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Lightning Radiations Towards the H.V Electric Power Systems

DIB Djalel[α] & LABAR Hocine[σ]

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The induced transient over-voltages in the electric systems following electromagnetic radiations of the lightning represent the most severe constraint and most significant on the electrical power networks.

In this paper we present an lightning analysis in the capacity as a transient source of surge current following model MTLE chosen among others, then an original contribution which defines an analytical model of the electromagnetic field radiated by the lightning for a particular situation and which gave satisfactory results by simulation compared with experimental measurements that we carried out us even at the laboratory of high voltage in EPFL in Switzerland and also of the other authors like G Berger, M.Uman and Rakov in Florid.

A computation of the induced overvoltages in overhead electric lines on the basis of electromagnetic coupling model of Taylor interpreted the limit of our work in this paper

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I. Introduction

The lightning can touch a power line by striking either a conductor or a tower or an earth wire, causing the important overvoltage's classified like the most dangerous constraints for the electric systems.

The direct and indirect impact of the lightning on the overhead line is illustrated by the bidirectional propagation of overvoltage wave of several hundred kV, it's the most harmful constraint in the coordination of insulations. The physical phenomenon of the lightning corresponds to an impulse power source, namely a very fast succession of discharges of an enormous electricity quantity. The form of real wave is very variable: it consists of a rise face until the maximum magnitude (1 μs to 20 μs) follow-up of a decrease tail of a few tens of microseconds. The spectral field associated extends in a band with KHz to MHz.

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The principal objective in this work is to be interested in the coupling electromagnetic phenomenon between the field radiated by the lightning and the overhead line, while passing by the analysis of the various parts which enters in this state, the source of disturbances, the coupling devices and the victim.

In a first part, we are interest to the return stroke current as a source of disturbance and its space-temporal distribution along the lightning channel. A presentation of the existing models in the literature on this current i(z', t).

Before analysing the coupling phenomenon, we tried to give an interesting detail on the evaluation of the electromagnetic field radiated by the lightning while basing on 03 assumptions:

1. The model of calculation of Uman [5] with three components of the field: Electric vertical, electric horizontal and magnetic azimuth.
2. Experimental measurements which we carried out at the laboratory of high voltage LRE-EPFL (Switzerland) on the electromagnetic fields radiated by the lightning pulses during the last trimester 2005.
3. Data experimental collected and offered by one of the leaders in this field professor Rachidi of LRE-EPFL in Switzerland

The model of Taylor is selected to analyze in term of this paper the transient electromagnetic coupling of the lightning with the overhead line. A new analytical formulation for the electromagnetic fields computation was developed in the temporal field and for not very particular conditions then integrated in a data-processing routine where the results were satisfactory.

II. Modelling Of The Lightning Return Stroke

For a excellent protection of the electric systems against the disturbances generated by the lightning, it is necessary to know and characterize its impulse electromagnetic field. This is why in the last few years, several models of the return stroke, with various degrees of complexity, were developed [1,3,5,8] in order to allow the evaluation of electromagnetic radiation. One of the major difficulties related to the modelling of the lightning channel resides in the fact that the current cannot be measured that at the base of the channel; however, to determine the radiated electric and magnetic fields, it is necessary to know the current distribution along the channel, a significant property which makes the difference between the models proposed on the space and temporal distribution of the current along the lightning channel i(z', t).

We present a summary of the existing models in table I and we adopt thereafter model MTLE (Modified transmission line) also named: model of the engineers modified, proposed by Nucci and Rachidi [4] and approved by results convincing by several authors in various works [4,5,6,9].

a) The Modified Transmission Line model, MTLE

Established by Nucci, Rachidi [4], the model MTLE corrects the defects of the TL model while keeping its simplicity by allowing an easy use in the coupling computation, based on this formulation of the space-temporal distribution along the channel of the current *i(z', t),* defined by :

$$i(z',t) = i(0,t - z'/v)\exp(-z'/\lambda) \qquad z' \le vt \qquad (1)$$

$$i(z',t) = 0 \qquad z' > vt$$

b) The Current at the Base of Lightning Channel

It is single the measurable parameter and represents a significant contribution in spatial-temporal modelling of the return stroke current along the lightning channel. Various analytical expressions can be used to simulate the pace of the lightning current.

Among those, the exponential functions, used by several authors and who have the advantage of having analytical Fourier transforms, which makes it possible to analysing directly in the frequential domain.

$$i(0,t) = I_{01}.(e^{-\alpha t} - e^{-\beta t}) + I_{02}.(e^{-\gamma t} - e^{-\delta t}) \qquad (2)$$

I_{01}, I_{02}, α β γ *and* δ are the parameters which determine the exponential wave form [3].

More recently, Heidler [4,5] proposed a new analytical expression to simulate the current:

$$i(0,t) = \frac{I_0}{\eta}\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n} exp(-t/\tau_2)^n \qquad (3)$$

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

I_0 the magnitude of the current in the channel base

$\tau 1$ is the time-constant of the face

$\tau 2$ is the constant of decrease

η is the factor of correction factor of magnitude and n is an exhibitor ranging between 2 and 10.

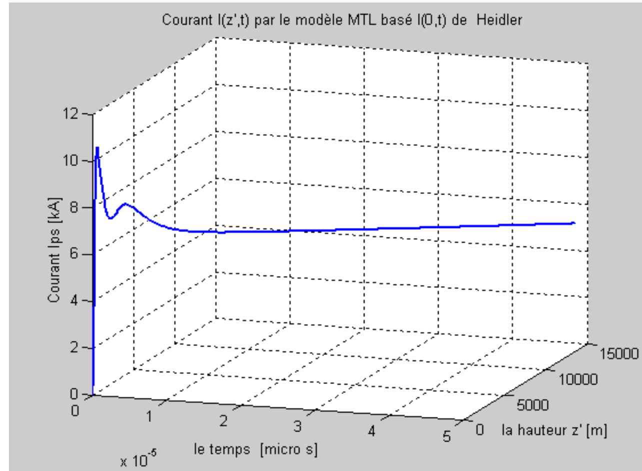


Fig. 1 : Current in lightning channel of the Model MTLE with i(0, t) of Heidler

III. Electromagnetic Lightning Radiation

The study of the disturbances generated by the lightning implies us directly in the electromagnetic compatibility domain (EMC) of which the final objective, is to make compatible the functioning of the electric and electronic system sensitive in a disturbed electromagnetic environment, while respecting some the 03 following criteria:

- No interferences with other systems.
- No susceptibility to the other systems emissions.
- No interferences of the system with itself.

To reduce the disturbances caused by the lightning electromagnetic radiation, must about it act on:

- The source, by decreasing its disturbing capacity, which is not always realizable (like the action on the climate to avoid the lightning).
- The victim, by increasing its immunity or by decreasing its susceptibility.
- Mode of the coupling, by reducing its effectiveness.

The principal device of the coupling in our case, is the electromagnetic field produced and radiated by the lightning, the evaluation of various dimensions of this last, is the most significant stage for such a subject.

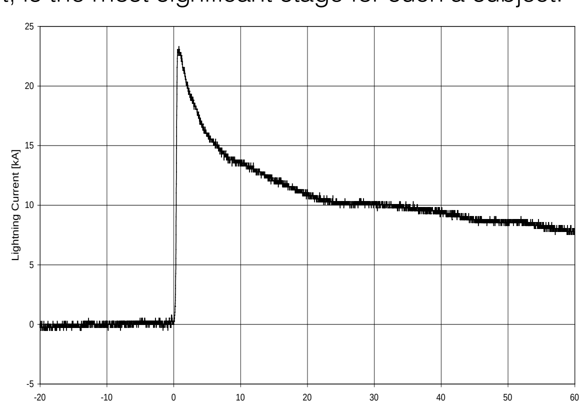


Fig. 2 : Current at the lightning channel base, experi mental measurement

a) Computation of the Electromagnetic Field

The electromagnetic field radiated by a lighting discharge ground-cloud, is in general calculated on the basis of model geometry adopted by Uman[1] presented in Fig. 3. The lightning channel is regarded as a one-dimensional vertical antenna with height *H,* placed above a perfectly conducting plan. The return stroke current is propagated vertically starting from the ground with a speed *v*, its space-temporal distribution *i(z', t)* determines the electromagnetic field in any point of space. By application of the Maxwell's equations to the geometry adopted for the general case with a perfectly conducting ground, makes it possible to obtain the electromagnetic field equations of Uman [1].

If we considered the finished ground conductivity, these equations use the Sommerfeld integrals whose analytical or numerical evaluation, will be a very delicate mission.

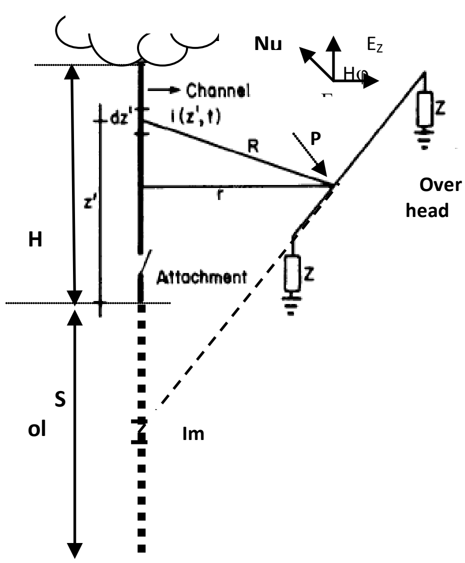


Fig. 3 : Illustration model and the geometry adopted of the problem

By supposing a perfectly conducting ground, simpler expressions of the components vertical and horizontal of the electric field and the azimuth component of the magnetic field, can be to develop according to the images theory by the expressions below (4,5,6), whose three terms intervening in the equations (4) and (5) representing respectively the fields electrostatics, induction and radiation, while the first term of the equation (6) represents the induction field and the second, the radiation field. The expressions of the lightning electromagnetic field are introduced in numerical routines [11] and give results very close to those to experimental measurements presented in [4].

$$E_r(r,z,t)=\frac{1}{4\pi\varepsilon_o}\left[\int_{-H}^{H}\frac{3r(z-z')}{R^5}\int_0^t i(z',\tau-R/c)d\tau dz' + \int_{-H}^{H}\frac{3r(z-z')}{cR^4}i(z',t-R/c)dz+\int_{-H}^{H}\frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right]$$

$$E_z(r,z,t)=\frac{1}{4\pi\varepsilon_o}\left[\int_{-H}^{H}\frac{2(z-z')^2-r^2}{R^5}\int_0^t i(z',\tau-R/c)d\tau dz'+\int_{-H}^{H}\frac{2(z-z')^2-r^2}{cR^4}i(z',t-R/c)dz'-\int_{-H}^{H}\frac{r(z-z')}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right] \quad (5)$$

$$B_\phi(r,z,t)=\frac{\mu_o}{4\pi}\left[\int_{-H}^{H}\frac{r}{R^3}i(z',t-R/c)dz' + \int_{-H}^{H}\frac{r}{cR^2}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right] \quad (6)$$

$$R=\sqrt{(z-z')^2+r^2} \quad (7)$$

$$H=v(t-\frac{R}{c})$$

Er, Ez : are the Horizontal and vertical electric field ; Hϕ is Azimuth magnetic field.

b) The Influence of Finished Ground Conductivity

Only, the horizontal component of the electric field, which is much more affected than the others by the finished ground conductivity, Cooray and Rubinstein [6] proposed an approach (8) according to which the horizontal field with a height z above the soil can break up into two terms (4,5,6).

One horizontal field calculated for infinite ground conductivity and the second, represents the effect of the finished ground conductivity, the total horizontal field is given into frequential domain by:

$$\underline{E}_r(r,z,j\omega)=\underline{E}_{rp}(r,z,j\omega)-\underline{H}_{\phi p}(r,0,j\omega)\frac{c\mu_0}{\sqrt{\varepsilon_{rg}+\sigma_g/j\omega\varepsilon_0}} \quad (8)$$

when $\underline{H}_{\varphi p}(r,0,j\omega)$ and $\underline{E}_{rp}(r,z,j\omega)$ are respectively, the Fourier transforms of the azimuth magnetic field on the ground level and horizontal electric field at altitude Z, these two grantors are calculated by supposing a perfectly ground conductivity.

IV. New Model of Electromagnetic Field

The variety of the electromagnetic field equations used and presented in several work is very limited, which reduces possibilities of the profound and beneficial analysis. This limitation must with the complexity of the phenomenon and its dependence with other external parameters which are difficult to identify and to quantify.

From there, we propose an analytical development, based on the equations of Master and Uman (4,5,6) to succeed has a formulation which depends only on time for a possible original proposition. The extreme difficulties encountered in the computing process are due primarily, to the not stability of the distance R of the observation place to the propagation the current impulse along the lightning channel and the complicity of variation between the propagation time, the speed, the ground conductivity and the geometrical parameters of the selected model.

With a fixed distance R of observation, we could have a result encouraging by new analytical expressions (9,10,11) of the electromagnetic fields in Fig. (6).The principle of our development consists in integrating the terms which depend on time τ between 0 and t, then we integrated the resulting expression which depends only on z' between - H and H.

For this particular case, our objective is achieved by the simpler form of the electromagnetic field which depends only on the time of propagation.

The result was satisfying comparatively those already found by other authors with digital techniques and experimental measurements.

a) Material and Methods

To carry out our measurements of electromagnetic fields at the laboratories of high voltage at LRE/EPFL in Switzerland, we used the following equipment:

- A generator Marx 1100kV.
- A transformer of power HVof the type HEYFELY.
- Sensors of fields electric and magnetic.
- A fast Numerical Oscilloscope.
- Probes and transformers of current for adaptation.
- A copper bar 07 m length
- Support vertical reliable of 0 with 8m
- Resisting and Inductees loads.
- Lightning Arrester H.V.

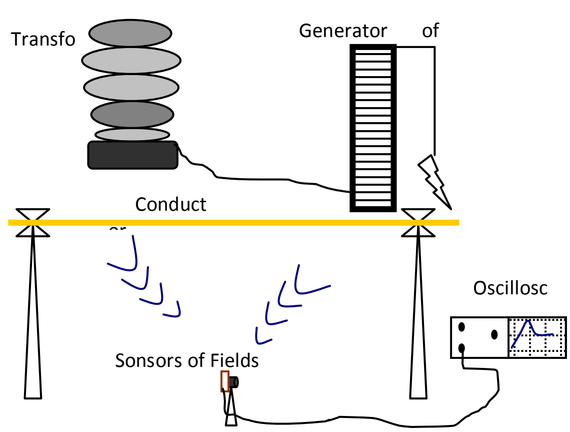


Fig. 4 : Equipment of experience measurements

The general principle of the method is to inject into the conductor starting from the generator of Marx of the impulse waves of the lightning with various magnitudes (from 40 to 800 kV) and polarities and in measurements thereafter the electric and magnetic fields according to the distance from the conductor on the ground and the sensor to the conductor.

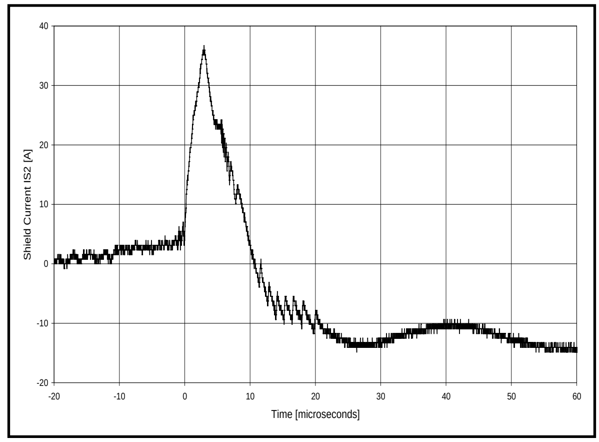


Fig. 5 : a) Lightning current impulse in overhead line closed with a ground resistance, measurements 2006 EPLF, by D.Dib

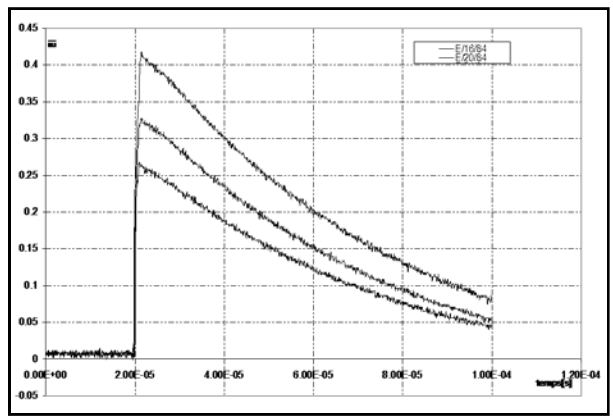


Fig. 5 : b) Magnetic field radiated by the lightning current impulse at different distances, measurements 2006 EPLF by D.Dib

The process of development is spread out over the following stages

a. Application of the selected model of current MTLE.
b. Application of the model two-exponential in the representation of the current at the channel base
c. Calculation of the electric charge quantity deposited on the soil by the lightning.
d. Calculation of the variation of derived for the return stroke current by micro second.

The use of the expressions (4), (5) and (6) in the development, leads us to very complex forms of integration, which makes the spot very delicate. The idea to fix the distance R from observation and to block its variation is just to check the validity of our development per comparison with the already existing numerical results and with measurements experimental realized by authors announced in the references.

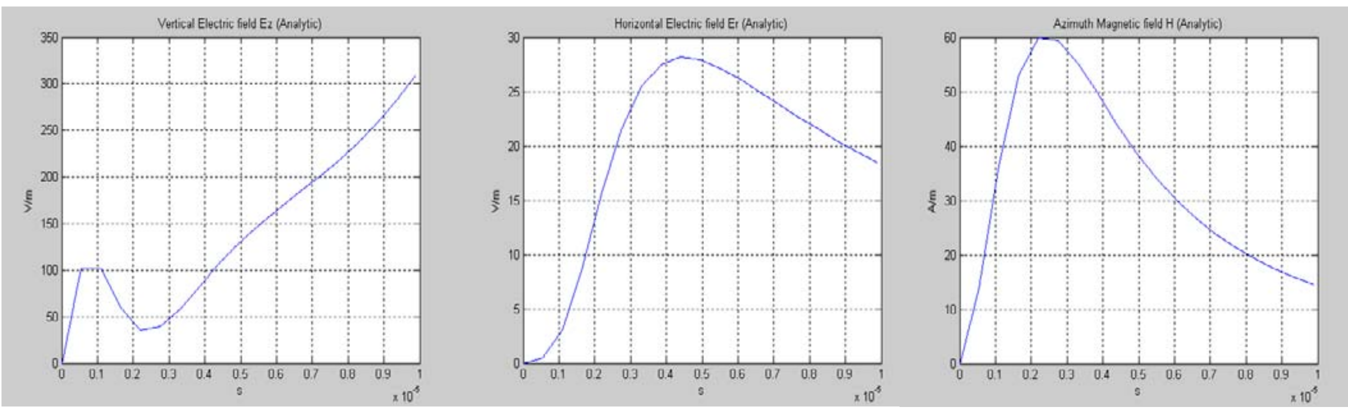
In result, we give hope encouraging for a future analytical development which generalizes a real cartography of the electromagnetic fields radiated by the lightning channel. Our development, we are broken at the model which dependent only to time (9, 10, 11).

$$E_r(t,z,r)=\frac{1}{4\pi\varepsilon_0}I_0\left\{\frac{3r}{R^5}(M_1.S_1-M_2.S_2)+\frac{3r}{cR^4}(M_0.S_1-M_{01}.S_2)+\frac{r}{c^2R^3}(-\alpha.M_0.S_1+\beta.M_{01}.S_2)\right\} \quad (9)$$

$$E_z(t,z,r)=\frac{1}{4\pi\varepsilon_0}I_0\left\{\frac{1}{R^5}(M_1.S_{11}-M_2.S_{22})+\frac{1}{cR^4}(M_0.S_{11}-M_{01}.S_{22})+\frac{r^2}{c^2R^3}(\alpha.M_0.T_1+\beta.M_{01}.T_{11})\right\} \quad (10)$$

$$H_\varphi(t,z,r)=\frac{1}{4\pi\varepsilon_0}I_0\left\{\frac{1}{R^3}(M_0.T_1-M_{01}.T_{11})+\frac{1}{cR^2}(-\alpha.M_0.T_1+\beta.M_{01}.T_{11})\right\} \quad (11)$$

Mij, Sij, Tij: are the terms of partial fields according to time, the distances r, z and the parameters which define the wave shape of the lightning current for an explicit and simple presentation. The following figures are the result of these new expressions of fields



(a) (b) (c)

Fig. 6 : Electromagnetic fields calculated by the new formulation: a) vertical, b) horizontal, c) magnetic azimuth

V. Over Voltages Induced In The Electric Lines

The over voltages induced in the overhead lines following the lightning electromagnetic radiation were studied and calculated by several authors [4,5,6,9] where the most recent model is that of Nucci and Rachidi [6]. Of our share, we limited to expose a model often used for such an evaluation; it is the model of Taylor.

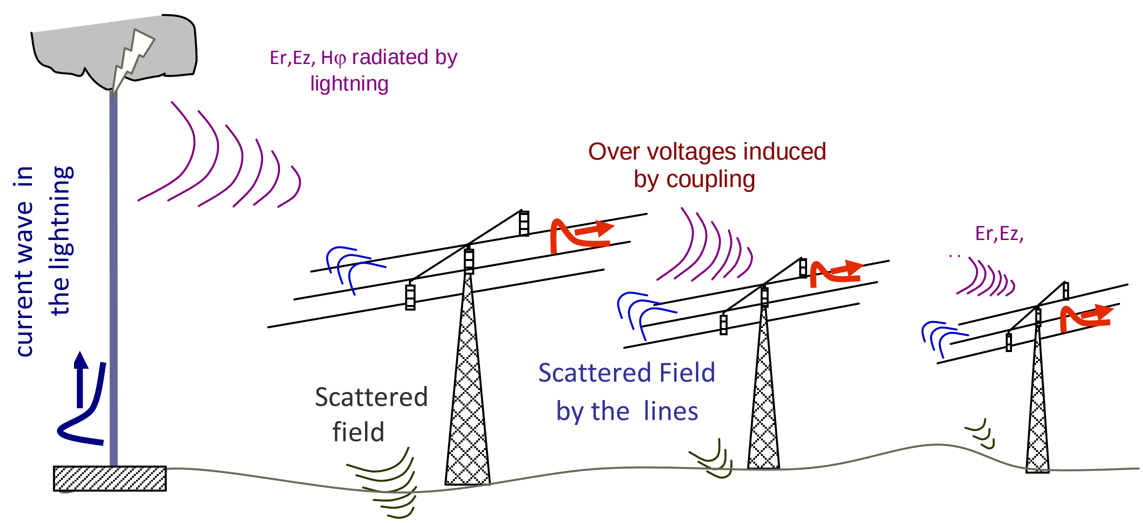


Fig. 7 : Electromagnetic coupling Phenomenon and illustration of induced overvoltages in electric power line

a) Equations of the Electromagnetic Coupling

From the first Maxwell's equation expressed for the total fields and by applying the theorem of Stokes, Taylor [3] proposes its equations (15) of the coupling according to the exiting electric and magnetic fields in Fig. 7.

The electromagnetic fields exiting E^{e} and B^{e} represent the sum of the incidental fields E^{Inc} and B^{Inc} and of the reflected fields by the ground.

$$\vec{E}^{e} = \vec{E}^{inc} + \vec{E}^{ref}$$

$$\vec{B}^{e} = \vec{B}^{inc} + \vec{B}^{ref}$$

The electric and magnetic total fields E and B are obtained by adding to the exiting fields E^{e} and B^{e}, the reaction of the line by the diffused field (`scattered field ') E^{S} and B^{S}:

$$\vec{E} = \vec{E}^{e} + \vec{E}^{s}$$

$$\vec{B} = \vec{B}^{e} + \vec{B}^{s}.$$

By also neglecting the transverse conductance G' , the Taylor coupling model is defined by the following system

$$\frac{dU(x)}{dx} + j\omega L' I(x) = -j\omega \int_0^h B_y^e(x,z)dz \qquad (12)$$

$$\frac{dI(x)}{dx} + j\omega C' U(x) = -j\omega C' \int_0^h E_z^e(x,z)dz$$

b) Boundary conditions

$$U(0) = -Z_A I(0) \text{ et } \quad U(L) = Z_B I(L)$$

c) Equivalent circuit of coupling model

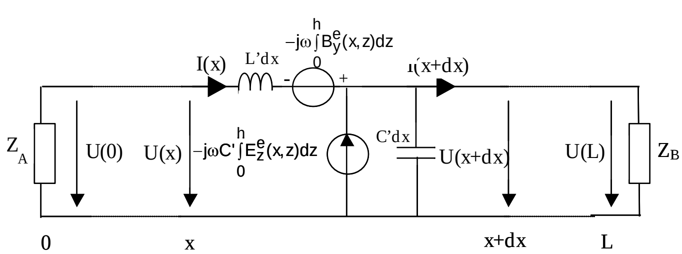


Fig. 8 : Equivalent circuit of coupling model of Taylor [5]

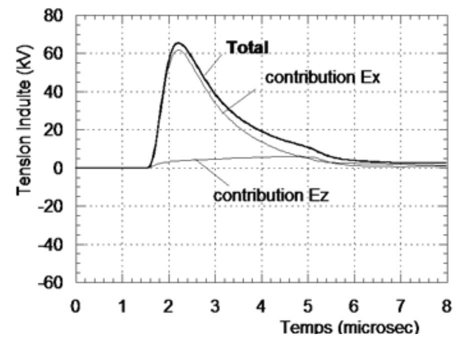


Fig. 9 : Induced over voltages calculated by Taylor model [5]

VI. Conclusion

The consequences of this work were very beneficial for a better coordination of electric insulations owing to the fact that we studied and analyzed the impact of the most severe constraint on the electric systems.

A theoretical description of the existing models on the spatial and temporal distribution of the current of the lightning return stroke along the channel and the adoption of MTLE model was the principal support for the work in this paper, because it represents the radiation source and in the coupling process.

With the current model MTLE and the electromagnetic field equations of M. Uman, we tried to reformulate a new analytical expression, but the instability, the speed and the variation between several parameters defining the phenomenon implied us in a very complicated calculation.

After using a method of approximation in particular for the observation distance R, we could create for this particular case where R is fixed, a new analytical model of the three components of the electromagnetic field.

A comparison between results and those which exist in the literature of other authors in theorycal and experimental forms us led to a result adjacent and encouraging.

In prospects, we consider future work to generalize the case and to take all the electric, physical and geometrical parameters in consideration thus to have a better identification of the behavior of the electromagnetic field radiated by the lightning and a more precise computation of induced overvoltages.

VII. Appendix

Table of symbols and abbreviations

BG	Bruce-Golde model
MTLE	Modified transmission line model with exponential current decay with height
MTLL	Modified transmission line model with linear current decay with height
TCS	Traveling current source model

MTL	Transmission line model
TL	Transmission line
Er(r,φ,z',t) volt/meter V/m	Lighting produced horizontal electric field in time domain
E_z(r,φ,z',t) volt/meter V/m	Lighting produced vertical electric field in time domain
Hφ(r,φ,z',t) ampere/mA/m	Lighting produced azimuthal magnetic field in time domain
i(z',t) ampere A	Current distribution in the lightning channel carried by the *dz'* at time *t*
i(0,t) ampereA	Lightning return-stroke current pulse
H km	Height of the lightning channel
Ioi kA	Amplitude parameter of the lightning channel base current
ν m/s	Lightning return-stroke velocity
r meter m	Horizontal distance between the channel and the observation point
R meter m	Distance from the dipole to the observation point
n	Exponent having values between 2 to 10
λ meter m	Decay constant of the wave current with propagation
ε_0 f F/m	Permittivity of free space
φ degree °	Angle
η	Amplitude correction factor
μ_0 H/m	Permittivity of the vacuum;
σ_0 siemen S	permeability of the vacuum
τ1 µs	Front time constant
τ2 µs	Decay time constant
α, β, γ, θ neper/meter	Attenuation constants determined the current wave forme
Cc m/s	Wave velocity (speed of light)

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