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Contribution to the Modeling of Electromagnetic Lightning Transients in High Voltage Power Transmission Lines Connecting Regions With High Storm Density

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Abstract

The power grid connects electricity production to end uses, providing a physical link for the circulation of energy flows while providing services to the community. The rapid development of technology makes power grids increasingly complex, transmission lines play a crucial role in electricity transmission. However, transient phenomena such as short circuits caused by lightning can propagate between substations, affecting power distribution and requiring real-time management of electrical quantities to maintain the frequency and efficiency of these systems. This paper deals with the modeling of electromagnetic transients due to lightning in high-voltage lines, especially in thunderstorm areas. The bi-exponential model allows us to faithfully represent the lightning shock wave and its impact on these lines. The modeling of the lightning electromagnetic field and its coupling with a high-voltage line were carried out using Maxwell's equations and a transmission line model. The FDTD method allowed us to present the results of the voltages and currents induced by this field in the time domain. We used the Laplace transform to obtain frequency results. The study applied to the test network in the Democratic Republic of Congo shows that the voltages induced by lightning, linked to the amplitude of the disturbing current, jeopardize the life and safety of HV equipment. The 2D simulations highlight the importance of the coordination of the insulation to guarantee the stability of the power transmission lines. Integrating a passive ohmic-capacitive damping circuit in the control part of the protection system dedicated to tropical areas could attenuate the electromagnetic lightning transients and improve the performance of the high-voltage line.

Keywords: modeling, electromagnetic transient, lightning, Induced voltage, induced current, HV power line, Telegraph equations, Maxwell’s équations, transmission line model, FDTD method, Laplace transform, insulation coordination.

1. Introduction

The transmission network is responsible for transporting energy from production centres to consumption or distribution points (CHIKEUR Hadjer, 2019), (F. Rachidi, 2004). It comprises overhead or underground lines that form a space connecting different parts of the network, which allows the integration of production equipment offered to end users (Schneider Electric, 2010). This network consists of electrical nodes called "Substations", whose task is threefold: to connect lines of the same voltage, to evacuate energy from production sources to the network and to connect networks of different voltages (CHIKEUR Hadjer, 2019), (Dib Djalel, 2007) Significant development of electrical energy transmission networks in their various organs, which ensure optimal distribution of power transmissions, frequency maintenance, compensation of electrical energy, electrical transmissions, reactive energy and real-time information on the latest properties of electrical quantities make it possible to ensure control and management, which gradually leads to the study of various disorders; depending on the mode of transmission (radio waves, telecommunications networks, energy distribution networks, lightning, nuclear electromagnetic pulse (NEMP) etc.), the form (interruptions, flicker, high frequencies) and whether they affect electrical organs or people (Dib Djalel, 2007), (Coulon, F. & Jufer, M, 1984), (Lasne, L, 2004), (Van Cutsem, T, 1998), (Dib Djalel, 2007), (A. Haddouche, D. Dib, & A. Benrettem, 2007), (D. Dib, A. Haddouche, & F. Chemam, 2007) & (Bassesuka SNA, 2022).

The risks of network overvoltage are mainly linked to the breakdown or even destruction of equipment (lines, transformers, switches, cables) causing a service interruption.

To optimize the operation of electrical networks and ensure their sustainability (cost reduction, continuity of service, reliability, safety and quality), it is necessary to analyze electromagnetic transients in the design phase of electrical networks (Dib Djalel, 2007) and (CHIKEUR Hadjer, 2019). In addition, understanding transient phenomena makes it possible to significantly coordinate electrical insulation and therefore the optimal distribution of power transmissions, frequency maintenance, reactive energy compensation and real-time information, their characteristic electrical quantities and above all the reliable and efficient implementation of protection devices (CHIKEUR Hadjer, 2019).

According to the work proposed by (Bassesuka SNA, 2022), (A. Ametani, Convenor (JP), & M. Paolone, Secretary (IT),2013) based on the modeling applied to the calculation of electromagnetic transients in electrical systems.

The objective is to study the electromagnetic transient modeling of lightning in high-voltage transmission lines located in areas with high thunderstorm density and to simulate the overvoltage levels on the lines by proposing possible solutions to improve their performance. It should be noted that areas with high thunderstorm density have implications that must be carefully considered when designing the implementation of high-voltage transmission systems to ensure the safety, reliability and efficiency of the electrical supply in thunderstorm areas where lightning is frequent, by relying on the existing protection system to optimize their operating conditions. For this, there are several equations to be applied to illustrate this phenomenon, the lightning channel model has been chosen to demonstrate the electromagnetic phenomenon. Several analytical models describing the lightning current flow have been developed. The model chosen in this study is a bi-exponential function that not only admits the Laplace transform but also takes into account the propagation speed and the decrease in amplitude of the lightning current, thus allowing a good representation of the phenomenon. The modeling of the coupling between the lightning phenomenon and the HV line is based on the transmission line model using telegraph equations. The resolution of these FDTD equations allowed us to present the results in the time domain. Then, the results in the frequency domain were obtained using the Laplace transform.

To optimize the insulation coordination of HV lines against transient electromagnetic lightning phenomena, the results presented in this article show that the integration of a passive ohmic-capacitive damping circuit in the control part of the protection system towards tropical areas can reduce the effects of electromagnetic lightning transients on the HV line and thus optimize its performance.

2D simulations based on the proposed models were developed ensuring the consistency of the different models by comparing the fractal dimensions of the results of our programs with those obtained experimentally.

2. Theoretical Models

It is mainly a theoretical model of electromagnetic effects. Exposure to transient overvoltages weakens electronic components and circuits without the user realizing it, shortening the lifespan of devices and increasing the risk of failure that can cause burns.

2.1 Electromagnetic Models of Lightning

High-voltage transmission line components are the most exposed to disturbance during lightning discharges. The study of their transient behavior is generally based on the theory of transmission lines with R, L, C and G electrical components (Spiegel, MR, 1975), (Allab, K, 1984) & (Affolter, JF, 2000). Lightning current is impulsive in nature, characterized by peak value, rise time to maximum amplitude and decay time, as shown in figure (1) below.

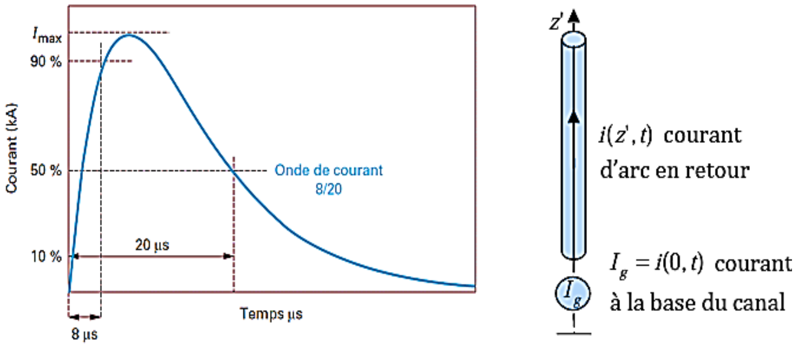

Figure 1. Figure Title Typical Current Wave in the Lightning Channel (Bassesuka SNA, 2022), (Nsekere Nzukuru, 2009)

The bi-exponential model given by equation (1) was chosen because it gives the advantage of exponential functions used by several authors and the Laplace transform (CHIKEUR Hadjer, 2019), which makes it possible to directly analyze the frequency domain. The use of the latter gave results more consistent with experimental observations (Guerrieri, S. & al, 1998), (Nsekere Nzukuru, 2009) & (F. Heidler, 1985).

$$i(t) = I_0(e^{-At} - e^{-Bt}) \tag{1}$$

Where:

I_0: Represent the amplitude of the lightning current in kA;

A: is the reciprocal of the descent time;

B: is the reciprocal of the rise time.

Calculating the electromagnetic field radiated by lightning requires knowledge of the current distribution along the lightning channel. (Ianovici, M. & Morf, JJ, 1983), (Aguet, M. & Morf, JJ, 1987), (Guerrieri, S., et al, 1998), (Yang, G., et al, 2017), (Uman, MA & McLain, DK, 1970) & (Rachidi, F, 2002).

Taking into account the different models used that we cannot cite all of them, the current at the base of the lightning channel *i(0,t)* can be determined as a function of the height and time of the lightning channel, as shown in Figure 2 below (CHIKEUR Hadjer, 2019).

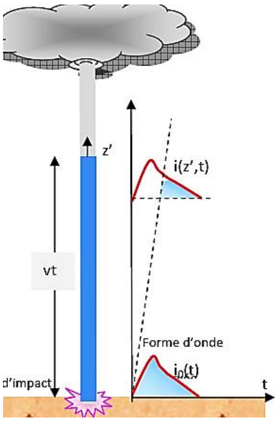

Figure 2. Spatio-Temporal Distribution According to the BG Model (Bassesuka SNA, 2022), (D.Dib, A. Haddouche & F. Chemam, 2007)

Mathematically, the current distribution is defined by (D.Dib, A. Haddocuhe & F. Chemam, 2006):

$$\begin{cases} i(Z,t) = i\left(0, t - \frac{z}{\mu}\right) \text{pour} \quad Z \le \mu.t \\ i(Z,t) = 0 \ \text{ pour} \quad Z \le \mu.t \end{cases} \tag{2}$$

With:

Z: Height of the point considered in the lightning channel in km;

μ: Current propagation speed in the lightning channel. It is between 0.9 and 1.9×10 8m/s.

By replacing the time variable (t) $(t - z/\mu)$ with expression (1), we, therefore, obtain the model of the spatiotemporal distribution of the lightning current (F. Heidler, 1985), (Emanuel Petrach, 2004), (A. Ametani, Convenor (JP), & M. Paolone, 2013), (P. Druet, 2001) and (Benoit De Metz-Noblat, 1993).

$$i(t) = I_0\left[e^{-A(t-\frac{z}{\mu})} - e^{-B(t-\frac{z}{\mu})}\right] \tag{3}$$

An accurate calculation of the electromagnetic field emitted by the lightning channel can be carried out by solving the integral equation (antenna theory) in an electric field (EFIE) using the moment method (CA Nucci, 1995), (Guerrieri, S. & al, 1998), (Bassesuka SNA, 2022), (Nsekere Nzukuru, 2009) & (RF Harrington, 1968). We can also use the dipole formalism because its implementation is not too demanding and leads to acceptable precision (MA Femme, D. Kenneth McLain, captain E. & Philip Krider, 1975) 1998), (SNA, 2022) & (Metsa Near, 2009) & (RF Harrington, 1968). The geometry often used for these calculations is presented in Figure 3 below (Emanuel Petrach, 2004).

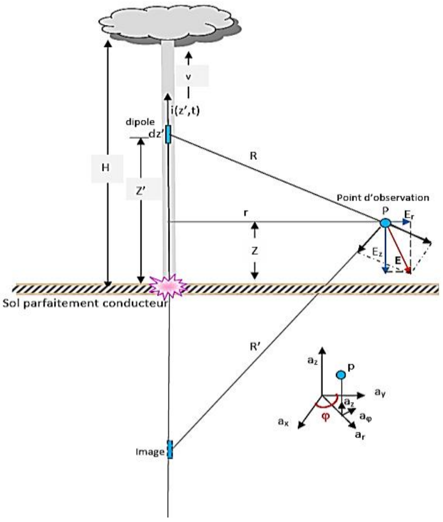

Figure 3. Geometric Quantities Involved in the Electromagnetic Field Equations (Bassesuka SNA, 2022), (F. Heidler, 1985), (Emanuel Petrach, 2004), (A. Ametani, Convenor (JP), & M. Paolone, 2013), (P. Druet, 2001) & (Benoit De Metz-Noblat, 1993)

This part aims to model the electromagnetic field of lightning if we consider the vertical lightning channel on the ground (see Figure 3 above). All electromagnetic phenomena are thus governed by Maxwell's four equations, in their general forms, these equations are written (Bassesuka SNA, 2022), (Yang, G., & al, 2017) & (Emanuel Petrach., 2004):

The Maxwell-Faraday equation:

$$rot\vec{E} - \mu\frac{\partial\vec{H}}{\partial t} = 0 \tag{4}$$

The Maxwell-Ampère equation:

$$rot\vec{B} + \mu\vec{J} = 0 \tag{5}$$

The equation for the conservation of magnetic flux:

$$Div\vec{B} = 0 \tag{6}$$

The Maxwell-Gauss equation:

$$Div\vec{E} - \varepsilon\rho = 0 \tag{7}$$

Legend :

ρ: is the volume charge density in C/m ^{3}

$\vec{D}$: is the electrical induction in AS/m ^{2}

$\vec{E}$: is the electric field in V/m

$\vec{B}$: is the magnetic induction in T

$\vec{H}$: is the magnetic field in A/m

$\vec{J}$: is the surface density of the current in A/m ^{2}

Thus, to completely define the electromagnetic phenomenon inside an isotropic and homogeneous medium, characterized from the electromagnetic point of view by an electrical conductivity σ, a dielectric permittivity ε, and a magnetic permeability μ, we add to the previous equations (4)-(7) the laws of behaviour in this environment (Mellers, B. A, 2000), (Guemri, B,2004), (Bermudez Arboleda, J.L, 2003), (Degauque, P. & Hamelin, J, 1990) & (Orzan, D, 1998) :

Ohm's law:

$$\vec{J} = \sigma\vec{E} \tag{8}$$

The magnetic relationship:

$$\vec{B} = \mu\vec{H} \tag{9}$$

The dielectric relationship:

$$\vec{D} = \varepsilon\vec{E} \tag{10}$$

Once the source-field relationships and the electric-magnetic field relationships are characteristic of the medium, we define the four Maxwell equations which induce transition conditions at the interfaces between two electrically and magnetically different media. By integrating them between two very close points on the one hand and the other hand in the surface separating these two environments, the result allows us to deduce the conservation of the normal component of the magnetic induction, the preservation of the tangential component of the electric field, the discontinuity of the normal component of the electric induction, due to surface charges and the discontinuity of the tangential component of the magnetic field, due to surface currents.

$$\vec{n}.\left(\vec{B}_{2n} - \vec{B}_{1n}\right) = 0 \tag{11}$$

$$\vec{n} \times \left(\vec{E}_{2t} - \vec{E}_{1t}\right) = 0 \tag{12}$$

$$\vec{n}.\left(\vec{D}_{2n} - \vec{D}_{1n}\right) = q_s \tag{13}$$

$$\vec{n} \times \left(\vec{H}_{2t} - \vec{H}_{1t}\right) = \vec{J}_s \tag{14}$$

The method of temporal calculation of the electromagnetic field is based on the radio dipole model consisting of discretizing the physical support (the antenna: the channel) into small cells called “dipoles”. The field at any point in space is obtained by superposition of the contributions of all the dipoles.

The calculation of the magnetic field is based on the definition of the rotational vector potential $\vec{A}$ magnetic:

$$\vec{H} = \frac{1}{\mu_0} rot\vec{A} \tag{15}$$

Moreover,

$$d\vec{H} = \frac{1}{\mu_0} rot(\overrightarrow{dA}) \tag{16}$$

The variation of the vector potential can be written as follows:

$$d\vec{A} = d\overrightarrow{A_z}(t) = \frac{\mu_0}{4\pi}\frac{i(z',t-\frac{R}{C})}{R}\,dz\vec{u}_z \tag{17}$$

Using the identity:

$$\frac{\partial}{\partial R} i\left(z',t-\frac{R}{C}\right) = -\frac{1}{C}\frac{\partial}{\partial t} i\left(z',t-\frac{R}{C}\right) \tag{18}$$

We obtain the expression of the azimuthal magnetic induction in cylindrical coordinates (CHEKHMOUM Saliha, 2015):

$$dB_{\varphi} = \frac{\mu_0\, dz'}{4\pi}\left[\frac{r}{R^3} i\left(z', t-\frac{R}{C}\right) + \frac{r}{cR^2}\frac{\partial}{\partial t} i\left(z', t-\frac{R}{C}\right)\right] \tag{19}$$

The temporal relationships of the magnetic fields radiated by an electric dipole are deduced from Maxwell's equations and image theory. They are defined by the following relationships (Guemri, B,2004), (Bermudez Arboleda, J.L, 2003), (Degauque, P. and Hamelin, J, 1990) & (Orzan, D, 1998):

$$\begin{cases} H_{\phi p(r,z,t)} = \dfrac{1}{4.\pi}.\left[\underbrace{\int_{-H}^{H} \dfrac{r}{R^3}.i\left(z_c, t-\dfrac{R}{c_o}\right)dz_c}_{Induction} + \underbrace{\int_{-H}^{H} \dfrac{r}{c_o.R^3}.\dfrac{\partial i}{\partial t}\left(z_c, t-\dfrac{R}{c_o}\right)dz_c}_{Rayonnement}\right] \\ H_{zp(r,z,t)} = \dfrac{1}{4.\pi.\varepsilon_0}.\left[\begin{array}{l} \underbrace{\int_{-H}^{H}\left(\dfrac{2.(z-z_c)^2-r^2}{R^5}.\int_0^t i\left(z_c, \tau-\dfrac{R}{c_o}\right)d\tau\right)dz_c}_{\text{Électrostatique}} \\ +\underbrace{\int_{-H}^{H}\left(\dfrac{2.(z-z_c)^2-r^2}{c_o.R^4}.i\left(z_c, \tau-\dfrac{R}{c_o}\right)\right)dz_c}_{Induction} \\ +\underbrace{\int_{-H}^{H}\left(\dfrac{r^2}{c_o^2.R^3}.\dfrac{\partial i}{\partial t}\left(z_c, \tau-\dfrac{R}{c_o}\right)\right)dz_c}_{Rayonnement} \end{array}\right] \end{cases} \tag{20}$$

The electric field calculation model is obtained through the following relationship (A. Ametani, Convenor JP, & M. Paolone, 2013):

$$\vec{E} = -\overrightarrow{grad}\varphi - \frac{\partial \vec{A}}{\partial t} \tag{21}$$

With the Lorentz condition:

$$Div\vec{A} + \frac{1}{c^2}\frac{\partial \varphi}{\partial t} = 0 \tag{22}$$

After converting the spatial derivative into a temporal derivative, we obtain the expression of the electric field in cylindrical coordinates which result from three contributions as follows (Guemri, B,2004), (Bermudez Arboleda, J.L, 2003), (Degauque, P. and Hamelin, J, 1990) and (Orzan, D, 1998):

$$\begin{cases} dE_z(x,y,t) = \\ \dfrac{\mathrm{dz}'}{4\pi\varepsilon_0}[\dfrac{2(z-z')^2-r^2}{R^5}\int_0^t i(z', \tau-\dfrac{R}{c})d\tau + \dfrac{2(z-z')^2-r^2}{cR^4} i\left(z', t-\dfrac{R}{c}\right) - \dfrac{r^2}{c^2R^3}\dfrac{\partial}{\partial t} i(z', t\dfrac{R}{c})] \\ dE_z(x,y,t) = \\ \dfrac{\mathrm{dz}'}{4\pi\varepsilon_0}[\dfrac{2(z-z')^2-r^2}{R^5}\int_0^t i(z', \tau-\dfrac{R}{c})d\tau + \dfrac{2(z-z')^2-r^2}{cR^4} i\left(z', t-\dfrac{R}{c}\right) - \dfrac{r^2}{c^2R^3}\dfrac{\partial}{\partial t} i(z', t\dfrac{R}{c})] \end{cases} \tag{23}$$

2.2 Lightning-HV Line Interaction Model

To model the interaction between the lightning phenomenon and the energy components of the high voltage line (D. Dib, 1997) & (Aguet, M. & Ianovici, M, 1982), we hypothesized that the Lightning wave is a controlled system, the excitation is considered to be the lightning current and the response of the system is the overvoltage level of the power components during the propagation of the lightning current in the network (Cooray, V, 2003), (Nucci, CA, Diendorfer, G., Uman, M., Rachidi, F., Ianoz, M. & Mazzetti, C, 1990), (Ianovici, M. & Morf, JJ, 1985), (Cockquerelle, JL, 1999). (Rachidi, F, 1991), (Sommerfeld, A, 1909), (Degauque, P. & Hamelin, J, 1990) & (CHIKEUR Hadjer, 2019). For this purpose, the energy components involved in the lightning current flow circuit are the guard wire and the phase conductor which are treated as detectors, the lightning arrester protection element and the last flow phase of the lightning current is the earth network of the HV substation (De la Rosa, F., K. Cummins, L. Dellera, G. Diendorfer, A. Galvan, J. Huse, V. Larsen, California. Nucci, F. Rachidi, VA Rakov, H. & Torres MA Two, 2000).

2.2.1 Guard Wire Model (Pylon)

Installed on HV lines (Aguet, M. and Morf, JJ, 1981), these are conductive wires stretched over the phase lines. They are connected to the ground by pylons. They form a phase line protection network, receiving lightning above, see figure 4 below (Frédéric Élie, 2004), (Frédéric Élie, 2005), (Aguet, M. & Ianovici, M, 1982) & (CHIKEUR Hadjer, 2019). When a lightning strike of intensity i strikes the guard wire, it emits an intensity $i/2$ in one of the directions. The guard wire is connected to the earth by a cable with an inductance L crossing the pylon and a very small series resistance R ($R <$ approximately 50Ω). Part of the current $x.i/2$ passes through this connection and flows towards the earth, while the other part $(1/2 - x).i$ propagates further in the guard conductor (Gardiol, F, 1996), (Haddad, A. and Warne., D, 1996), (Begamudre, RD, 1986), (Roy, G., Gary, C. & Hutzler, B, 1988), (Gary, C, 1995) & (Pelissier, R, 1975). The crossing of the current through the ground connection creates a potential difference $u(t)$ at its ends (between the top of the pylon and the ground), as demonstrated by equation (4) below (Frédéric Élie, 2004), (CA Nucci,.1995), (Bassesuka SNA, 2022) & (Nsekere Nzukuru, 2009).

$$u(t) = R.i(t) + L\frac{di(t)}{dt} \tag{24}$$

With:

$u(t)$: Potential difference between the pylon head and earth in kV;

R: Resistance of the pylon in Ω;

L: Inductance cable of pylon in Henry [H].

$i(t)$: lightning current in kA.

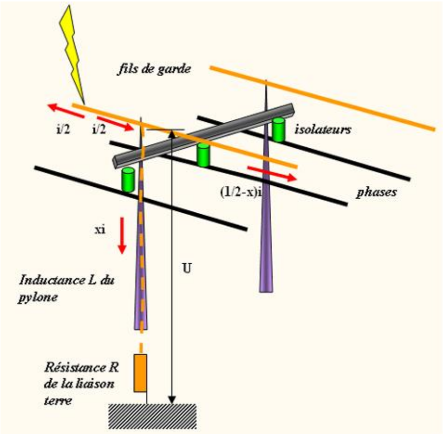

Figure 4. Lightning Strike Hitting the Guard Cable of pylon. (Frédéric Élie, 2005), (CA Nucci,1995), (Guerrieri, S., & al, 1998), (Bassesuka SNA, 2022), (Nsekere Nzukuru, 2009) & (RF Harrington, 1968).

2.2.2 Simplified Model of the HV Power Line

Lightning is a high-frequency phenomenon, its propagation model follows the description of HV lines with distributed constants (Bassesuka SNA, 2022). This means that (CHIKEUR Hadjer., 2019) the resistive, inductive and capacitive components of the circuit have characteristics per unit length. Let R', L' and C' be these quantities according to Figure 5 below (Frédéric Élie, 2005). (Bassesuka SNA, 2022) & (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D. Poljak, & K. Kerroum, 2014).

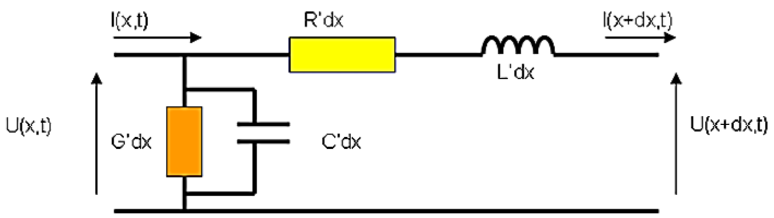

Figure 5. Simplified Model of Propagation of an Overvoltage in a Power Line (Frédéric Élie, 2005) & (Bassesuka SNA, 2022)

Each line of length dx is characterized by the elementary resistance *R'dx* in series with the elementary inductance L'dx and the elementary conductivity *G'dx* in parallel with the elementary capacitance *C'dx*. The quantities *R'* and *G'* represent the line losses due to the incomplete insulating dielectric and the Joule effect of the conductor (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D. Poljak, & K. Kerroum, 2014).

To obtain a coupling model between a lightning strike and a high-voltage line passing through a phase conductor, we consider two approaches (Haddad, A. & Warne, D,1996), (Begamudre, RD, 1986), (Denno, K, 1922), (Roy, G., Gary, C. & Hutzler, B, 1988), (Pelissier, R, 1975), (Ianovici, M. & Morf, JJ, 1983), (Aguet, M. & Morf, JJ, 1987) & (Guerrieri, S., & al, 1998):

- Case of the line subject to an electromagnetic disturbance from lightning (Indirect impact illustrated by Figure 6 below);

- Case of the line under direct lightning shock is presented in Figure 7 below.

For this purpose, the conductor formalism following the Agrawal model is well suited to study the interaction between the lightning wave and the structure of the wire. This formalism has the advantage of simple implementation and acceptable calculation times (Bassesuka SNA, 2022) & (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D. Poljak, & K. Kerroum, 2014).

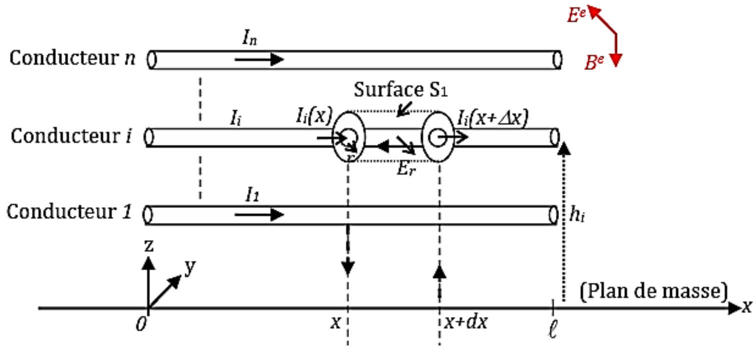

Figure 6. Geometry of a line with n conductors illuminated by an external electromagnetic field (Bassesuka SNA, 2022), (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D.Poljak & K. Kerroum,. 2014).

In this formulation, the coupling equations are the so-called stray voltages, "stray voltage" and total currents. For a line with linear parameters independent of frequency. From the two equations of Maxwell-Faraday and Maxwell-Ampère and after some mathematical manipulations, the line equations are expressed as follows (Bassesuka SNA, 2022), (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D. Poljak, & K. Kerroum, 2014) & (Sommerfeld, A, 1909):

$$\frac{\partial\,[u(x,t)]}{\partial x} + [R].[i(x,t)] + [L]\frac{\partial\,[i(x,t)]}{\partial t} = [E(x,h,t)] \tag{25}$$

$$\frac{\partial[\,i(x,t)]}{\partial x} + [G].[u(x,t)] + [C]\frac{\partial\,[u(x,t)]}{\partial t} = [0] \tag{26}$$

Or :

$[E(x,h,t)]$: is the vector containing the tangential component of the exciting electric field on each conductor; $[u(x,t)]$: is the vector of diffracted voltages in the time domain; $[i(x,t)]$: is the vector of line currents in the time domain. $[R]$, $[L]$, $[G]$and $[C]$: are respectively the matrices of resistances, inductances, conductances and linear capacitances of the line (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D.Poljak & K. Kerroum, 2014).

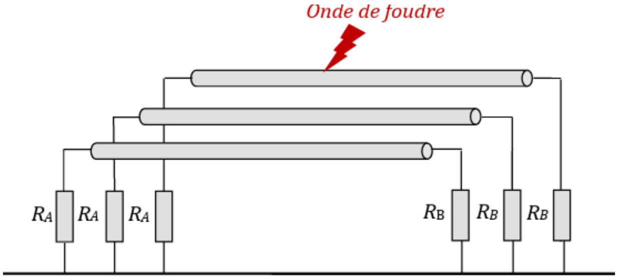

Figure 7. Direct Impact of a Lightning Wave on an Overhead Line. (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D.Poljak, & K. Kerroum, 2014) & (Affolter, JF, 2000)

When lightning directly strikes the overhead line Figure 7 (Bassesuka SNA, 2022), (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D. Poljak, & K. Histoire, 2014). This is a local injection at one point. Equations (5) and (6) then take the following form (Bassesuka SNA, 2022), (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D. Poljak, & K. Kerroum, 2014):

$$\frac{\partial\,[u(x,t)]}{\partial x} + [R].[i(x,t)] + [L]\frac{\partial\,[i(x,t)]}{\partial t} = 0 \qquad (27)$$

$$\frac{\partial[\,i(x,t)]}{\partial x} + [G].[u(x,t)] + [C]\frac{\partial\,[u(x,t)]}{\partial t} = [0] \qquad (28)$$

2.2.3 Surge Protector Model

The nonlinear resistive behaviour of ZnO varistor elements is represented by the expression of current versus voltage (*V* = *f(I)*) extracted from the voltage-current characteristics of the surge protection, see Figure 8 below.

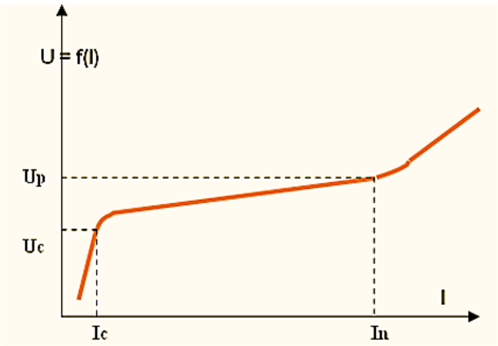

Figure 8. *V =f(I)* **Characteristic** of the surge protector. (Haddad, A. & Warne, D, 1996), (Begamudre, RD, 1986), (Denno, K, 1922), (Roy, G., Gary, C. & Hutzler, B, 1988), (Pelissier, R, 1975), (Ianovici, M. & Morf, JJ, 1983), (Aguet, M. & Morf, JJ, 1987) and (Guerrieri, S., & al, 1998)

The non-linear behaviour of ZnO surge protection elements can be represented by the following general expression :

$$i(t) = \vartheta.\frac{du(t)}{dt} \qquad (29)$$

With: ϑbeing the slope of the line, *u(t)* a potential difference in kV and i(t) the lightning shock wave in kA.

2.2.4. HV line Earthing Model

Insulation coordination studies and electromagnetic compatibility studies of high-voltage electrical network structures often require consideration of the flow of transient currents to the ground through earth connections (Bassesuka SNA, 2022). The transient behaviour of grounding systems under the influence of lightning strikes is studied using several approaches, within the framework of our work, for reasons presented above, the transmission lines approach presented in Figure 9 below is well suited (Haddad, A. & Warne, D,1996), (Begamudre, RD, 1986), (Denno, K, 1922), (Roy, G., Gary, C. & Hutzler, B, 1988), (Pelissier, R, 1975), (Ianovici, M. & Morf, JJ, 1983), (Aguet, M. & Morf, JJ, 1987) and (Guerrieri, S., & al, 1998).

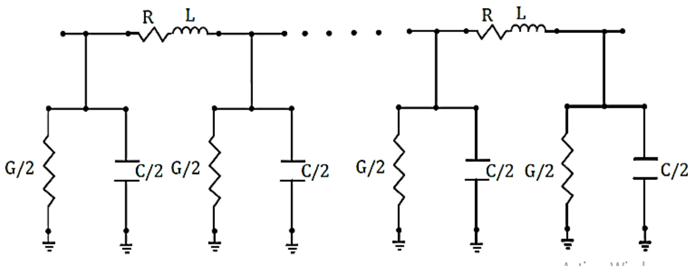

Figure 9. Model of Pylon Earth Network Under Lightning Shock (Bassesuka SNA, 2022).

When the lightning current moves towards the ground, according to the Maxwell-Gauss theory we observe the distribution of the potential difference around the earth connection due to the propagation of the electric field (Bassesuka SNA, 2022). Modeling the propagation of lightning through the grounded network of HV lines is obtained using telegraph expressions. The earth network of the HV line being local and reduced, we can recognize that the circulation of current in the ground takes place mainly through the transverse elements [G] and [C]; the distribution of current and potential around the earthing is weakly linked to the variable **x**.

$$\frac{\partial[\,i(t)]}{\partial t} = [G].[u(t)] + [C]\frac{\partial\,[u(t)]}{\partial t} \tag{30}$$

With;

$[u(t)]$: is the vector of diffracted voltages in the time domain;

$[i(t)]$: is the vector of currents injected into the ground in the time domain.

$[G]$ and $[C]$: are respectively the matrices of conductances and linear capacities of the earthing of HV lines. (Bassesuka SNA, 2022) & (B. Nekhoul, B. Harrat, L. Boufenneche, M. Chouki1, D.Poljak, &K. Kerroum, 2014).

2.3 Equation of Subsystems in the Spatio-Temporal and Frequency Domains

2.3.1 Space-Time Domain

To analyze the relationship between lightning and the components modelled above by solving the telegraph equations using FDTD, the energy components are alternately divided into current and voltage nodes, as shown in Figure 10 below. Two consecutive nodes of the same type are separated by an interval Δx (CHIKEUR Hadjer, 2019).

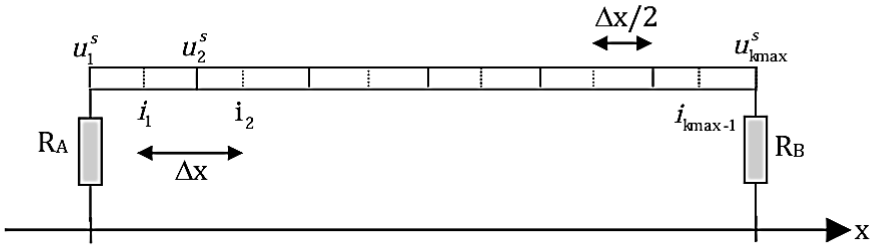

Figure 10. Spatial Discretization of a Conductor (CHIKEUR Hadjer, 2019)

Note that the end nodes are voltage nodes and that the tangential excitation electric field of the wire is calculated from the current nodes (CR Paul, 1994) & (CHIKEUR Hadjer, 2019). As in space, the current and voltage are shifted by half a time step. More precisely, the current samples are before the voltage, see equation 11 below which illustrates the intertwining of voltages and currents in space and time.

$$\begin{cases} u_k^n = u((k-1)\Delta x, n\Delta t)) \\ i_k^{n+1/2} = i(\left(k-\frac{1}{2}\right)\Delta x, (n+\frac{1}{2})\Delta t)) \\ E_k^{n+1/2} = E(\left(k-\frac{1}{2}\right)\Delta x, (n+\frac{1}{2})\Delta t)) \end{cases} \tag{31}$$

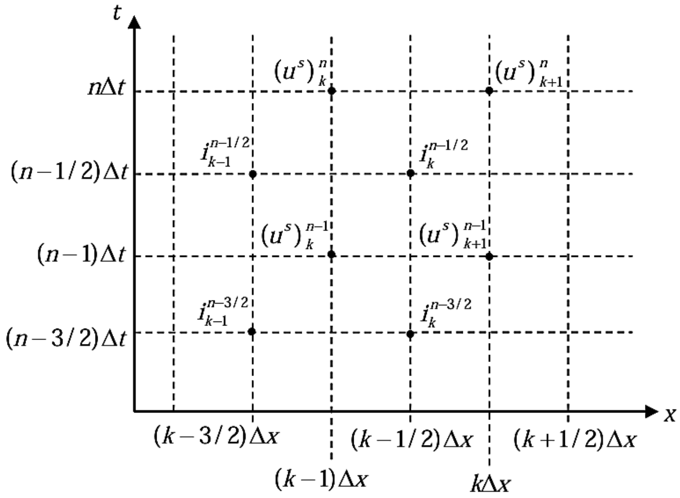

Figure 11. Spatial and Temporal Discretization of Voltage and Current

By applying the above principle to equations (24-30), we obtain the FDTD voltage propagation models for the following energy components (Allab, K, 1984) & (Spiegel, MR, 1975):

- Guard wire:

$$u_k^{n+1} = -u_k^n + \left(R + \frac{2L}{\Delta t}\right) i_k^{n+\frac{3}{2}} + (R-1) i_k^{n+1/2} \tag{32}$$

- HT line:

$$u_k^{n+1} = \frac{\Delta t}{L.C.\Delta x}\left[u_{k+1}^n - u_{k-1}^n\right] + u_k^n + \frac{R.\Delta t}{L.C} i_k^{n+1/2} \tag{33}$$

- Surge protector:

$$u_k^{n+1} = u_k^n + \frac{\Delta t}{2.\vartheta}\left(i_k^{n+\frac{3}{2}} + i_k^{n+\frac{1}{2}}\right) \tag{34}$$

- Grounding:

$$u_k^{n+1} = \frac{\left(\frac{C'}{2} - \frac{G'}{2}\right)}{\left(\frac{G'}{2} + \frac{C'}{2}\right)} u_k^n + \frac{i_k^{n+\frac{3}{2}} - i_k^{n+\frac{1}{2}}}{\left(\frac{G'}{2} + \frac{C'}{2}\right)\Delta t} \tag{35}$$

2.3.2 Frequency Domain

To analyze the relationship between lightning and the components modelled above by solving the telegraph equations in the frequency domain, we apply the Laplace transform to equations (24-30) (Allab, K, 1984) & (Spiegel, MR, 1975). Our goal is to find different transfer functions of energy structures to develop a model of the lightning shock wave flow circuit to Earth. We then propose an approach that leads to its optimization.

- Guard wire frequency model

$$G_1(p) = \frac{I(p)}{U(p)} = \frac{1/L}{\frac{R}{L} + p} \tag{36}$$

- Frequency model of the surge protector

$$G_2(p) = \frac{I(p)}{U(p)} = \frac{\vartheta}{p} \tag{37}$$

- Frequency model of the HV line earth network

$$G_3(p) = \frac{U(p)}{I(p)} = \frac{(1/C)p}{\frac{G}{C} + p} \tag{38}$$

2.4 Model of Transient Impedance of Lightning Shock Wave Flow

Transient impedance is a passive element which must act on the speed of flow of the lightning current through the earthing of the HV-pylons; this current is considered as a disruptive excitation to the system. The cascading of the transfer functions $G_1(p)$, $G_2(p)$, and $G_3(p)$makes it possible to obtain this impedance.

$$G(p) = G_1(p) * G_2(p) * G_3(p) \tag{39}$$

Inserting equations 36-38 into expression 39 gives the following transient impedance:

$$G(p) = \frac{(\vartheta/LG')}{p^2+\left(\frac{R}{L}+\frac{G'}{C'}\right)p+\frac{R}{L}*\frac{G'}{C'}} \tag{40}$$

With: G': conductance of the earth network in Ω^{-1}

C': Earth network capacity in nF

R: Resistance of the pylon guard wire in Ω

L: Inductance of the pylon guard wire in mH.

After obtaining the transfer functions of all the flow components of the lightning shock wave, the functional diagram of the system is shown in Figure 12 below:

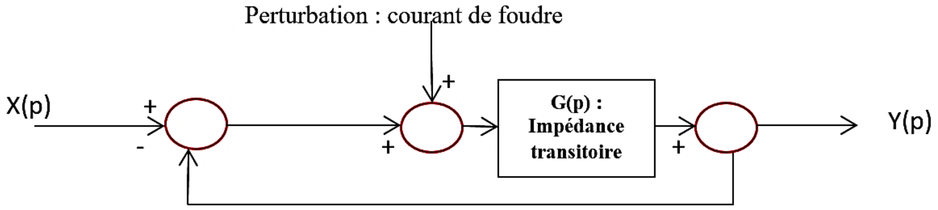

Figure 12. Model of the Lightning Shock Wave Flow circuit.

2.5 Optimized Lightning Shock Wave Flow Circuit Model

Optimizing the lightning shock wave flow circuit consists of minimizing the magnitude of overvoltages on the HV-line to ensure coordination of the insulation of the energy components that compose it. The model of the damping impedance of the effects of the disturbing current is given by:

$$Y_{RC} = \frac{1}{R_a} + j\omega C_a \tag{41}$$

For : $j\omega = p$:

$$Y_{RC}(p) = \frac{1}{R_a} + C_a p \tag{42}$$

From Y_{RC} we draw Z_{RC} by the following relation:

$$Z_{RC}(p) = \frac{1}{Y_{RC}(p)} = -\frac{1/C_a}{\frac{1}{R_a.C_a}+p}$$

$$Z_{RC}(p) = -\frac{1/C_a}{\frac{1}{R_a.C_a}+p} \tag{43}$$

Optimized circuit model is shown in Figure 13 below:

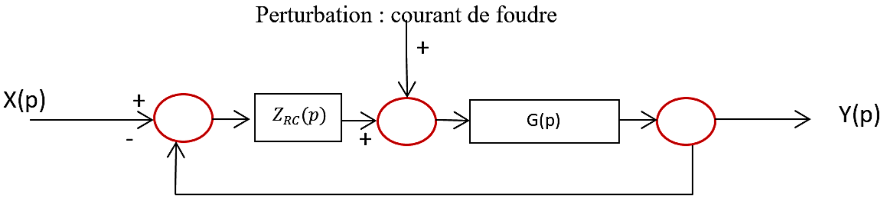

Figure 13. Optimized model of the lightning shock wave flow circuit

3. Simulation Results

3.1 Declaration of Proposed Model Parameters

3.1.1 Lightning Current (ABS.N., 2022)

✓$I_0 = 25\ kA$

✓$A = 1{,}4 * 10^4 s^{-1}$

✓$B = 6 * 10^5 s^{-1}$

✓$\mu = 1{,}9 * 10^8$m/s

✓$Z = 0km - 1km\ et\ 2\ km$

3.1.2 HV Pylon Guard Wire (220 kV West interconnected network of SNEL/DRC., 2023)

✓ $R = 0{,}07\ \Omega/km$

✓ $L = 1{,}01\ mH/km$

✓ l =262 km

3.1.3 HT line (Wave Impedance) (ABS.N., 2022)

✓$Z_c = \sqrt{R^2 + X^2} = 50\ \Omega$

✓$R = 0{,}07\ \Omega/km$

✓$L = 0{,}4397\ mH/km$

✓$Z_c = \sqrt{R^2 + X^2} = 50\ \Omega$

✓ l =262 km

3.1.4 Surge Protector (220 kV West interconnected network of SNEL/DRC., 2023)

✓$\vartheta = 0{,}25$: Dielectric constant of materials specific to the surge arrester.

3.1.5 Grounding of HV Pylons **(** (220 kV West interconnected network of SNEL/DRC., 2023))

✓ $G' = 0{,}28\ \Omega^{-1}$: conductance of the earth network in Ω^{-1}

✓ $C' = 0{,}011 nF$: Earth network capacity in nF

3.1.6 Impedance of the Effects of Lightning Disturbance Current

✓ $R_a = 6{,}9\ \Omega$: resistance in Ω^{-1}

✓ $C_a = 0{,}016 nF$: Capacity in nF

3.1.7 Simulation Time

✓ t= 0 to 30 µs.

✓ $\Delta t = 1\ \mu s$

3.2 Results

3.2.1 Time Domain

By applying the calculation codes developed above in the Scilab 6.11 environment, we obtained the results presented in figures 14 to 22 below compared to the experimental results taken from (CHIKEUR Hadjer., 2019) see figure 15, (CHEKHMOUM SALIHA., 2015) see figure 17 and (NSEKERE Nzukure., 2009) see figure 19.

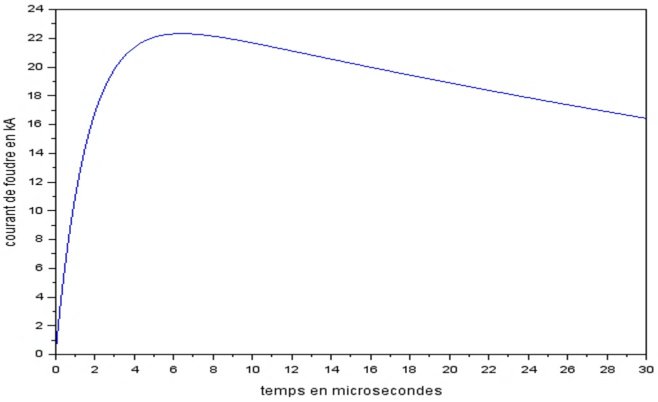

Figure 14. Current Base of the Lightning Channel (simulation result)

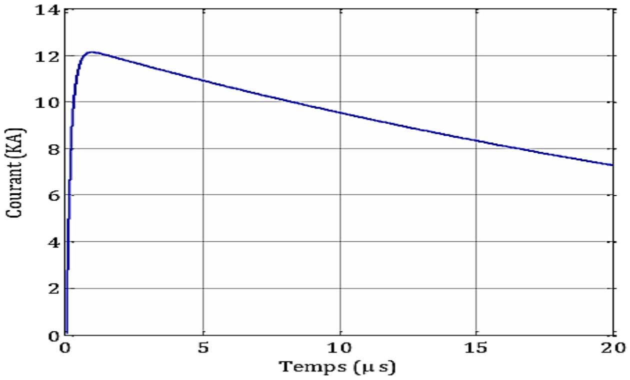

Figure 15. Current Base of the Lightning Channel (CHIKEUR Hadjer., 2019)

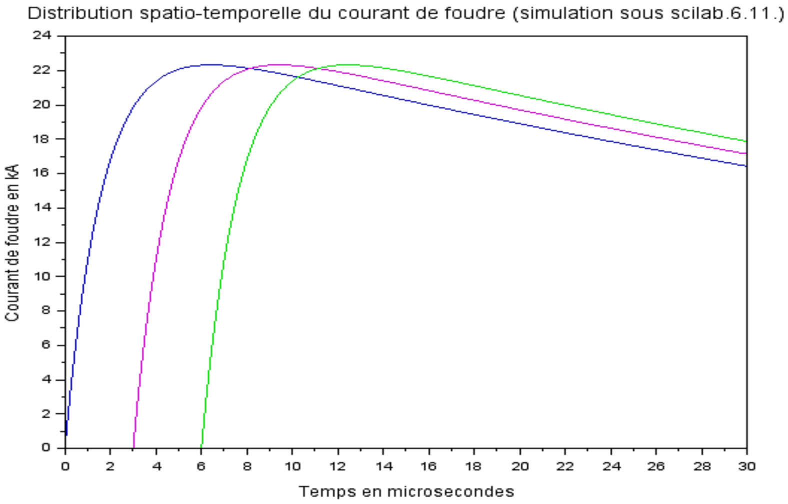

Figure 16. Spatio-Temporal Distribution of the Returning Arc Current Along the Channel (0km in blue, 1km in purple and 2 km in green) (simulation result)

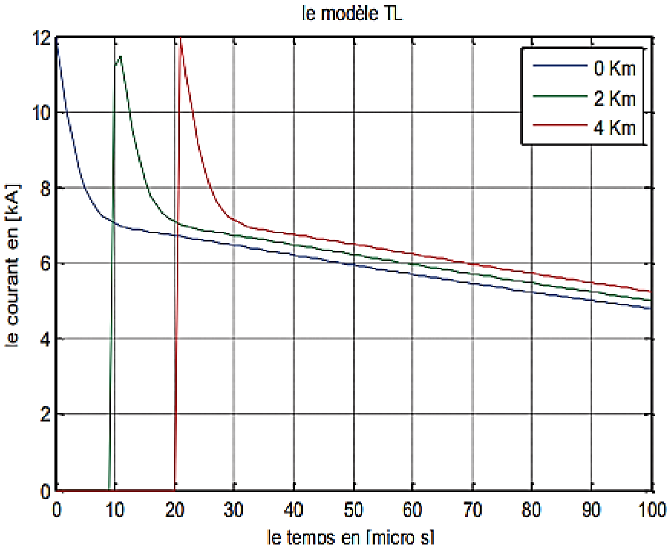

Figure 17. Spatial and Temporal Distribution of the Returning Arc Current Along the Channel (CHEKHMOUM SALIHA., 2015).

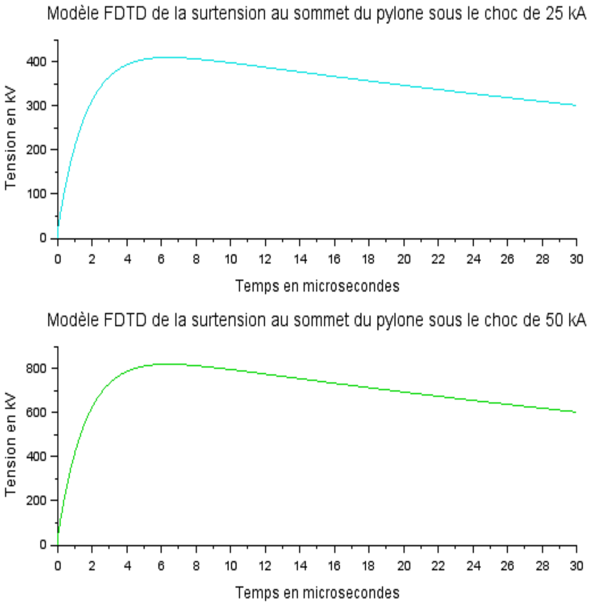

Figure 18. Overvoltage the Top of the Pylon Under the Shock of 25 kA and 50 kA (simulation result)

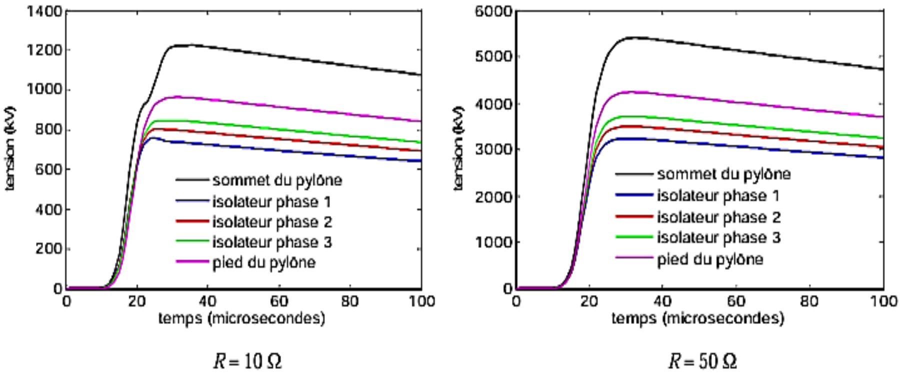

Figure 19. Tensions, First Arc (NSEKERE Nzukuru., 2009)

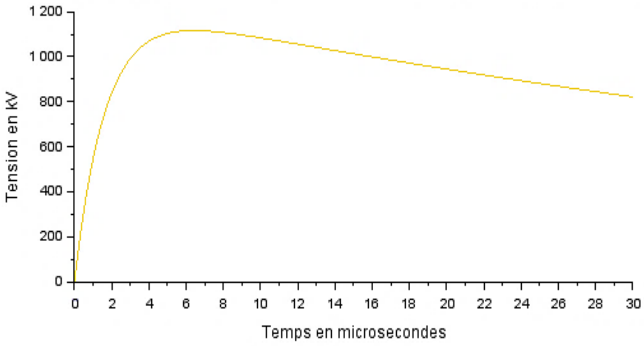

Figure 20. Overvoltage the Phase Conductor Under the Shock of 25 kA (simulation result)

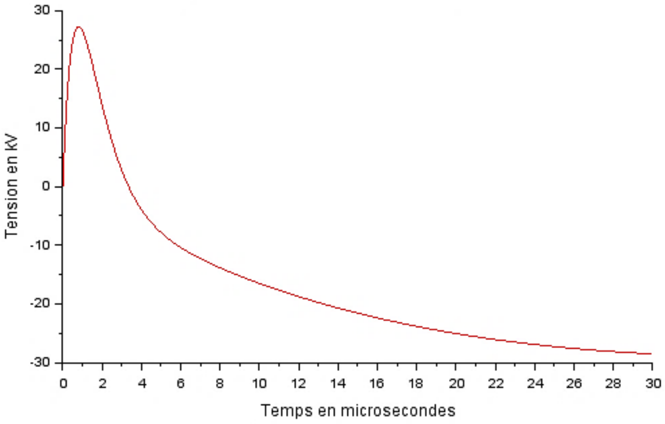

Figure 21. Overvoltage Level the Earthing Tower Under the Shock of 25 kA (simulation result)

3.2.2 Frequency Domain

By applying the frequency domain calculation codes above with the Scilab 6.11 environment, the results presented in Figures 22 to 25 below were obtained.

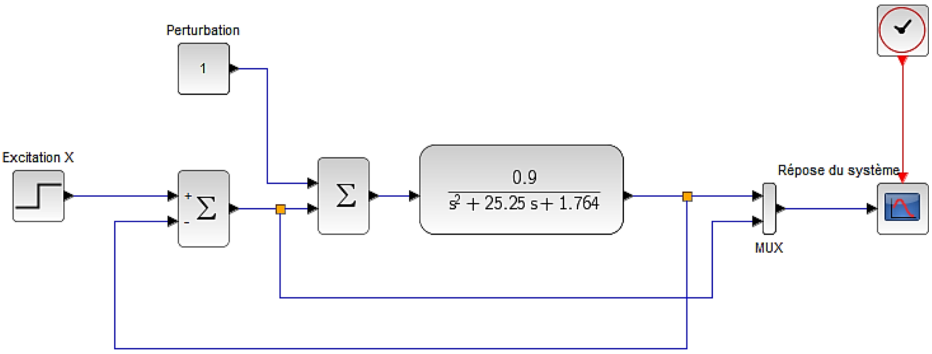

Figure 22. Frequency Model of the Transient Impedance of the Lightning Shock Wave Flow Under scilab 6.11 environment

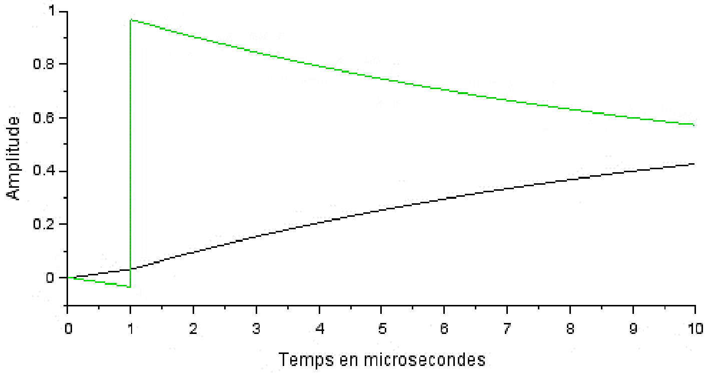

Figure 23. The Behaviour of the Current Injected Into the High Voltage Line in the Green Curve and the Overvoltage on the Guard Wire, Lightning Arrester and HV Pylon Earthing Assembly in the Black Curve

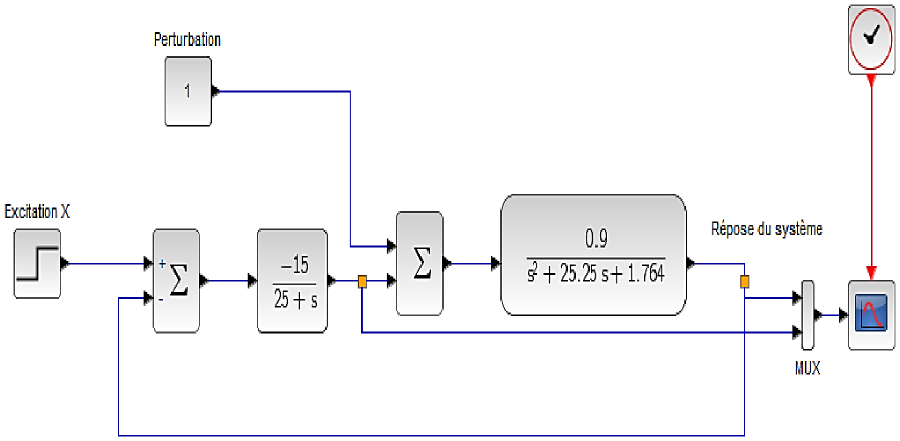

Figure 24. Optimized Model of the Transient flow Impedance of the Shock Wave Under scilab 6.11 environment

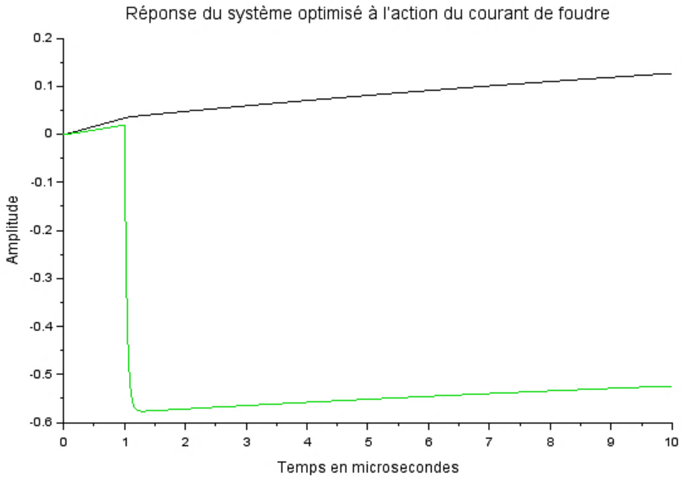

Figure 25. Influence of the RC Damping Impedance on the Action of the Lightning Current (green curve) and the Overvoltage on the Guard Wire, Lightning Arrester and Pylon Earthing Assembly (black curve)

4. Discussions of Results

Transmission lines are most susceptible to interference during a lightning strike. The study of their transient behaviour generally relies on transmission line theory, which includes electrical components such as R, L, C, and G. There are several equations to model them, depending on the shape and properties of the material used in transmission. The bi-exponential model was chosen to obtain the results of various simulations and used for analytical modelling of the problem addressed

For this, the following results were obtained:

With experimental data taken from the work of (ABS.N., 2022), Figure 14 shows that the current wave at the base of the lightning channel is impulsive, and is characterized by the rise and fall time descent, the result obtained is close to the experiments proposed by (CHIKEUR Hadjer., 2019) to reproduce a typical lightning wave obtained by measurements see Figure 15.

Figure 16 describes the spatiotemporal distribution of the lightning current and shows that at heights below the return arc front $z' \leq \mu.t$, this current is equal to the current at the base of the lightning channel and at heights above the return arc front $z' > \mu.t$, this current is negative or even zero. This result is similar to that proposed by (CHEKHMOUM SALIHA, 2015) see Figure 17.

Figure 18 shows the overvoltage levels at the top of the tower under the shock of 25 kA and 50 kA. These curves show that the lightning shock at the top of the pylon reaches 400 kV for 25 kA and 800 kV for 50 kA. The results presented highlight the risk of increasing the potential of pylon earthing. These results are similar to those presented in the work proposed by J. P. NZURU NSEKERE in 2009 see Figure 19.

Figure 20 rather represents the temporal evolution of the voltage induced by lightning in the phase conductor and also shows that this voltage is directly proportional to the temporal variation of the disturbing current. For the 25 kA lightning shock injected at a point in the network, the overvoltage reaches 1100 kV. The results presented highlight that the risk of flashover of a phase insulator essentially depends on the following factors:

- the earthing impedance of the pylon;
- the characteristics of the lightning current wave (peak value, rise time, etc.);
- the geometric characteristics of the pylon and the line (height, span, phase position, etc.).

Figure 21 shows the surge level at the grounding tower under 25 kA shock. This overvoltage reaches 28 kV, which is dangerous for the equipment and the environment of the HV pylon with the risk of electrocution. Figure 22 gives the frequency model of the coupling of the lightning shock wave on the HV line under the Scilab 6.11 environment. This block diagram allowed us to obtain the results presented in Figure 23. The latter demonstrates the behaviour of the current injected into the HV line before correction (in a green curve) and the overvoltage on the guard wire, surge arrester and update assembly. The pylon earth after correction by counter reaction with unit return (in a black curve).

Finally, Figure 24 shows the frequency model for coupling the lightning wave on the HV line in the Scilab 6.11 environment. This functional diagram leads to the results of Figure 25 and last shows that in addition to existing protection devices, the integration of a parallel RC damping impedance in the control part of these devices makes it possible to reduce the effects of transient disturbances Electromagnetic lightning, with the response time of the circuit is reduced to 1.3 microseconds, a value included in the response time interval recommended by standard IEC 62305-01 of the International Electrotechnical Commission. This helps prevent stress and dielectric wear, which can reduce the life of high-voltage equipment.

5. Conclusions

Transmission systems HV play a crucial role in the power electrical system and constitute an interface between electrical production and consumption. It is therefore necessary to ensure its protection, especially in regions with high thunderstorm density.

For this article, we analyzed the behaviour of the HV line in the event of electromagnetic disturbances due to lightning. To do this, we are interested in the study of the spatio-temporal distribution of the lightning current wave to model the overvoltages caused by atmospheric discharges and study their effects on the energy components of HV power lines. After theoretical considerations, during which we developed mathematical models that helped us define the problem, we simulated a practical case where the HV power line is supplied by a 220 kV source, it results that the lightning current is of an impulse nature and characterized by the rise and fall time. The voltage level caused by lightning in this studied system is directly proportional to the temporal variation of the disturbing current.

The results presented in this paper highlight the risk of stress and wear of dielectrics, which could shorten the life of high-voltage equipment. To minimize the effects of electromagnetic lightning transients and thus optimize the performance of HV power lines while ensuring their insulation coordination, in addition to the existing protection system, this work proposes to integrate into the control part of the latter, in particular the protection system intended for tropical areas, a parallel RC damping impedance which will have the mission of optimizing the effects of electromagnetic lightning transient disturbances.

These results can be used for practical applications in the engineering and design of high-voltage transmission systems. Also, can guide policymakers.

An analysis of the results of the applications treated with direct lightning strikes shows that the transmission line theory is very useful and represents an adequate model for the study of lightning transients; The results obtained are more than acceptable compared to the antenna theory. However, note that the results (currents and voltages) at all points of the directly affected structures are acceptable in terms of rhythm and amplitude.

The lightning phenomenon is natural, therefore the model used in our work may prove to be limited knowing the random nature of the storm discharge. From the perspective of this article, and to complete our study, it would be important to take into account the impact of the uncertainties of the different parameters constituting a high-voltage transmission system (in the design phase). These parameters are essentially geometric (distance, position of wiring) or electromagnetic (discharge intensity, intrinsic characteristics of materials). They naturally influence the EMC performance of the electrical system. It would also be very interesting to address the problem of electromagnetic lightning transients using the theory of inhomogeneous transmission lines, which would take into account all the electromagnetic interactions between cells that occur after the discretization of the HV power lines.

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- Associate editors
- Consulting editors of the journal in which the article is to appear.

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Authors’ contributions

I would like to inform your journal that this article did not have the contribution of other authors except the reviewers who were able to make a relevant contribution during the examination of the article and My scientific assistant Tuka Biaba Samuel Garcia, Electrical Engineer was tasked with conducting surveys on all areas of high storm activity in the Democratic Republic of Congo crossed by the Inga-Kinshasa HT line, 262 km long and the subject of case studies in this article. And, specify the places where there are more storm disturbances. Professor Doctor Engineer Bassesuka Sandoka Nzao Anthony.

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I would like to inform your journal that the financing of this article is done with my own means.

Competing interests

I declare that there are no known competing financial interests or personal relationships that could appear to influence the work reported in this article.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal’s policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

Open access

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