

Realistic Modeling of Lightning Induced Disturbances in a Buried Shielded Cable Network

L. Boussayoud¹ and B.Nekhou¹

¹Department of Electrical Engineering, University of Jijel – Algeria, nek_cem @univ-jijel.dz

When the electromagnetic radiation emitted by the lightning channel couples to the shields of overhead or buried cables, it induces large currents causing transient overvoltages between the internal conductors and the shield. These disturbances can alter the insulation of the cable and can cause the proper operation of the electrical devices connected to it. For the analysis by simulation of the electromagnetic coupling between a buried shielded cable and a lightning channel, this paper presents a modeling developed from the extended transmission line theory and the topological electromagnetic formalism. It also discusses the role of a bare shield wire buried parallel to the shielded cable to reduce these disturbances. We validate the modeling used by comparing our calculation results with those achieved by measurement and we propose some applications to highlight the role of the shielding wire in reducing the disturbances induced in the shielded cable.

Index Terms— Disturbances, lightning channel, modeling, shielded cable, transmission lines

I. INTRODUCTION

During the update of the bibliography relating to this work to properly situate the state of the art on the analysis of electromagnetic coupling between a lightning channel and a shielded cable, we noted that this problem, although treated for several decades, remains current. Indeed, the very rich and abundant bibliography specific to this subject, whether old or very recent, highlights the particular interest in quantifying the disturbances induced by a natural external electromagnetic wave (lightning wave), of industrial origin (power transmission line, etc.) or even nuclear (IEMN). From these different works it emerges that the optimization of the operation and protection of electrical devices is only possible if the latter are developed with consideration of their electromagnetic environments. This implies for the energy or information transmission network:

- prior knowledge of the disturbances to which any overhead line or overhead or buried cable is likely to be subjected.
- knowledge of the interaction between the disturbance and the wire structure (bare wire conductors or shielded cable). This particular interest in the study of this question by modeling has allowed the development and proposal of various formalisms from the most rigorous (antenna theory) to the most simplified (circuit theory and simplified line theory).

In the case of an overhead transmission line (bare filiform conductors or cable) illuminated by a transient electromagnetic wave whose frequency spectrum does not exceed 10 MHz (case of lightning), the Field-Multiconductor Transmission Line equations is well suited for the study of induced disturbances. In addition to the very acceptable accuracy of the results, this formalism using classical line theory to represent a set of bare and parallel conductors or a shielded cable placed above a ground of finite electrical conductivity, offers the advantage of easy implementation and acceptable calculation times. In this approach, only the earth return impedance is considered. When the cable is buried, it has been shown that classical line theory affects the accuracy of the calculation results. To overcome this drawback and improve the calculation results, in this work we use extended line theory [1]. In this case, the buried shielded cable is

modeled as a Multiconductor Transmission Line (MTL) considering both the earth return impedance and the earth return admittance resulting from the ground displacement currents. To model the electromagnetic coupling of a lightning wave with a buried shielded cable network, we use the "Electromagnetic Topology" approach [1]. We develop this formalism from the general solution of the Taylor equations [2] which have the advantage of being expressed as a function of the total current and the total voltage. We analyze some solutions to reduce lightning-induced electromagnetic disturbances in a buried shielded cable.

II. THEORETICAL ELEMENTS OF MODELING FORMALISM

The general Field-Multiconductor Transmission Line equations in frequency were developed by Taylor [2]:

$$\frac{\partial}{\partial x} [\hat{U}(\omega, x)] + [\hat{Z}(\omega)] [\hat{I}(\omega, x)] = [\hat{U}_f(\omega, x)] \quad (1)$$

$$\frac{\partial}{\partial x} [\hat{I}(\omega, x)] + [\hat{Y}(\omega)] [\hat{U}(\omega, x)] = [\hat{I}_f(\omega, x)] \quad (2)$$

With:

$[\hat{U}_f(x, \omega)]$ and $[\hat{I}_f(x, \omega)]$: source vectors expressed as a function of the incident electromagnetic wave $([\vec{E}^i], [\vec{B}^i])$ [2].

$[\hat{U}(x, \omega)]$ and $[\hat{I}(x, \omega)]$: total voltage vector and total current vector of dimension Nc (Nc : number of conductors of the MTL).

$[\hat{Z}(\omega)]$ and $[\hat{Y}(\omega)]$: are the complex per unit length impedance and admittance matrices of the MTL.

From the general solution of the system of equations (1) and (2), for a line of length l , whose origin $x_0=0$, we can deduce the following relationship between the electrical quantities at the input ($x_0=0$) and output ($x=l$) of the line [2]:

$$\begin{bmatrix} [I_{2NC}] - \begin{bmatrix} [\phi_{11}(l)] & [\phi_{12}(l)] \\ [\phi_{21}(l)] & [\phi_{22}(l)] \end{bmatrix} \end{bmatrix} \begin{bmatrix} [\hat{U}(\omega, l)] \\ [\hat{I}(\omega, l)] \\ [\hat{U}(\omega, 0)] \\ [\hat{I}(\omega, 0)] \end{bmatrix} = \begin{bmatrix} \hat{U}_{FT}(\omega, l) \\ \hat{I}_{FT}(\omega, l) \end{bmatrix} \quad (3)$$

Where $[\phi_{11}(l)], [\phi_{12}(l)], [\phi_{21}(l)], [\phi_{22}(l)]$, are the elements of the

Chain matrix deduced by modal analysis [2].

The total forced functions $[\hat{U}_{FT}(\omega, l)]$ and $[\hat{I}_{FT}(\omega, l)]$ are given in [2] and I_{2Nc} is identity matrix of order $2 \times Nc$.

Let us recall that the solution of the equation system (1) and (2) only allows the analysis of the disturbances induced in a homogeneous MTL. The theory of MTL is rarely used for the case of a single line. Indeed, MTLs often form interconnected networks through electrical circuits. The work of BLT [3] and C.R. Paul [2] has made it possible to represent complex line networks with an electromagnetic topology for the analysis of currents and voltages induced by an electromagnetic wave. To study the latter, the complete system is divided into several subsystems that interact with each other. By representing these systems in a graph, we obtain what is called a hierarchical electromagnetic topology. The interaction between the subsystems, in this case the MTLs, can be in conducted mode or in radiated mode. The perimeter of each subsystem defines its protection, such as its shielding or its metal screens. The advantage of this approach is that each subsystem can be treated with the method appropriate to it. Figure 1 represents an example of a simple topological network on which each of the junctions and each of the MTLs (tubes) are listed by an arbitrary numbering. The complete structural description of the network also assumes knowing the length and the number of elementary wires constituting each MTL.

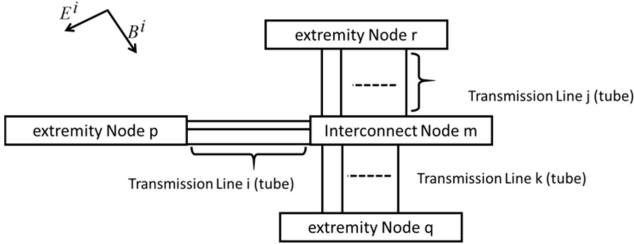


Fig. 1. Network of transmission lines illuminated by an electromagnetic wave.

Mathematically, using the topological formalism, the configuration in figure 1 is translated by a matrix equation as follows (4) [1]:

$$[\hat{M}] \times [\hat{X}] = [\hat{h}] \quad (4)$$

$$[\hat{M}] = \begin{bmatrix} [\hat{M}_1] \\ [\hat{M}_2] \end{bmatrix} : \text{network topological representation matrix;}$$

$[\hat{M}_1]$: submatrix of propagation, constructed from the Chain matrix representation (3) of each MTL in the network;

$[\hat{M}_2]$: submatrix of electrical relations (Kirchhoff laws KCL and KVL) on all the nodes of the network.

$[\hat{X}]$: vector of unknowns (currents and voltages on all the nodes of the network). $[\hat{h}]$: source vector (sources due to external electromagnetic excitations).

III. VALIDATION

To reduce electromagnetic lightning transients on buried shielded cables, typically a shielding wire is used. This wire is laid just above the cable and parallel to it. In the case of indirect impact of lightning, the example analyzed is the one already studied in [4]. This application (see figure 2) deals

with the case of a conductor placed in a PVC pipe with a radius of 1cm where the insulation is air. The conductor has a length of 100m and a radius of 0.5 cm. The assembly (conductor + pipe) is buried at a depth $d=1m$ in a homogeneous soil. A shielding wire (bare copper wire with a diameter of 5 mm) is then placed above the pipe at a distance ds respectively equal to 1m, 0.5m then 0.2m ($ds=1m, 0.5m$ and $0.2m$). The lightning channel (vertical antenna of height $h=2000m$) is located 20 m from the cable (see figure 2). The current at the base of the channel is defined by a bi-exponential:

$$i(t) = 1.1 \times I_0 (e^{-\alpha t} - e^{-\beta t}), I_0 = 12kA; \alpha = 9.2 \cdot 10^4 s^{-1}; \beta = 0.5 \cdot 10^7 s^{-1}$$

The current along the channel is represented by the MTL model [4] with $\lambda=2 km$ and $v=1.310^8 m/s$.

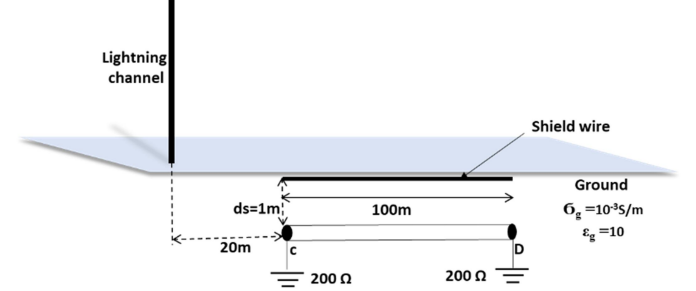


Fig.2. Position of the lightning channel and buried cable.

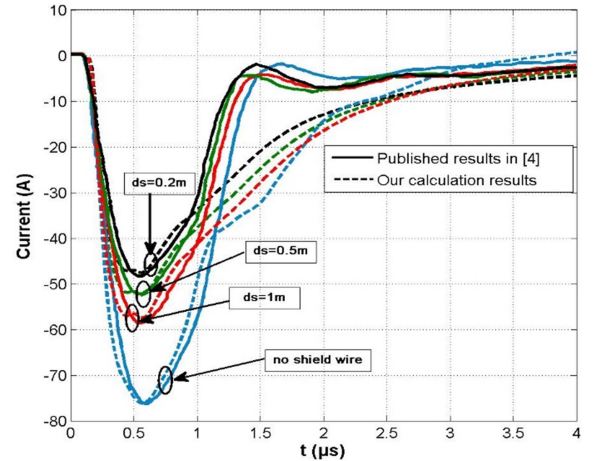


Fig. 3. The induced current in the cable at point C.

The comparison in figure 3 shows good agreement between the results obtained by the two models in amplitude and in the general shape (temporal variation). We recall that the electromagnetic model used in [4] consists of solving Maxwell's equations in the time domain by the numerical method FDTD.

REFERENCES

- [1] L. Boussayoud and B. Nekhou, "Transient electromagnetic lightning disturbances induced in the collector cables of a wind farm", *Electric Power Systems Research* 241 (2025) 111345.
- [2] C. R. Paul, "Analysis of Multiconductor Transmission Lines", Wiley Interscience, 1994.
- [3] C. E. Baum, K. L. and F. M. Tesche, "On the Analysis of General Multiconductor Transmission-Line Networks", *Note USNC/URSI*, October 1976
- [4] Bo Yang and al., "numerical study of lightning-induced currents on buried cables and shield wire protection method", *IEEE transactions on electromagnetic compatibility*, vol. 54, no. 2, april 2012.