International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-3, Issue-11, November 2016

# The impacts of direct lightning bolt on the Ngo-Brazzaville line in Congo

**Rodolphe GOMBA, Alphonse OMBOUA**

*Abstract*— **The importance of line Ngo-Brazzaville (220 kV, 207 km) requires operators to avoid cuts that can increase the risk of instability. We see it is quite rare that a storm that occurs in areas crossed by this line will not cause triggering. We note that lightning discharges constitute the main causes of unscheduled power cuts on the electricity lines of Congo; however, we ignore the peak values of voltage waves that result. In regions with high level keraunic like Congo, reducing insulation failures due to lightning is a concern in the management of overhead lines. This article clarifies the peak values of surges that can be reached on the electricity network, in order to enlighten the operators as for precautions to observe about the insulation coordination of protective equipment related to lightning.**

**For these surge's calculations of atmospheric origin (case of lightning), we considered the Heidler function for modeling the wave of the lightning current. This methodology led us to specially treat the effects of direct lightning bolt that constitute the worst case because they generate most destructive shock wave that indirect thunderbolt.**

*Index Terms*— **Congo, Impacts, lightning bolt, line, Surge.**

## I. INTRODUCTION

Surges generated by lightning on power lines are among the concerns of operators, because of the disastrous effects they cause on the stability of power grids and destruction of protective equipment that are accompanied. Several cases are possible: lightning bolt on the phase conductors; on the guard cable (in full scope or the top of the pylon); on the floor near an overhead line, etc.

In the heart of Central Africa, Congo straddles the equator; it rains a lot and keraunic level is very high up to more than 100 lightning bolts per year.

It is therefore easy to understand why the power lines of the Congo are often the seat of atmospheric surges (lightning). This article deals with surges due to direct lightning bolt on a power line of Congo, by presenting a calculation approach based on modeling of the wave of the lightning current.

## II. THE LINE AND ITS PROBLEMS

Storms that occur in areas crossed by that line often generate surges in the electrical network. Given the severity of the resulting of surges due to lightning bolt and to protect the network from adverse effects both in the transformer station as subscribers, the city of Brazzaville is often without electricity during heavy rains. For being in safe from power surges, the National Society of Electricity (SNE) prefers meanwhile, stopping the supply of electric power. The configuration of this line is the next:

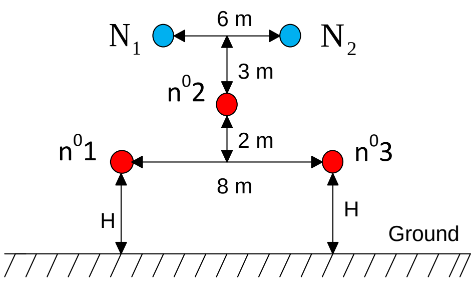


Figure 1: Configuring of Ngo –Brazzaville line

$n^0 1$, $n^0 2$ and $n^0 3$ are the phase conductors, $N_1$ is the first guard cable and $N_2$ is the second guard cable that incorporates optical fiber. The $n^0 1$ and $n^0 3$ phases are located fourteen (14) meters from the ground; other dimensions are shown in the figure above (Figure 1).

## III. MODELLING OF THE CURRENT WAVE OF LIGHTNING

From the physical point of view, the phenomenon of lightning is complex; research and references to this subject are numerous. The over the years, several analytical models have been developed to represent the wave of the lightning current. So, the analytical model that we use in this article is the function of Heidler.

The figure below provides an illustration of the wave of standardized lightning 1,2/50 $\mu s$ .

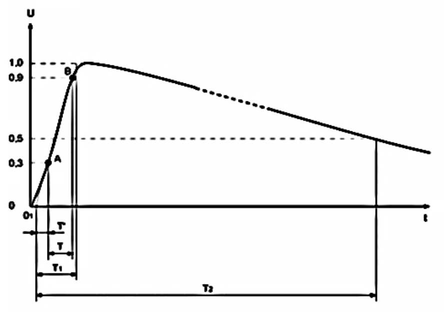


Figure 2: Example of the wave of standardized lightning (1,2/50 $\mu s$ ) by IEC 60 with $T_1 = 1{,}2\ \mu s$ and $T_2 = 50\ \mu s$

The usually adopted analytical model is proposed by Heidler, frequently known as <<function of Heidler>>, where the wave of lightning is represented by the current of base channel by the following expression [1]:

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$$i(t) = \frac{I_0}{\eta} \frac{(t/\tau_1)^n}{1+(t/\tau_1)^n} \exp\left(-\frac{t}{\tau_2}\right) \quad (1)$$

$$\eta = \exp\left[-\left(\frac{\tau_1}{\tau_2}\right)\left(n\frac{\tau_2}{\tau_1}\right)\right]^{\frac{1}{n}}$$

$\eta$ : the correction factor of the amplitude of wave;

$I_0$ : the current amplitude of the base channel;

$\tau_1$ : the constant of rise time;

$\tau_2$ : constant of fall time;

$n$ : an exponent varying between 2 and 10.

The figure below shows the curve of the wave current of the lightning to result from parameters of the following table:

Table 1: The parameters of the current of lightning for $I_0$= 100kA [2].

| $\tau_1(\mu s)$ | $\tau_2(\mu s)$ | $n$ | $\eta$ |
|---|---|---|---|
| 19 | 485 | 10 | 0.93 |

The corresponding curve is the next:

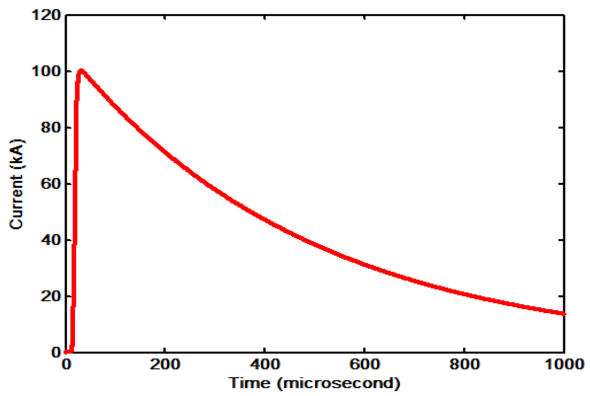


Figure 3: Wave current of lightning according to the function of Heidler.

After several measures of real lightning bolt [3], recommended values in literature and documentations are estimated of 100 kA. The Peak values of lightning currents in the Congolese tropics can reach value of 100 kA and lowest turn the order of 3 to 4 kA.

## IV. CHARACTERISTIC IMPEDANCE OF THE LINE

Electricity lines are systems with distributed constants, that is to say that the physical quantities (R, L, C) are distributed over all the length of the line and are thus not localized. And a length L of line can be considered as the sum of elements of length (dx) distributed along the latter.

An elements of length (dx) is characterized by a resistor (rdx), an inductance (ldx), a capacity (cdx) and conductance (gdx).

r, l: the resistance and inductance longitudinal per unit length;

c, g: the capacity and conductance transverse per unit length;

For this Ngo-Brazzaville line, model easy to use is the one in pi. Indeed, the pi model allow to model lines of length lower than or equal to 240 km. Here is, the diagram of a high voltage line:

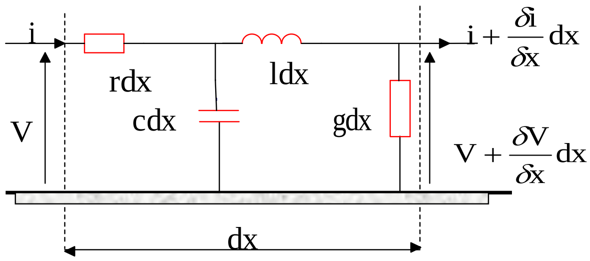


Figure 4: Diagram of a high voltage line

According to the laws of KIRCHOFF:

$$\begin{cases} v(x) - v(x+dx) = v_r + v_l \\ i(x) - i(x+dx) = i_c + i_g \end{cases}$$

$$\begin{cases} -\frac{\delta v}{\delta x}.dx = v_r + v_l \\ -\frac{\delta i}{\delta x} dx = i_c + i_g \end{cases} \quad (2)$$

As $i$ and $v$ are sinusoidal we have:

$$v_r = ri.dx \;;\; v = (jl\omega).idx \;;\; v = \left(\frac{1}{g.dx}\right).i_g$$

$$i_g = v.g.dx \;;\; i_c = v.(jc\omega).dx$$

By replacing the voltages and currents above in the relation (2) we obtain the following:

$$\begin{cases} \frac{dv(x)}{dx} = -Z_l.i(x) \\ \frac{di(x)}{dx} = -Y_t.v(x) \end{cases} \quad (3)$$

With $Z_l = r + jl\omega$ (longitudinal impedance)

$Y_t = g + jc\omega$ (Transverse admittance)

Differentiating members of both equations of System (3) above, we obtain:

$$\begin{cases} \frac{d^2v(x)}{dx^2} = Z_l.Y_t.v(x) \\ \frac{d^2i(x)}{dx^2} = Y_t.Z_l.i(x) \end{cases}$$

We suppose that: $\gamma_\omega^2 = Z_l.Y_t$ and therefore:

$$\gamma_\omega = \sqrt{(r + jl\omega)(g + jc\omega)}$$

$\gamma_\omega$ is the propagation constant of the wave on the line. We find the following equations:

$$\begin{cases} \dfrac{d^2v(x)}{dx^2} = \gamma_\omega^2 v(x) \\ \quad et \\ \dfrac{d^2i(x)}{dx^2} = \gamma_\omega^2 i(x) \end{cases} \tag{4}$$

Considering $Z_0$ as impedance characteristic of the high-voltage line:

On the one hand, we have:

$$Z_0 = \frac{v(x)}{i(x)} \tag{5}$$

On the other hand, deriving v(x) in relation to x we obtain:

$$Z_0 = \frac{dv(x)}{di(x)} \tag{6}$$

By dividing the two equations of the relations (12), we find:

$$\frac{dv(x)}{di(x)} = \frac{z_l}{Y_t}\frac{i(x)}{v(x)} \tag{7}$$

Relating the relations (5) and (6) in (7), we find:

$$Z_0 = \sqrt{\frac{r + jl\omega}{g + jc\omega}} \tag{8}$$

$$Z_0 = \left(\frac{r^2 + (l\omega)^2}{g^2 + (c\omega)^2}\right)^{\frac{1}{4}} \exp\left(j\frac{\theta}{2}\right) \tag{9}$$

The complex impedance of the module is:

$$|Z_0| = \left(\frac{r^2 + (l\omega)^2}{g^2 + (c\omega)^2}\right)^{\frac{1}{4}} = \sqrt{\frac{l}{c}}\left[\frac{1 + \left(\frac{r}{l\omega}\right)^2}{1 + \left(\frac{g}{c\omega}\right)^2}\right]^{\frac{1}{4}}$$

$$\left(\frac{r}{l\omega}\right)^2 \approx 0 \quad \text{et} \quad \left(\frac{g}{c\omega}\right)^2 \approx 0$$

r and g are negligible, the parameters inductive and capacitive become so preponderant, the characteristic impedance is:

$$Z_0 \approx \sqrt{\frac{l}{c}} \tag{10}$$

The characteristics of the Ngo –Brazzaville line:

Length: 207 km;

Linear capacitance: $C = 9{,}033\,nF/km$;

Resistance per unit length: $r = 0{,}057\,\Omega/km$;

Linear Reactance: $x = l\omega = 0{,}404\,\Omega/km$.

We then find the characteristic impedance $Z_0 = 377{,}41\,\Omega$

## V. CALCULATION OF SURGES GENERATED BY BOLT OF DIRECT LIGHNING

A bolt of direct lightning is one that touches directly, at least one of the active conductors. In most cases, the bolts of direct lightning are the most severe on electrical equipment. Indeed, the surges from them can reach thousands volts with strong currents on the lines.

In this type of striking down, there are three cases: the lightning strikes a single conductor, two conductors simultaneously or three conductors of phase simultaneously. Network designers have planned an insulation coordination to surges of lightning 1050 kV between line and pylon, it's the highest level planned by the standards of a network to 220 kV.

### 1.1 Bolt of direct lightning on one conductor of phase

When lightning strikes a single conductor of phase, for example, the n$^0$1 conductor, there is a current wave which is injected on this conductor. This current wave which propagate at either side of the point of impact is the half wave of the lightning current is fell on the conductor.

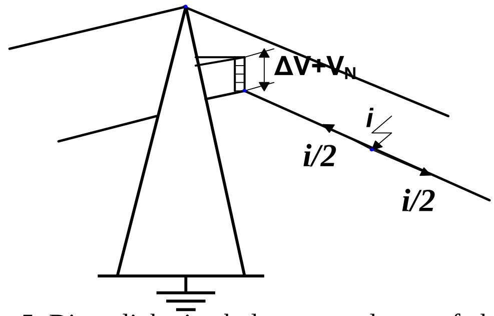


Figure 5: Direct lightning bolt on a conductor of phase

The current wave $\frac{i(t)}{2}$ causes overvoltage on the n$^0$1 conductor $\Delta V_1(t)$ given by the classic formula [4], [5]:

$$\Delta V_1(t) = Z_0 \frac{i(t)}{2}$$

With $Z_0$ the characteristic impedance of the line. The surge on conductor n$^0$1 Struck down is:

$$\Delta V_1 = Z_0 \frac{I_0}{2\eta} \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} \exp\left(-\frac{t}{\tau_2}\right) \tag{11}$$

The corresponding curve is the next:

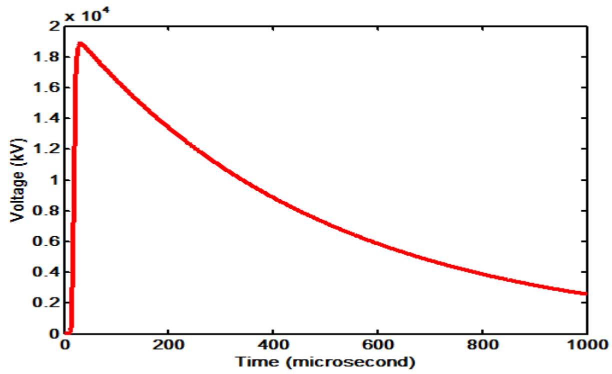


Figure 6: Curve of surge on the n$^0$1 conductor struck down.

The maximum surge on the n$^0$1 conductor in relation to the modeling of lightning wave with the function of Heidler is:

$$\Delta V_1 = 18\,893\,kV$$

The surge wave is similar to that of the lightning current, however it may be changed after the propagation, corona or by reflections at the extremity.

At a given point of the line, for example the first pylon encountered by the wave, the voltage may possibly grow until the occurrence of the initiation of the insulator chain (circumvention of the insulator), if the following condition is true: $\Delta V_1 + V_N \geq V_{CR}$

$V_N$ is the peak voltage between the phase and the fitting of the pylon of the line at the natural frequency, $V_{CR}$ is the critical starting voltage of the insulator chain.

The surge above is that due to the fall of lightning on one conductor of the line (it was considered such as the $n^0 1$ conductor). At the same time, the current $\frac{i(t)}{2}$ injected into the $n^0 1$ conductor will generate surges induced on the other two $n^0 2$ and $n^0 3$ conductors as represented here.

### 1.2. Surges induced on the $n^0 2$ and $n^0 3$ conductors

Considering that the conductors are great lengths to their diameter, we have:

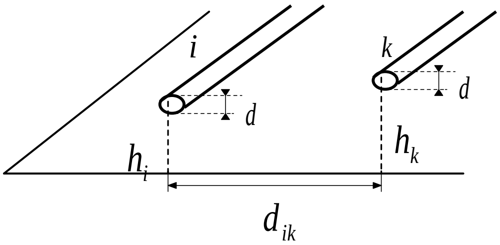


Figure 7: Arrangement of two conductors

The mutual inductance between the two conductors $i$ and $k$ of the line and in the presence of soil is the real part $m_{ij}$ of the complex inductor $\underline{L}_{ik}$ [6].

$$\underline{L}_{ik} = \frac{\mu_0}{4\pi} \ln\left[\frac{(h_i + h_k + 2\underline{\delta})^2 + d_{ik}^2}{(h_i - h_k)^2 + d_{ik}^2}\right] \qquad (12)$$

$d_{ik}$ : Horizontal distance of the two conductors (distance between their projections on the ground);

$h_i$ : Average height of the conductor $i$ above the ground;

$h_k$ : Average height of the conductor $k$ above the ground;

$\underline{\delta}$ : Penetration depth of the current wave in the ground [6], [7] and [8];

$$\underline{\delta} = \frac{1}{\sqrt{j\mu_0 \sigma \omega}}$$

$\mu_0$ (H/m) : Permeability of vacuum;

$\sigma$ (S/m) : Soil electrical conductivity.

The mutual inductance per unit length $m_{ik}$ will be written:

$$m_{ik} = \frac{\mu_0}{4\pi} \frac{\sqrt{\alpha_{ik}^2 + \beta_{ik}^2}}{(h_i - h_k)^2 + d_{ik}^2} \qquad (13)$$

$$\alpha_{ik} = (h_i + h_k)^2 + \sqrt{8}(h_i + h_k)|\underline{\delta}| + d_{ik}^2$$

$$\beta_{ik} = 4|\underline{\delta}|^2 + \sqrt{8}(h_i + h_k)|\underline{\delta}| \ ; \qquad |\underline{\delta}| = \frac{1}{\sqrt{\mu_0 \sigma \omega}}$$

**Penetration depth** $\delta = |\underline{\delta}|$

In the case of Ngo and Brazzaville measuring the resistivity of the soil revealed values close to 1000 Ω.m, far beyond the traditional results of 200 Ω.m. Thus for a frequency of 50 Hz, the depth of current penetration into the ground takes the following value:

$$\delta = 1592{,}4 \ m .$$

The coefficients $m_{ik}$ have the values:

$m_{12}$=0, 0514 H/m; $m_{13}$=0, 0160 H/m

$h_1$=$h_3$=14 m; $h_2$=16 m; $d_{12}$=4 m; $d_{13}$=8 m;

$\alpha_{12}$=1, 3604. $10^5$ $m^2$; $\beta_{12}$=1, 0278 .$10^7$ $m^2$

$\alpha_{13}$=1, 2696. $10^5$ $m^2$; $\beta_{13}$=1, 0269 .$10^7$ $m^2$

$\mu_0$=4π.$10^{-7}$; δ=1592, 4 m

Literature information that beyond a distance of L=1500 meters of the impact point of lightning on the line, lightning surge is virtually no danger because of the priming possible, spark gaps, and made the ground at the pylons.

$$M_{ik} = m_{ik} \times L \qquad (14)$$

That is: $M_{12}$=77,1 Henry and $M_{12}$=24 Henry

The induced flux through the $n^0 2$ and $n^0 3$ conductors are:

$$\phi_2 = M_{12}.\frac{i(t)}{2} \text{ and } \phi_3 = M_{13}.\frac{i(t)}{2}$$

The surges $\Delta V_2$ and $\Delta V_3$ corresponding, in absolute value are:

$$\begin{cases} \Delta V_2 = \left| -\dfrac{d\phi_2}{dt} \right| = \dfrac{1}{2} M_{12} \dfrac{di(t)}{dt} \\ \\ \Delta V_3 = \left| -\dfrac{d\phi_3}{dt} \right| = \dfrac{1}{2} M_{13} \dfrac{di(t)}{dt} \end{cases} \qquad (15)$$

By the method of the logarithmic derivative in relation to time on the basis of Heidler function, we obtains:

$$\frac{di(t)}{dt} = \left[ \frac{n}{t} \frac{1}{1+(t/\tau_1)^n} - \frac{1}{\tau_2} \right] i(t) \qquad (16)$$

Substituting (16) into the equation (15), we find:

$$\Delta V_k = \frac{M_{ik}}{2} \left[ \frac{n}{t} \frac{1}{1+(t/\tau_1)^n} - \frac{1}{\tau_2} \right] i(t) \qquad (17)$$

with k=2 and k=3

The corresponding curve of the induced surges is the next:

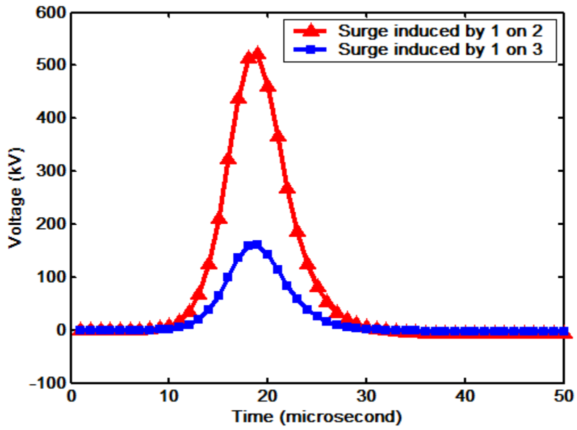


Figure 8: Curve of induced surges on the $n^0 2$ and $n^0 3$ conductors according to the function of Heidler

The following table gives the values of lightning surges on the three conductors of the Ngo-Brazzaville line.

Table 2: Surge in first case

| Lightning bolt on one phase conductor for example $n^0 1$ conductor | | |
|---|---|---|
| Conductors | Maximum Voltage Conductor | |
| | Notation | Value kV |
| | | Function of Heidler |
| $n^0 1$ | $\Delta V_1$ | 18 893 |
| $n^0 2$ | $\Delta V_2$ | 520,3531 |
| $n^0 3$ | $\Delta V_3$ | 161,99776 |

### 1.3. Direct lightning bolt on two phases conductors simultaneously

When lightning of the intensity $i(t)$ falls simultaneously on two phases conductors (Example the $n^0 1$conductor and the $n^0 2$ conductor), the intensity of lightning splits in half on both active conductors. The respective surges on each of the two conductors are:

$$\Delta V_1 = \Delta V_2 = Z_0 \frac{i}{4}$$

The corresponding curve is:

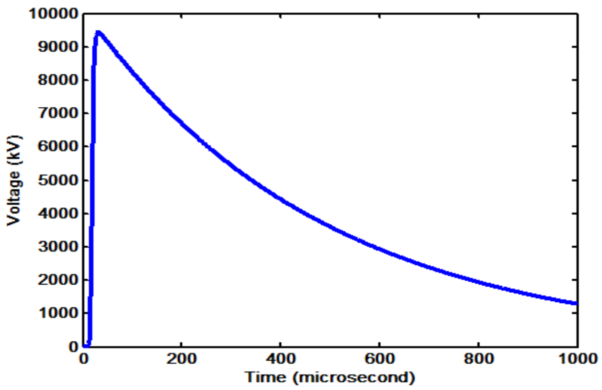


Figure 9: Curve of the surge on the $n^0 1$ and $n^0 2$ conductors according to the function of Heidler

The surge on the $n^0 3$ conductor is the sum $\Delta V_3$ of the surges $\Delta V_{13}$ and $\Delta V_{23}$ induced by $n^0 1$ and $n^0 2$ conductors respectively on $n^0 3$ conductor:

$$\Delta V_3 = \Delta V_{13} + \Delta V_{23}$$

Referring to relations (17), is deduced $\Delta V_{13}$ and $\Delta V_{23}$ so that:

$$\Delta V_{k3} = \frac{M_{23} I_0}{4\eta}\left[\frac{n}{t}\frac{1}{1+(t/\tau_1)^n} - \frac{1}{\tau_2}\right]\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n}\exp(-\frac{t}{\tau_2})$$

With k=1 and k=2.
We obtain the next curves:

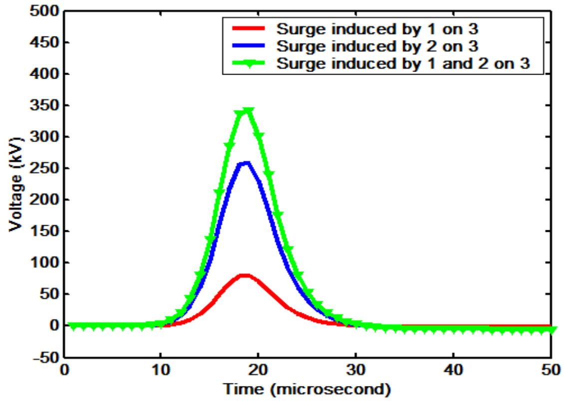


Figure 10: Curves of surges induced simultaneously by $n^0 1$ and $n^0 2$ conductors according to the function of Heidler.

The maximum values of surges is in the following table:

Table 3: Surge in second case

| Lightning bolt on two phase conductors for example the $n^0 1$ and $n^0 2$ conductors | | |
|---|---|---|
| Conductors | Maximum Voltage Conductor | |
| | Notation | Value kV |
| | | Function of Heidler |
| $n^0 1$ | $\Delta V_1$ | 9446,6 |
| $n^0 2$ | $\Delta V_2$ | 9446,6 |
| $n^0 3$ | $\Delta V_3$ | 341,16 |

### 1.4. Direct lightning bolt on three phases conductors simultaneously

When lightning strikes the three conductors, the intensity of lightning split into three on three active conductors, the surge on each conductor is:

$$\Delta V = \Delta V_1 = \Delta V_2 = \Delta V_3 = Z_0 \frac{i}{6}$$

The corresponding curve of Surge is:

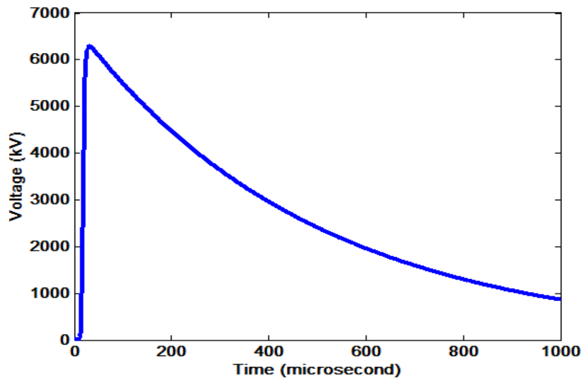


Figure 11: Curves surges simultaneously on the three phase conductors according to Heidler function

The maximum values of surges is in the following table:

Table 4: Surge in the third case

| Lightning bolt simultaneously on the three phase conductors ($n^0 1$, $n^0 2$ et $n^0 3$) | | |
|---|---|---|
| Conductors | Maximum Voltage Conductor | |
| | Notation | Value kV |
| | | Function of Heidler |
| $n^0 1$ | $\Delta V_1$ | 6297,7 |
| $n^0 2$ | $\Delta V_2$ | 6297,7 |
| $n^0 3$ | $\Delta V_3$ | 6297,7 |

## VI. STUDY ANALYSIS

It is possible to reduce the number of release of the electricity lines and insulation breaks due to lightning by adequate installation of guard cables and the appropriate earthing at the pylons. These earthing should be checked regularly. Indeed, the literature information that beyond 1, 5 kilometers from the point of impact of lightning on the line, lightning surge is virtually no danger. It is desirable that excessive surge can not propagate to the electrical post. In this case, the use of lightning rod at the entrance of the electrical post, with earthing of low impedance is capital. It is important to realize earthings of low impedance for all the pylons located about 2 km from the posts.

Generally, when there is priming at the insulator chain (at the spark gaps), after a given time, the switching devices are set to automatically reset. In tropical regions (case of Congo), this reclosing often causes a further opening of the fact that the ionization of the air. The reclosing time must, therefore, be more important to hope that the complete deionization of the air occurred. It is best to use long insulators for having, the longer leakage paths. In the area of Brazzaville where the risk of lightning is huge, the maintenance of insulators becomes imperative. It is recommended that periodical washing with distilled water.

## VII. RESULTS

In all cases enumerated here, we may end up with surges reaching 18 850 kV, extremely value above 1050 kV the highest level of phase-pylon surge provided by the requirements for a network to 220 kV.

The situation is more catastrophic when lightning strikes a single phase conductor if it struck simultaneously two or three conductors.

Electricity of France provides for a 225 kV line, the priming voltage between phase and pylon about 1000 kV and the critical current around 5 kA [9].Here, to put the network safe from power surges related to lightning, the obvious and safest solution is to realize during storms, the power cut from the power station. By prioritizing the requirements of the continuity of service, we have to rely on the appropriate earthing at the pylons.

## VIII. CONCLUSION

This study reveal that 18 893 kV is the value of surge, can be attained in a phase during a lightning bolt on the Ngo-Brazzaville line. To limit the damage, it is essential to realize earthing with very low resistances $R_T < 1\ \Omega$ on pylons and equip the pylons of the insulators with several chains by phase, in order to drain very high currents during a priming or circumvention by the arcing.

In the area of Brazzaville, where the risk of lightning is huge, maintenance of insulators becomes imperative. Their periodic washing with distilled water is recommended.

This article reveals the gravity of the situation of lightning bolts on the electric network in the Congo with the values of the surges could exceed the limits of the standards.

It is up to the designers of the networks and the manufacturers of electrical equipments, to study provisions that can adapt to such situations for the uninterruptible power supply, even during storms and lightning bolts of such extent. In order to protect the network, the importance of surges due to lightning strikes still leaves avail the solution of the general power cut during major storms.

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