\ ns$$

The electric field is parallel to the ground, and the propagation direction is inclined at Ψ=45° in relation to the ground and at φ=60° in relation to the vertical plane passing through the first part of the line.

The voltages calculated by the two previous models at the both ends (points A and C) and at the discontinuity point (B) of this line are respectively shown in Figures 11 and 12. They are compared to a computation done by MOK and COSTACHE [8].

4.2 Multi-conductor line

Multiwire line consisting of three parallel conductors illuminated by a biexponential plane wave identical to the one described in §4.1.2. The electric field is parallel to the conductors and the propagation vector perpendicular (Figure 14).

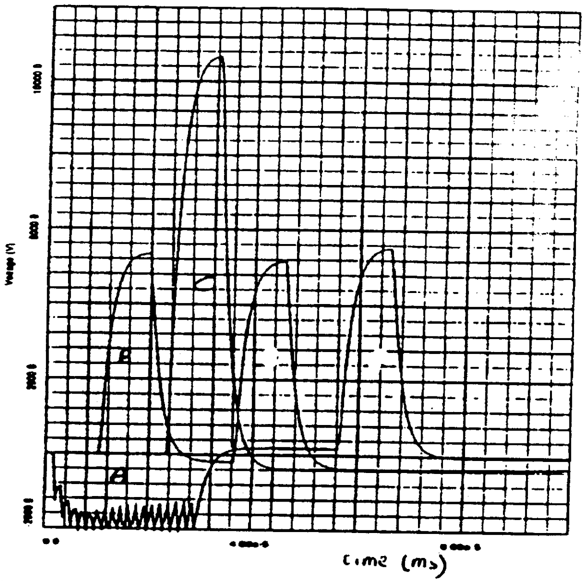

Figure 11 - EMTP Voltage Values at Line Terminals
(line divided into 20 sections)
(Model 1)

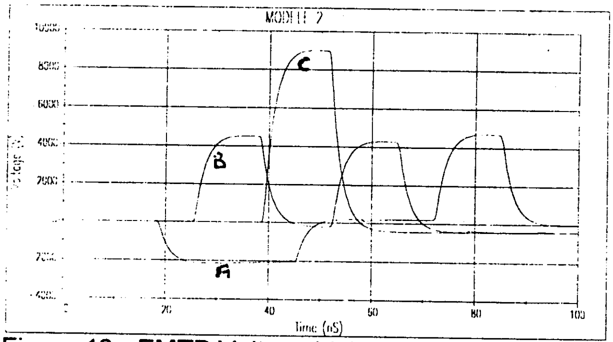

Figure 12 - EMTP Voltage Values at Line Terminals
(Model 2)

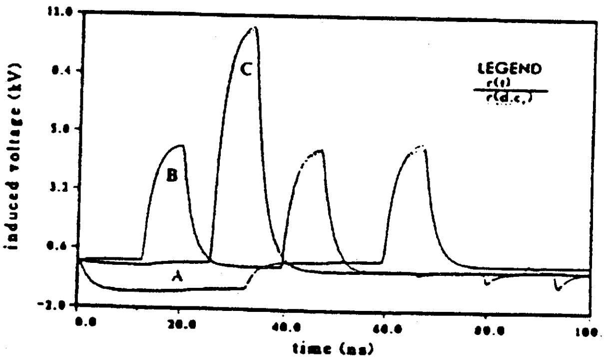

Figure 13 - Calculated Voltage Values at Line Terminals [8]

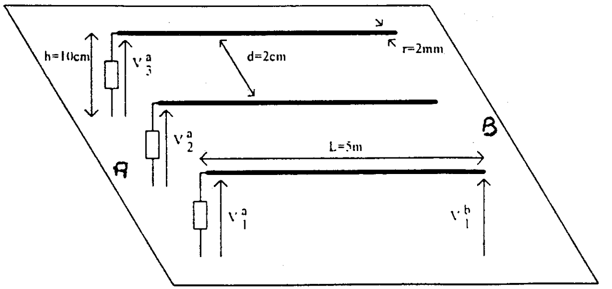

Figure 14 - the configuration considered: each of the conductors is matched at one end (called A) and is left in open circuit at the other end (called B)

The induced voltage values calculated by EMTP, models 1 and 2, are shown in figures 15 and 16 respectively. Calculation by the finite differences method is shown in Figure 17.

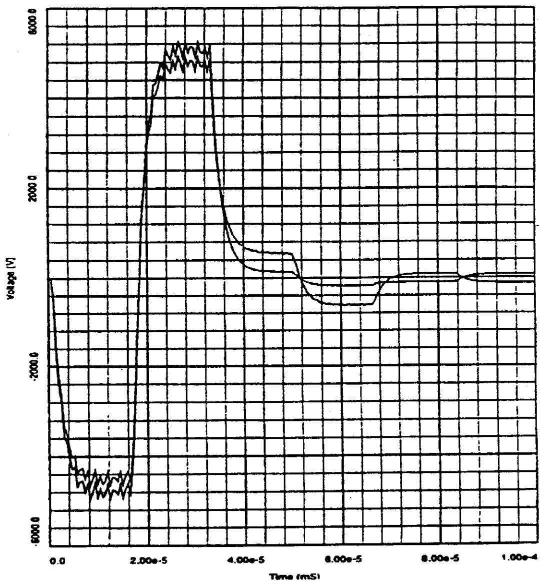

Figure 15 - EMTP (Model 1) calculation. The 5-metre line is divided into 20 sections of 25 cm. On each of the 3 conductors a voltage source corresponding to the horizontal electric field is placed between the sections.

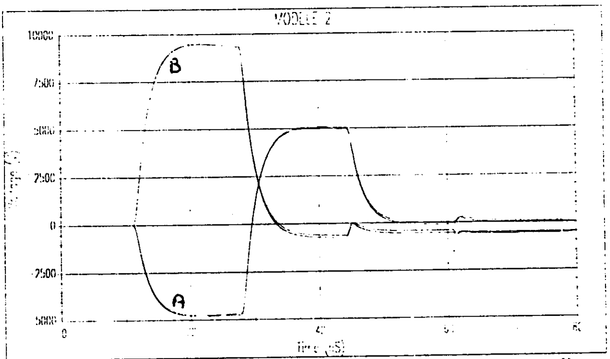

Figure 16 - EMTP (Model 2) voltage values at line terminals

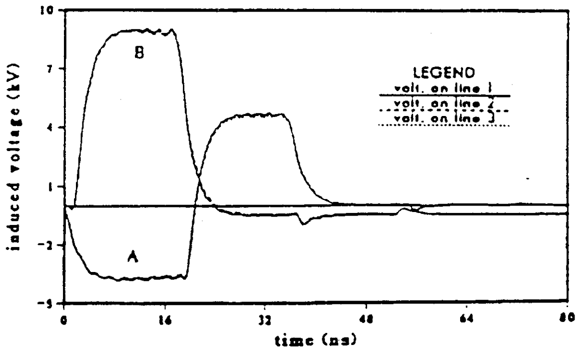

Figure 17 - Calculation by the Finite Differences Method of Voltage Values at Both Line Terminals [5]

5 Discussion of the Two Models

It should first be noted that while the two models described both give correct results, the basis of approach differs considerably and it is up to the user to decide on the model that best suits his requirements.

Both models take into account the factors included in EMTP [9] libraries (line models, non-linear models of protective items, etc.) and thus enable complex networks subject to total or partial electromagnetic illuminations to be examined.

The model based on distributed sources does not require the use of a coupling calculation code. It can however mean considerable calculating time if the idea is to represent an illuminated circuit requiring numerous segments to be created; for example, representing the illumination of a ramified network or very long lines.

The second model can be used to avoid this difficulty by taking the illumination of each line separately. Coupling can be synthesized on a line of any length using just two sources, the line being regarded by EMTP as a quadrupole. This is especially suited to networks with a complex topology and to very long lines. However, it requires the use of a coupling code in order to calculate the two source terms to be input into EMTP. This has the advantage of using algorithms designed to resolve the coupling (e.g. finite differences method). These enable the line to be very precisely divided into sections but it does not, however and for the time being, integrate EMTP line models into the calculation of equivalent sources. This could be solved by using the model based on the input of distributed sources so as to calculate the equivalent sources.

Notation

(Et, Bt) Total electromagnetic field

(E^e, B^e) Exciting electromagnetic field

(E^d, B^d) Diffracted electromagnetic field

(Vd, Id) Diffracted voltage and current

Y, C', G' : Line transverse admittance, capacitance and conductance per unit length,

Z, R', L' : Line series impedance, resistance load and admittance per unit length,

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