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Analysis of the Influence of the Earthing Resistance of Pylones on the Performance of the HVAC Line Facing Electromagnetic Transitories Lightning

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Abstract

The roles of electrical energy no longer need to be demonstrated since the industrial revolution of 1740 based on the use of new sources of energy, of which electrical energy is considered to be one of the greatest revolutions in the world. Despite this, we must note that electrical energy is changing the habits of human activity and, on the one hand, has consequences on its transport, the large quantities of which are transmitted by power lines, forcing them to operate more and more. more within their limits and unplanned outages increase the risk of instability. Storms, industrial pollution, and lightning strikes are the main causes of these unscheduled outages. In regions with a high keraunic level, the reduction of insulation breakdown due to lightning is, therefore, a major concern for designers and operators of HV lines. It is possible to reduce the number of tripping of power lines due to lightning by the proper installation of ground wires and by the appropriate grounding of pylons. In this article, we focus our research on the analysis of the impact of the earthing of the pylons on the performance of HV lines against lightning strikes. Considering these parameters and using the oldest and simplest analytical model as a time-varying current wave whose model is a difference of two decaying exponentials, we brought into contribution Maxwell's equations, the law of Ohm, telegrapher's equations, transmission line theory, and the FDTD method to model lightning-induced voltages as a function of HVAC tower grounding. This study was carried out on the Liminga-Funa 220 kilovolt alternating line in the DRCongo, located in a region where storm activity and industrial pollution are very high. Thus, the results obtained by simulation show that the peak voltage on the components of the HVAC line is a linear function of the impedance of the earthing of the pylon. The impedance value of the pylon earthing less than or equal to 10 Ohm dampens the atmospheric overvoltage and ensures good coordination of the insulation of the line elements in the event of a lightning strike at the top of the pylon for the first bow. But for the return arc taken in this case, the bypass of the insulator is unavoidable. The fractal dimensions of the results of our programs have been compared with those of the figures obtained experimentally.

Keywords: earthing grounding of HV lines, electromagnetic lightning transients, Ohm's Law, FDTD method, Modeling, Maxwell equations, Telegraphic equations

1. Introduction

The quality of electrical energy concerns all players in the energy sector, whether they are network managers, producers or suppliers of electrical energy. It has become a subject of great interest in recent years and, for economic reasons, the generalization of equipment sensitive to disturbances or generator of disturbances, the liberation of the electricity market which means that the quality of electrical energy has become one of the criteria of choice for the energy supplier rather than for the consumer.

Nevertheless, the design, construction, and operation of an electrical network are, based on the quality of supply of this energy, safety or protection, and the economy, as we have just pointed out. To achieve these objectives, one must know how to analyze to as properly model, and simulate regimes to study the phenomena that appear (Tuan Tran Quoc, 2012). The considerable development of the electrical energy transport networks in its various organs ensures an optimal distribution of the power transits, the maintenance of the frequency, the compensation of the reactive energy, and the knowledge in real-time of the electrical quantities which characterize this last one makes it possible to ensure its control, its command and gradually lead to studies of the various disturbances by their mode of transmission (Hertzian waves, telecommunication networks, energy distribution networks, lightning, nuclear electromagnetic impulse), by their form (interruptions, flicker, high frequencies). These disturbances affect electrical organs or humans (Dib Djalel, 2007).

According to the literature of (Kiessling F., Nefzger P., Nolasco J.F., Kaintzyk U, 2003), the large amounts of energy transmitted by power lines force them to operate more and more within their limits, and unplanned outages increase the risk of instability. Lightning strikes are the principal cause of unscheduled outages of power lines.

According to the work of (Tahar ROUIBAH Theme, 2015), a potential source of incidents, which, by nature, is difficult to control, is lightning. This phenomenon is relatively frequent, and most of the faults observed on the electrical energy transmission network per year are attributable to lightning, and it has always been a cause of disturbances in the use of electricity. An experience of some professionals of production companies, transport of electrical energy explains that this dangerous phenomenon is more frequent in stormy areasBecause lightning is a natural, unpredictable, and most harmful phenomenon on all electro-energetic systems (see also Ali Jazzar, 2013).

The energy carriers properly control the protection of the network against accidental or internal faults, on the other hand, the protection against lightning, a natural and external fault during an indirect impact where it radiates significant electromagnetic fields and which will induce by coupling electromagnetic waves of cruel surges in their targets, such as electric power transmission networks (Sanaa Kaouche., Bachir Nekhoul., Kamal Kerroum., Khalil El Khamlichi Drissi, 2021).

The different parameters of the lightning electromagnetic field seriously endanger the functionality of power systems, electrical equipment, and electronic devices (Karl Lundengård, Milica Rančić, Vesna Javor, Sergei Silvestrov, 2017). However, the mechanism of creating lightning is more complex. The lightning discharge current can be between 3 and 200 kA, about 1% is 140 kA or more, while about 50% exceeds 25 kA (Ndikwa Tchopkreo, 2019)(IEC 62305-03 (International Electrotechnical Commission (IEC, 2006)). There are two lightning strikes the direct impact results in the circulation of a strong electric current which heats the material and often causes mechanical damage. very significant, even spectacular. And the indirect impact is manifested by the appearance of lightning current and induces, on the one hand, a common mode voltage and an electromagnetic field of exceptional intensity likely to disturb the proper functioning of an electric power network.

But it should be noted the fairly recent requirements and the increasing quality of electrical systems, in particular reliability, and continuity of service as well as the ever-permanent concern to minimize the costs of unavailability leads to the observation that lightning has become a binding point. In improving the reliability of electrical systems (Tahar ROUIBAH Theme, 2015).

Consequently, the overvoltages induced by a direct or indirect lightning discharge can cause electromagnetic disturbances. These disturbances also often contribute to the total or partial destruction of equipment for the production, transport, and distribution of electrical energy. The unexpected natural damage to the electrical network, homes, animals, trees, etc. By lightning is a major concern for residences and energy production companies across the entire electrical network (Ndikwa Tchopkreo, 2019). The correct and effective protection of electrical systems against these disturbances requires knowledge of the physics of lightning and its electrical characterization (Dib Djalel, 2007). Protection against lightning disturbances also requires a grounding system to quickly drain fault currents into the ground (Xavier Legrand, 2007). This earthing system plays an essential role in the protection of individuals against electrical accidents and ensures the proper functioning of electrical installations (Semaan Georges., 2001).

The study, modeling, and simulation of the influence of the resistance of the earthing of the pylons on the performance of HV lines subjected to electromagnetic transients from lightning, the application of which is made on the 220-kilovolt line LIMINGA- FUNA in the Democratic Republic of Congo, located in a region where storm activity is very important is the objective of this article. Thus, to achieve this we have considered lightning as a time-varying current wave whose oldest and simplest analytical model is a difference of two decreasing exponentials (Cooray V., 2003). Then, we used Ohm's law, the telegrapher's equations, the transmission line theory, and the FDTD method to model the voltages induced by lightning as a function of the grounding + impedance. of HTAC pylon. Thus, the results obtained by simulation show that the overvoltage on the energy components of the HV AC line is a linear function of the impedance of the earthing of the pylon.

In view of the results obtained, the value less than or equal to 10 Ω for the earthing impedance of the HVAC pylon is a reasonable limit to avoid the risk of bypassing insulators or the loss of insulation of the line in the event of a thunderbolt at the top of the pylon for the first arc. But for the return arc taken in this case, the bypass of the insulator is unavoidable. It should also be noted that the propagation of the lightning shock wave at this precise moment is upstream and downstream.

2. Method

Through this article, we based ourselves on the study, the modeling, and the simulation of the influence of the resistance of the earthing of the pylons on the performances of the lines HV subjected to the transient electromagnetic of the lightning. HV AC power lines are the most exposed to disturbances during a lightning discharge. Their study of behavior is generally based on the theory of transmission lines with electric components R, L, and C (G Aguet, M. and Morf, JJ, 1987). Several equations exist for their modeling depending on the shape and characteristics of the material used in the installation. In this article, bi-exponential models (Guerrieri, S, and al, 1998) and so-called engineering models (Yang, G., and al, 2017)(Uman, MA, and McLain, DK, 1970) have been chosen and used for the analytical modeling of the lightning current by considering this current as a wave varying in time (Bruce and Golde, 1941) (Cooray V, 2003). The analysis and the in-depth study led us to use different physical laws such as Ohm's law, Maxwell's equations, the telegrapher's equations, and the FDTD method to model the voltages induced by lightning as a function of the earthing impedance of HVAC pylon. The 2D simulations based on the proposed models were presented as well as the verification of the consistency of the different models by comparing the fractal dimensions of the results of our programs with those of the figures obtained experimentally.

3. Theoretical Model

It is possible to reduce the number of tripping of power lines due to lightning by the proper installation of ground wires and good grounding of the line. In regions with a high keraunic level, reducing insulation failures due to lightning is therefore a concern of overhead line designers.

Using Kirchhoff's laws, telegraph equations and the FDTD method as well as transmission line theory, in this article we will address the following aspects:

- Electromagnetic interference;
- Lightning and aggression mechanism;
- Elements influencing the behavior of lightning on the electricity pylon;
- Modeling of the lightning impulse current;
- Modeling of the propagation impedances of the lightning current wave;
- Simulation of the performance of the HV line as a function of the earth resistance of the pylons.

Calculations will be made to the 220 Alternating current kilovolts (kV AC) LIMINGA-FUNA, located in an area where thunderstorm activity is very high while limiting our calculations to the aspects of lightning from the line about to the ground pylons.

3.1 Electromagnetic Interference

Any electromagnetic interference situation involves three different elements: a source of disturbance emission, a disturbance receiver (victim), and a coupling mechanism by which the disturbance reacts to the operation of the receiver.

3.1.1 The Source of Disturbance

Sources of electromagnetic disturbance can be characterized by (Nabil Ikhlef, 2002):

- Their origin: internal (maneuver), or external (lightning).
- Their temporal nature: permanent or transitory.
- Their frequency content.

3.1.2 Electromagnetic Coupling

Coupling is the phenomenon of propagation of disturbances that occurs between the source and the victim. The coupling modes can be classified according to the type of disturbance and according to the propagation medium, by conduction (characterized by currents and potential differences), or by radiation (characterized by electric and magnetic fields) (Pierre Degauque., Joël Hamelin, 1990).

3.2 Lightning and Aggression Mechanism

Lightning is defined by the passage of a very large transient current between two points normally isolated from the atmosphere. Lightning occurs between a cloud and the ground, between two clouds, or between two charged areas within a single cloud. These stored charges are, in all likelihood, generated by the movement of hot air in a forming cloud. Lightning is one of the unpredictable and harmful natural phenomena that has been mentioned by several researchers (Ndikwa Tchopkreo, 2019).

Famous researcher Benjamin Franklin alluded to when demonstrating a decade ago that his electric shock is gigantic. Many researchers have studied clouds and lightning, like Richard E. Orville who worked on the density of ground lightning in the United States in 1989. He reveals that the national lightning detection network is composed of 114 broadband magnetic direction finders for locating cloud-to-ground lightning. More than 13.4 million flashes have been recorded during this year. These various studies have made it possible to classify lightning strikes into different categories which are based on two important criteria:

- The first is linked to the origin of the discharge.
- The second to the polarity of the loads carried.

3.2.1 Lightning Electrical Parameters

The electrical parameters of lightning are (Dib Djalel, 2007):

- Courant à base du canal.
- Return arc speed.
- Electromagnetic field.

3.2.2 Lightning Strike on a Line

The general empirical formula indicating the lightning strike (total number of Lightning Strikes per year) of a line (pylons, phase, and guard cables) is given by (Aguet M., Ianovici M, 1982):

$$N_L = N_k.(N_1/30 + l/70).\beta.L/100 \tag{1}$$

With:

N_k = keraunic level; N_L = lightning strike of the line; N_1 = lightning strike of the highest horizontal conductor; L = length of the line in kilometers (km); l = width of the line in meter (m) (between the outer conductors); and β = influence factor of pylons and earth cables.

3.3 Elements Influencing the Behavior of Lightning on the Ground

The grounded are vital electrical circuits and elements that have essential in the protection against electrical accidents. Elements influencing the behavior of lightning on the earth network (Andolfato R., Bernardi L., Fellin L, 2000):

- Soil type;
- Soil resistivity;
- Resistance;
- Permittivity;
- Permeability.

3.4 Modeling of the Wave of the Lightning Current

This current is of a pulsed nature, and its shape is characterized by a peak value, a rising edge to the peak (or rise time), and a decay time.

3.4.1 The Exponential Double Function

The exponential functions are used by a certain number of authors and which have the advantage of having analytical Fourier transforms, that makes it possible to carry out a direct analysis in the frequency domain (Bruce., Golde., 1941) and (Cooray V., 2003):

$$i(t)=I_0\,[\exp(-At)-\exp(-Bt)] \tag{2}$$

With I_0 as the amplitude of the base current, A and B are time constants.

3.4.2 The Function of Heidler

The analytical expression of the current at the base of the lightning channel was presented by Heidler in 1985. The use of the latter gave results that correspond better to the experimental observations, this function is modeled as follows (Heidler F, 1985) :

$$i(0,t) = I_0/\eta.[(t/\tau_1)^n /1+(t/\tau_1) n].exp(-t/\tau_2) \tag{3}$$

With I_0 Amplitude of the base channel current; τ_1 Rise time constant, τ_2 Fall time constant; η correction factor of the amplitude of the wave, and n is an exponent varying between 2 and 10. Below are the lightning current parameters in relation to (4) above, for $n = 10$. These parameters depend on the protection level.

$$i(0,t)= I_{01}/\eta_1.[(t/\tau_{11}) n_1 /1+(t/\tau_{21}) n_1].exp(-t/\tau_{22})+ I_{02}/\eta_2.[(t/\tau_{11}) n_2 /1+(t/\tau_{21}) n_2].exp(-t/\tau_{22}) \tag{4}$$

Standard IEC 62305-01 (International Electrotechnical Commission (IEC), 2006) gives the following parameters of relation (3), for $n = 10$. These parameters depend on the level of protection (see table 1).

Table 1. Lightning Current Parameter

	First attempt			Consecutive short stroke		
	Level of protection			Level of protection		
Settings	I	II	III-IV	I	II	III-IV
I (kA)	200	150	100	50	37.5	25
η	0.93	0.93	0.93	0.993	0.993	0.993
$\tau_1(\mu s)$	19	19	19	0.454	0.454	0.454
$\tau_2(\mu s)$	485	485	485	143	143	143

The standard parameters of relation (4) corresponding to the first arc and the return arc of a lightning strike are found in the works of Berger (Berger K., Anderson R. B., Kroninger H, 1975).

3.4.3 Transmission Line Model

This model assimilates the lightning channel to a lossless transmission line where a current pulse propagates from the ground at a constant speed of the return arc "*v*". The Spatio-temporal distribution of the lightning current is defined by (Yang, G., et al. 2017) (Uman, M.A., D.K. McLain, 1970):

$$I_{fZ'} \leq v.t , \quad i(Z',t)= i(0, t -Z',t/v) \tag{5}$$

$$I_{fZ'} > v.t , i(Z',t)= 0 \tag{6}$$

3.5 Lightning Current wave Propagation Circuit Model

We will give in the following paragraphs, the tension at the top of the pylon, at the foot of the pylon, and on the pylon insulator chain, these relationships are taken from the reference (Anderson J.G, 1982).

3.5.1 Equivalent Impedance Encountered by the Lightning Current Wave

Z_i is the equivalent impedance encountered by the current wave when it falls on the top of the pylon, it is given by the relation:

$$Z_i =Z_\vartheta \times Z_\gamma / (Z_\vartheta +2Z_\gamma) \tag{7}$$

3.5.2 Pylon Current Wave Propagation Impedance

The propagation impedance of a pylon depends on its geometric shape. It can be calculated by the following relations (Sargent M.A., Darveniza M, 1969):

$$Z_T =30\times ln [2(h 2+r_2)/ r_2] \tag{8}$$

$$Z_T =60\times(ln [(\sqrt{2})\times 2h/r]-1) \tag{9}$$

With *ln* is the logarithm.

Relations (8) and (9) correspond respectively to the cone pylon and in cylinder model (see figure 1 below).

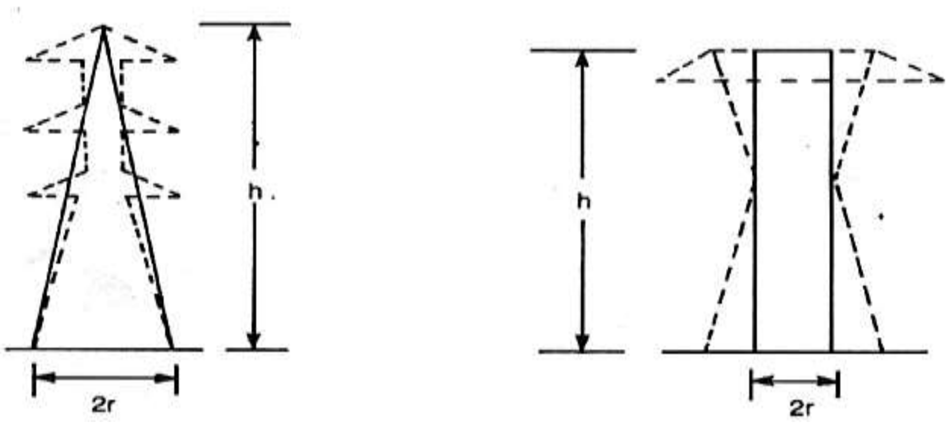

Figure 1. Models for the Calculation of the Propagation Impedance of a Pylon (Sargent M.A., Darveniza M, 1969)

3.5.4 Constant Wave Impedance Over Which all Current Components Operate to Contribute to the Voltage at the Top of the Pylon

$Z_{\aleph}$: This is the constant wave impedance over which all components of the current operation contribute to the voltage at the top of the pylon.

$$Z_{\aleph} = [\, 2(Z_{\vartheta})^2 \times Z_{\gamma} / (Z_{\vartheta} + 2Z_{\gamma})_2 \,] \times [(Z_{\gamma} - R)/(Z_{\gamma} + R)] \tag{10}$$

3.5.5 Current Wave Propagation Impedance of the Keep Wire

The earth wire propagation impedance is given by the following formula:

$$Z_{\vartheta} = 60.\ln (4h_S / d_S) \tag{11}$$

3.6 Electric Model of Pylons Earth Network

At very high frequencies, the grounding behavior is very different from that at power frequencies.

The electrical circuit in Figure 2 below is a representation in pi (π) of the High Voltage pylons earth network (Djamel, I., F.H. Slaoui, and S. Georges, 2018).

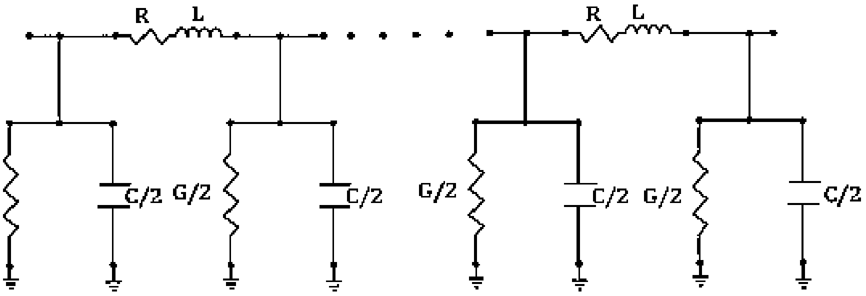

Figure 2. Representation of an earth electrode

The governing formulas for determining the resistance, the inductance of capacitor capacitance, and conductance of an earthing network are :

$$R = (\rho/\pi)\times A \tag{12}$$

$$L = (\mu_0/2\pi)\times A \tag{13}$$

$$C = S\times\varepsilon/\pi \tag{15}$$

$$G = 1/R \tag{16}$$

With:

$$A = [\ln [2l/\sqrt{(2\pi h)} - 1] \tag{17}$$

Where: l: Length of the electrode segment in meter (m); μ_0 Permeability of vacuum 4π $\times 10^{-7}$ kgmA^{-2} S^{-2} , r: Radius of the electrode in meter (m); ρ the resistivity of the ground in Ohm meter (Ω.m); h: Burial depth of the earthing electrode in meter (m) and ε Permittivity in Faraday/meter (F/m).

3.7 FDTD Modeling of Voltage and Current Induced by Electromagnetic Lightning Transients

The diagrams below represent a branch of an electricity pylon which is modeled as a transmission line, we apply Kirchhoff's law for the resolution and the FDTD method (see figure 3 below).

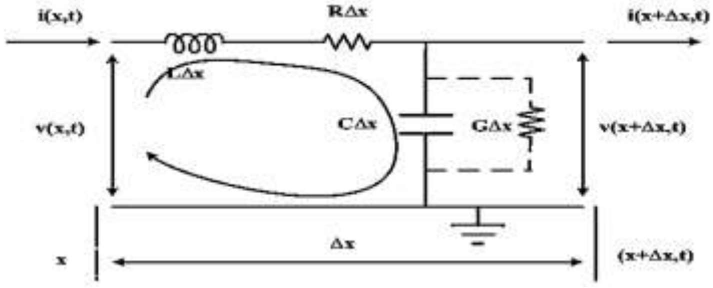

Figure 3. The long arm of the electricity pylon (Ndikwa Tchopkreo, 2019)

We show the following equations:

$$v(x+\Delta x,t)= v(x,t)-R.\Delta x.i(x,t)-L.\Delta x.\partial i(x,t)/\partial x \tag{18}$$

Similarly, we can get the equation for the second transmission line by:

$$i(x+\Delta x,t)= i(x,t)-G.\Delta x.v(x+\Delta x,t)-C.\Delta x.\partial V(x+\Delta x,t)/\partial x \tag{19}$$

By solving equations (17) and (18) by the FDTD method, we obtain the induced currents and the voltages induced by the electromagnetic effects:

$$I_k^{n+1/2} = (\left(\frac{L}{\Delta t}+\frac{R}{2}\right)^{-1}\left(\frac{L}{\Delta t}-\frac{R}{2}\right)I_k^n - \frac{U_{k+1}^n - U_k^n}{\Delta x}) \tag{20}$$

$$U_k^n = (\left(\frac{C}{\Delta t}\right)^{-1}[\left(\frac{C}{\Delta t}\right)U_k^n - \frac{U_{k+1}^{n-1/2} - U_{k-1}^{n-1/2}}{\Delta x}]) \tag{21}$$

3.8 Tension Model at the Top of the Pylon

The voltage at the top of the pylon, taking into account the successive reflections of the wave through the pylon is given by relation (Anderson J.G, 1982):

$$v_\gamma(t) = v_i(t)+ v_2(t) \tag{22}$$

$V_i(t)$ This is the voltage induced by the spatiotemporal distribution of the lightning current wave meeting the equivalent impedance as it falls at the top of the pylon.

$$v_i(t) = Z_i .I(t) \tag{23}$$

Z_i: This is the equivalent impedance encountered by the current wave when it falls on the top of the pylon.

$v_2(t)$: This is the voltage due to the current wave of the lightning reflected through the pylon. It is given by the relation:

$$v_2(t) = -Z_\aleph \sum_{n=1} I(t-2n\tau T)\Psi^{n-1} \tag{24}$$

3.9 Tension at the Foot of the Pylon

The voltage at the foot of the pylon at a time is due to the components below.

- the voltage wave which arrives at the foot of the pylon at time t and which is refracted - voltage waves due to the various reflections at the head of the pylon at times t

-2nτT and which are refracted.

It is then given by the relation:

$$v_2(t) = \alpha_\vartheta . Z_i[I(t) + \sum_{n=1} I(t-2n\tau T)\Psi^n] \tag{25}$$

3.10 Tension on the Insulator String

The voltage at any point of the pylon (at the level of the insulator string) is given by the relation:

$$v_{\psi}(t) = Z_i[\textstyle\sum_{n=0} I(t-2n\tau T-\tau_{\psi})\Psi^{n} - (1/\beta_{\partial})[\textstyle\sum_{m=1} I(t-2m\tau T-\tau_{\psi})\Psi^{n}]] \tag{26}$$

With τ_{ψ} is the propagation time of the wave from the top of the pylon to the insulator string. β_{∂} is the reflection coefficient of the pylon.

3.11 Analysis of the Influence of earth Resistance on line Performance

3.11.1 To Peak Voltage as a Function of the Pylon Earth Impedance, First Arc

To check the influence of earth resistance on line performance, we will consider the lightning current waves, the parameters of which are presented in table 1, for protection levels III-IV (as a reminder, the values peak lightning currents are 100 kA for the first arc and 20 kA for the return arc). This choice is explained by the fact that the peak current values of these waves are close to the values recommended in the literature, after several measurements of real lightning strikes (Standard IEC 62305-01, 2006).

The lightning current causes an extremely rapid change in the electromagnetic field and the waves induce surges in conductors located far from the point of impact; its effects are felt several kilometers away.

A lightning strike falling near a line develops a magnetic induction field large enough to create an induced overvoltage, the order of magnitude of which is expressed by the expression:

$$U_i = Z_0 \times (h/d) \times I_0 \tag{27}$$

$$Z_0 = (0.25/\pi) \times \sqrt{(\mu_0/\xi_0)} \tag{28}$$

With :

Z_0: characteristic impedance of the line in Ohm (Ω).

I_0 : Lightning current which varies from *20 kA* à*100 kA* ;

h : driver height in meters (m) ;

d : distance between the line and the point of impact in m or km.

Hence:

$$U_i = (0.25/\pi) \times \sqrt{(\mu_0/\xi_0)} \times (h/d) \times I_0 \tag{29}$$

Consider, as an indication, a three-phase *220* kilovolts (*kV*) power transmission line whose insulators have a shock wave withstand of 450 kilovolts (*kV*). It is assumed that the resistance of the earth electrodes is *25* Ohm (Ω). In a normal situation, no current circulates in the earth electrode and the voltage between a phase and the earth is *127.2* kilovolts (*kV*). Suppose lightning strikes one of the pylons releasing a current of 20-kilo Amps (kA) according to the figure below. This current flows through the earth electrode resistor and causes a voltage drop in it which is equal to:

$$v = I_0 \times R \tag{30}$$

Between the phase and the ground, a transient overvoltage is: of the order of:

$$v = v_{Pn} + I_0 \times R \tag{31}$$

4. Simulation

4.1 Results

Considering the pylon earthing resistance at 10 Ohm [Ω]. The *220* kiloVolts (kV) LIMINGA-FUNA HV line in DR Congo / KINSHASA (See figure 4 below) is the main energy supply corridor for the city of Kinshasa in the eastern, central and northern parts. She is currently experiencing several triggers mainly due to:

- frequent overloads because it is at the limit of its transit capacity: indeed, it does not reach its thermal limit but trips because of the voltage drop;
- lightning discharges: it is quite rare that a thunderstorm that occurs in one of the areas crossed by this line cannot trigger a trigger.

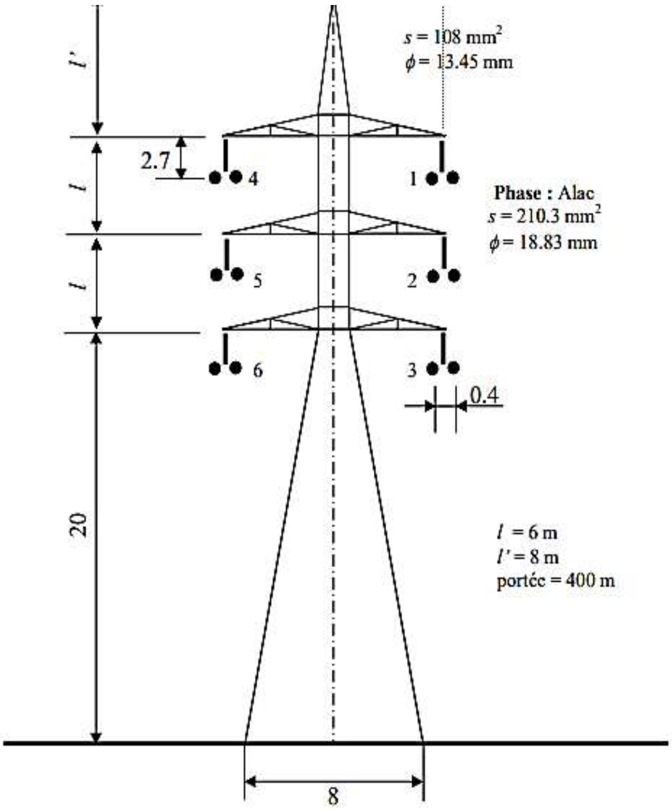

Figure 4. Geometric characteristics of the 220 kV line

By applying relations (8) and (9) to the line of figure 4, we obtain the wave impedances of the pylon and the ground wire respectively 159 Ohm (Ω) and 563 Ohm (Ω).

We simulate:

- The induced voltage $v_i(t)$ is the voltage induced by the spatiotemporal distribution of the lightning current wave meeting the equivalent impedance when it falls at the top of the pylon.
- the voltage $v_2(t)$ due to the current wave of the lightning reflected through the pylon.
- The tension at the top of the pylon.
- Influence of the earthing resistance on these two parameters.

With: $i(t)=I_0[exp(-At)-exp(-Bt)]$ which is the lightning current along the pylon. In the case of a direct impact with the following characteristics: $I_0=100kA$, $A=0.003$ S^{-1}, and $B=10^5$ S^{-1} , from the equation of the voltage due to the wave of the lightning current reflected through the pylon and that of the transient overvoltage between the phase and the ground, we obtained the following simulation results.

The results obtained by simulation are presented in figures 5, 6, 7, 8, and 9. To validate our models, we compared these results obtained by simulation with the literature (Grcev L., 2004) and (JP NZURU NSEKERE., 2009) presented respectively in figures 10 and 11.

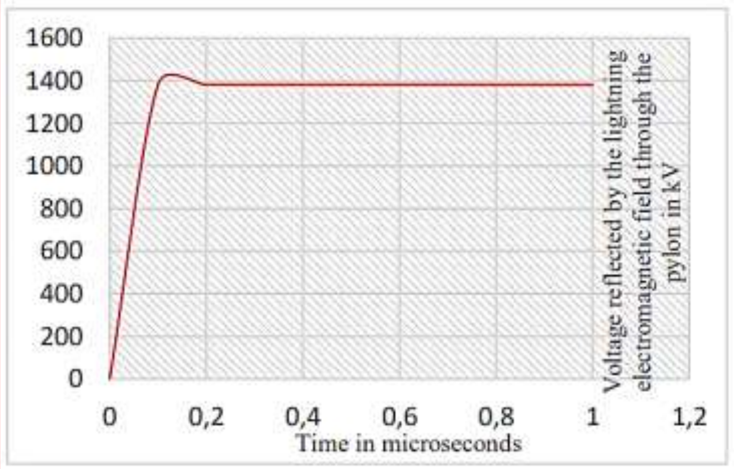

Figure 5. Voltage reflected by the Electromagnetic Field of Lightning Through the Pylon in kV With *R* = 10 Ohm (Ω) Pylon Resistance

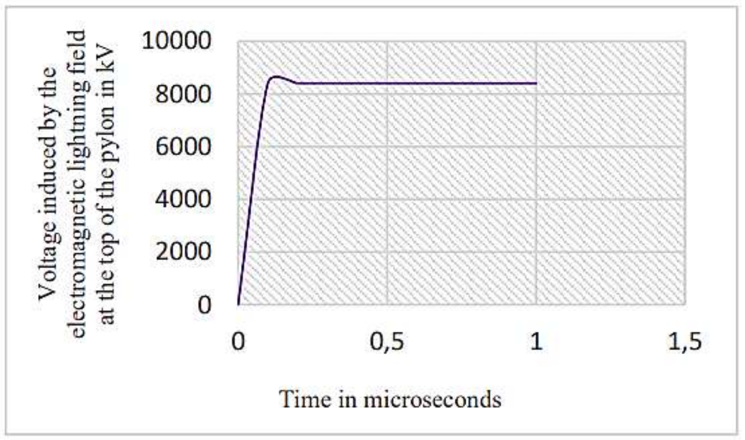

Figure 6. Voltage Induced by the Electromagnetic Lightning Field at the Top of the Pylon in kV with *R* = 10 Ohm (Ω) Pylon Resistance

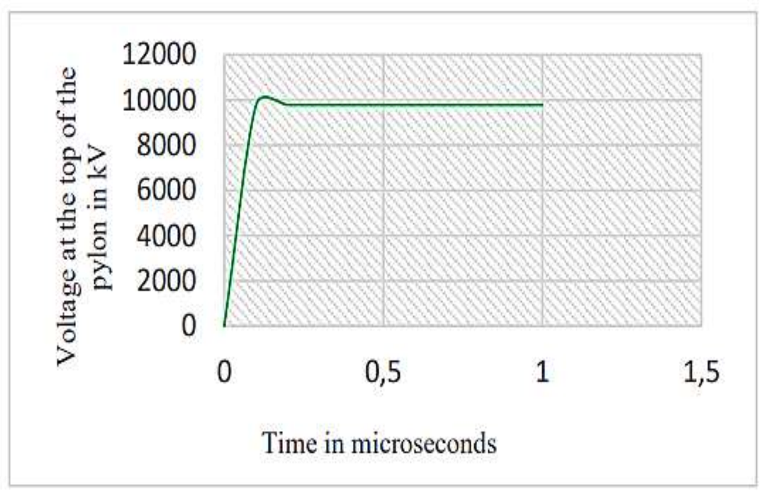

Figure 7. The Voltage at the Top of the Pylon in kV with *R* = 10 Ohm (Ω) Pylon Resistance

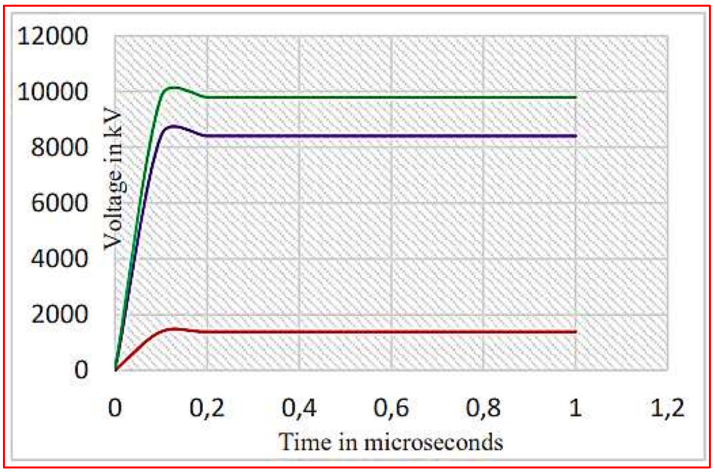

Figure 8. Superposition curves

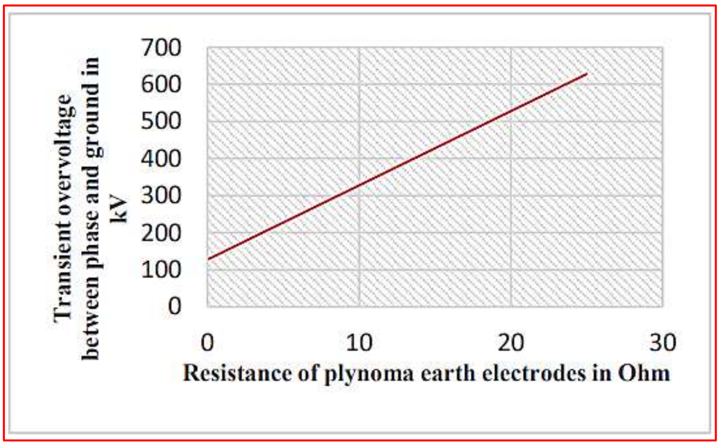

Figure 9. Peak Voltages as a Function of the Pylon Earth Impedance, Consecutive Short Stroke

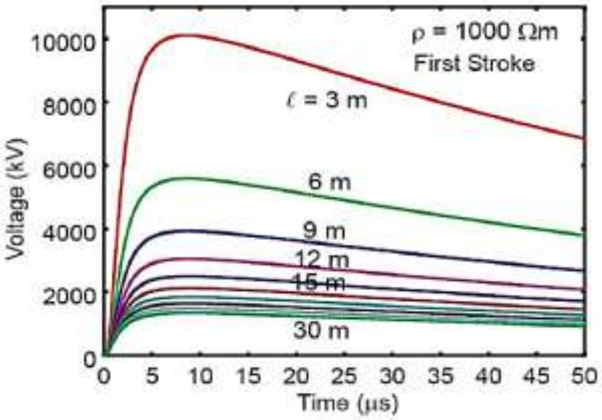

Figure 10. Voltage at the injection point of a lightning wave on a vertical cylindrical electrode, first arc (Grcev L, 2004)

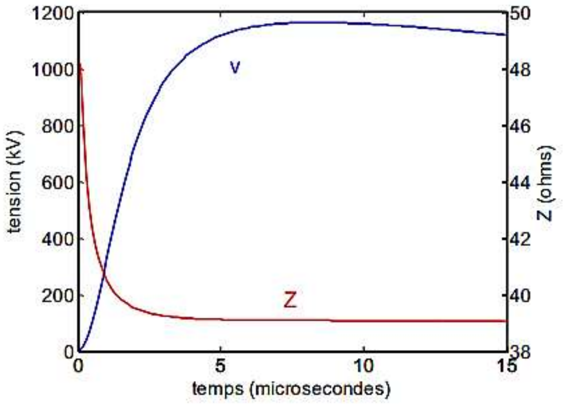

Figure 11. Transient behavior of a vertical cylindrical electrode facing the wave of lightning, first arc (left) and return arc (right), homogeneous ground (JP NZURU NSEKERE, 2009)

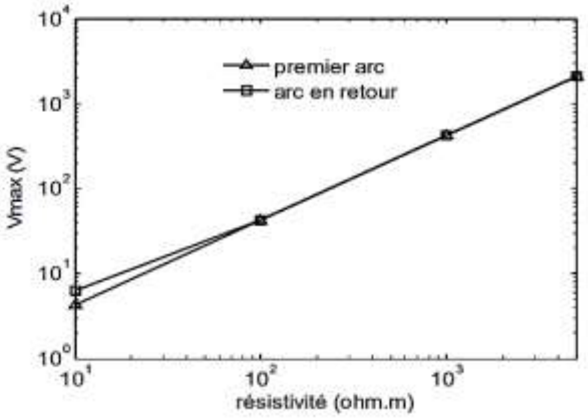

Figure 11. Peak voltages as a function of the earth impedance of the pylon, consecutive short blow.), ground in 4 layers of different resistivities (JP NZURU NSEKERE., 2009)

5. Discussion

In the case of a lightning strike at the top of a pylon, the results presented in figures 5, 6, and 7 show that the risk of flashover of the insulator of a line depends mainly 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, position of the phase.

This shows that the return arc is more constraining and contributes to the risk of short-circuiting the insulators because this overvoltage reaches critical values in this case 10000 kilovolts (kV). The reflection of the lightning wave generates an overvoltage with a maximum amplitude of 1400 kilovolts (kV), which can also disrupt the operation of the electrical energy network. These results can be compared with those of figures 10 and 11 obtained experimentally in the work of (Grcev L, 2004) and (JP NZURU NSEKERE., 2009).

Figure 9 shows the contribution of the earth resistance on the damping of the transient overvoltage induced by the electromagnetic field of lightning of 20 kilo Amperes kA in the conductors located far from the point of impact. For the first arc of the lightning wave, the peak voltages vary almost linearly with the earth impedance of the pylon. This result is close to the experiments proposed by (JP NZURU NSEKERE., 2009) see figure 11.

With regard to the results of the calculations, for the line being the subject of our study, the value of 10 Ω for the impedance of the pylon is a reasonable limit for the risk of flashover of the insulator in the event of a lightning strike at the top of the pylon for the first arch. But for the return arc taken in this case, the bypass of the insulator is unavoidable. In addition, to avoid the propagation of high voltages towards the substations, it is imperative to reduce the earthing resistances of the pylons as much as possible up to 2 km from the substation. The use of surge arresters, with low grounding resistances, is also imperative.

In this type of research field and because of the complexity of the phenomenon of lightning and the effects that accompany it, the situation is still fertile and requires more work for more reassuring protection of electrical, electronic, and energy systems. Our efforts always remain motivated to arrive at the complete and general development of the new formulations of the electromagnetic fields which translate the reality of the physical phenomenon.

The ideal would be to be able to deal with these induced phenomena by taking into account the stratification of the ground, as well as the presence of an object raised by contribution to the ground which can attract lightning near a line, which can generate very high amplitude overvoltages.

This last observation can be the subject of perspectives of our work.

6. Conclusion

The concept of earthing involves several areas of research. The operation of electrical installations depends closely on the earthing method of certain devices and the values of the parameters. Because of the simulation results, for a 220 kilovolts alternating (kV AC) line, located in a region where thunderstorm activity is very important, the value of 10 Ohm for the pylon impedance is a reasonable limit for the risk of skirting/bypass of the insulator in the event of a lightning strike at the top of the pylon for the first arc (25kA). But for the return arc (100 kA) taken, in this case, the skirting /bypass of the insulator is inevitable. The risk of bypassing the insulation of a phase depends essentially on the earth impedance of the pylon, the characteristics of the lightning current wave, and the geometric characteristics of the pylon and the line. It turns out that the return arc is more restrictive and contributes to the risk of bypassing the insulators which reach an overvoltage of critical values of 10,000 kV and the reflection of the lightning wave generates an overvoltage with maximum amplitude of 1400 kV capable of disrupting the electrical energy network.

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