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Coupling Phenomenon between the Lightning and High Voltage Networks

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***Abstract*—**When a lightning strike falls near an overhead power line, the intense electromagnetic field radiated by the current of the lightning return stroke coupled with power lines and there induced transient overvoltages, which can cause a back-flashover in electrical network. The indirect lightning represents a major danger owing to the fact that it is more frequent than that which results from the direct strikes.

In this paper we present an analysis of the electromagnetic coupling between an external electromagnetic field generated by the lightning and an electrical overhead lines, so we give an important and original contribution: We are based on our experimental measurements which we carried in the high voltage laboratories of EPFL in Switzerland during the last trimester of 2005, on the recent works of other authors and with our mathematical improvement a new particular analytical expression of the electromagnetic field generated by the lightning return stroke was developed and presented in this paper. The results obtained by this new electromagnetic field formulation were compared with experimental results and give a reasonable approach.

***Keywords*—**Lightning, overhead lines, electromagnetic coupling, return stroke, models, induced overvoltages.

I. Introduction

THE lightning can touch a power line by striking either a conductor or a tower or an earth wire, causing the significant overvoltages c 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 (from1 μs to 20 μ s) 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) is necessary after having to define the single measurable parameter in this stage which definite the current at the lightning channel base i(0, 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 Sea Rachidi of LRE-EPFL in Switzerland on the electromagnetic fields radiated by the lightning.

The models of Rachidi-Nucci, Taylor and Agrawal were 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 good 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].

TABLE I
EXISTING MODELS ON THE SPACE-TEMPORAL DISTRIBUTION OF THE CURRENT RETURN STROKE OF THE LIGHTNING

Models	Formulation
The Bruce and Golde model (**BG**) [4].	$i(z',t) = i(0,t)u\left(t - \frac{z'}{v}\right)$
The Transmission Line model (**TL**) of Uman and McLain[4]	$i(z',t) = i\left(0, t - \frac{z'}{v}\right)u\left(t - \frac{z'}{v}\right)$
The Master,Uman. Lin and Standler model (**MULS**) [1]. $I(z',t)=i_u+i_p+di_{cs}$	$I_u = \frac{2\pi\varepsilon_0 (H^2 + r^2)^{3/2}}{H} \frac{dE_{proche}(r,t)}{dt}$ $i_p(z',t) = exp\left(-\frac{z'}{\lambda_p}\right)i_p\left(0, t - \frac{z'}{v}\right)$ $di_{cs}(z'',t) = I_0 \exp\left(-\frac{z''}{\lambda_c}\right)\left\{\begin{matrix}\exp[-\alpha(t,t')] \\ -\exp[-\beta(t,t')]\end{matrix}\right\}dz$
The Travelling Current Source model (**TCS**) par Heidler [1].	$i(z',t) = i\left(0, t + \frac{z'}{c}\right)u\left(t - \frac{z'}{v}\right)$
The (**MTLE**) of Nucci and Rachidi [4] .	$i(z',t) = i\left(0, t + \frac{z'}{v}\right)exp\left(-\frac{z'}{\lambda}\right)u\left(t - \frac{z'}{v}\right)$
The Diendorfer and Uman model (**DU**) [5].	$i(z',t) = \left[i\left(0, t + \frac{z'}{c}\right) - i\left(0, \frac{z'}{v^*}\right)exp\left[\frac{(t - z'/v)}{\tau_D}\right]\right]u\left(t - \frac{z'}{v}\right)$

A. The MTLE (Modified Transmission Line model)

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.

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

$I_{o1}, I_{o2}, \alpha, \beta, \gamma$ *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 est l'amplitude du courant à la base du canal
$\tau 1$ est la constante de temps du front
$\tau 2$ est la constante de décroissance
η: est le facteur de correction d'amplitude et n est un exposant compris entre 2 et 10.

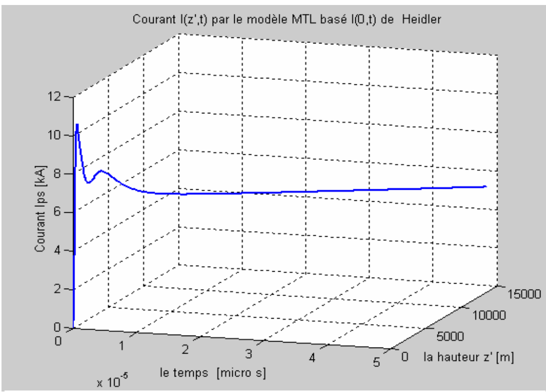


Fig. 1 Current in lightning channel of the Model MTLE with i(0, t) of Heidler

III. Electromagnetic Field Radiated by the Lightning

The study of the disturbances generated by the lightning implies us directly in the electromagnetic compatibility domain (CEM) of which the final objective, is to make compatible the functioning of the electric/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.

Most significant, is to take into account the problems of the CEM as of the conception phase and development of the new systems so, to guard itself against possible accidents related to a faulty operation. 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.

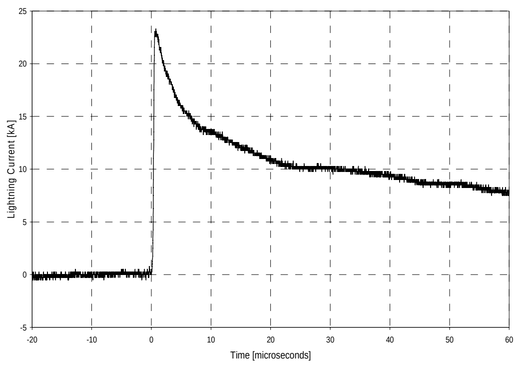


Fig. 2a

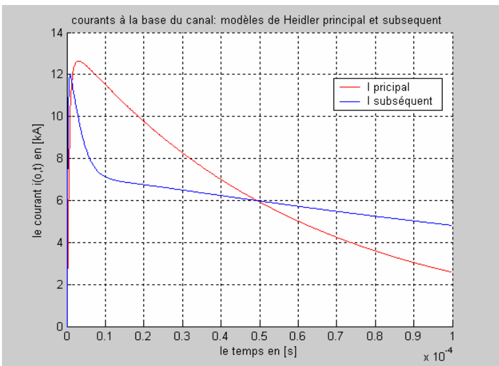


Fig. 2b

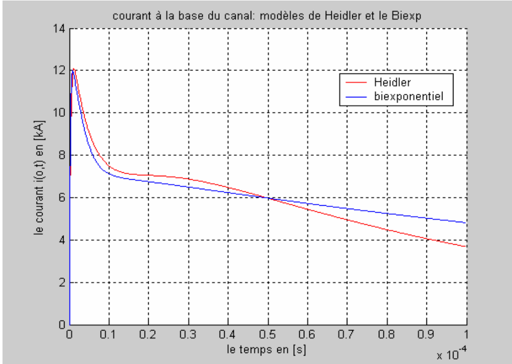


Fig. 2c

Fig. 2 Current at the lightning channel base,
a) experimental measurement, b) Heidler model
c) model of Heidler and two-exponential form

A. Calculation 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.

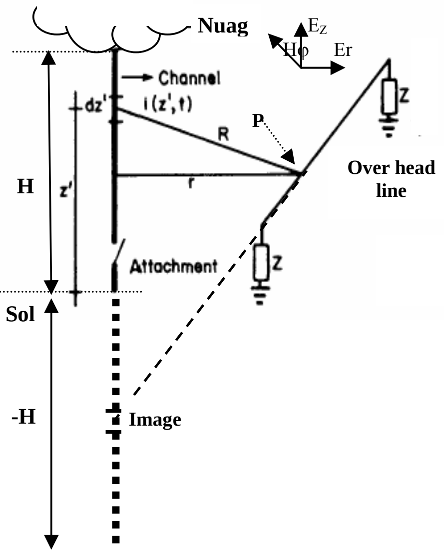


Fig. 3 Illustration model and the geometry adopted of the problem

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].

B. The Influence of the 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:

$$E_r(r,z,t) = \frac{1}{4\pi\varepsilon_0}\left[\int_{-H}^{H}\frac{3r(z-z')}{R^5}\int_0^t i(z',\tau-R/c)\,d\tau\, dz' + \int_{-H}^{H}\frac{3r(z-z')}{cR^4} i(z',t-R/c)\,dz + \int_{-H}^{H}\frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right] \quad (4)$$

$$E_z(r,z,t) = \frac{1}{4\pi\varepsilon_0}\left[\int_{-H}^{H}\frac{2(z-z')^2-r^2}{R^5}\int_0^t i(z',\tau-R/c)\,d\tau\, dz' + \int_{-H}^{H}\frac{2(z-z')^2-r^2}{cR^4} i(z',t-R/c)\,dz' - \int_{-H}^{H}\frac{r(z-z')}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right] \quad (5)$$

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

$$R = \sqrt{(z-z')^2 + r^2} \quad (7) \quad \text{and} \quad H = v(t-\frac{R}{c})$$

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

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 $\underline{H}_{\phi p}(r,0,j\omega)$ 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 Analytical Formulation 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. (4)

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.

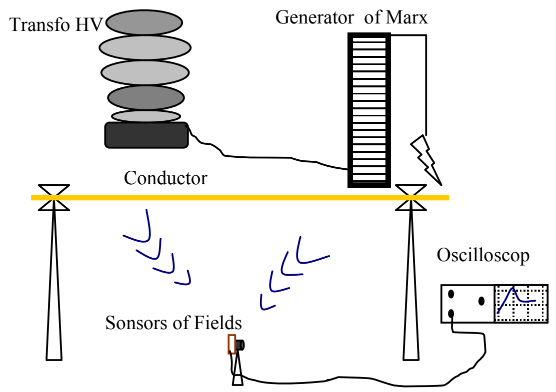
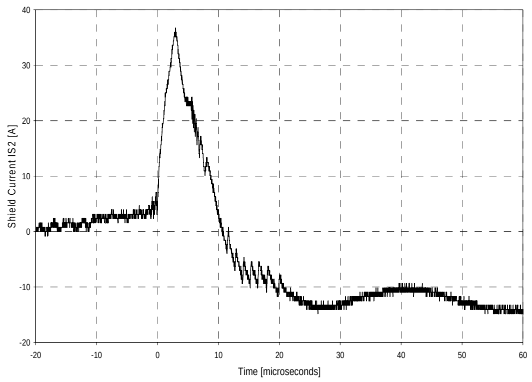


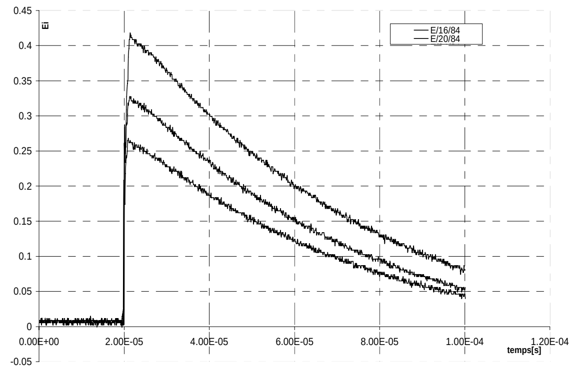
Fig. 4 Equipment of experience measurements

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.

In the appendix we presented by real images the equipment of our experiences in LRE/EPFL.



(Fig. 5a)



(Fig. 5b)

Fig. 5 a) lightning current impulse in overhead line closed with a ground resistance, measurements 2005 EPLF, b) magnetic field radiated by the lightning current impulse at different distances, measurements 2005 EPLF

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 (6), (7) and (8) 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 consequence, we give hope encouraging for a futur analytical development which generalizes a real cartography of the electromagnetic fields emission by the lightning channel. At the end of our development, we are ended at the expressions which dependent only to time (9,10,11).

When $M_{0,1,2}$, $S_{0,1,2}$, T_{11}: 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.

$$i(z',t-\frac{R}{C})=I_o\left\{\exp-\alpha\left(t-\frac{R}{c}-\frac{z'}{v}\right)-\exp-\beta\left(t-\frac{R}{c}-\frac{z'}{v}\right)\right\}\exp\left(\frac{-z'}{\lambda}\right) \tag{6}$$

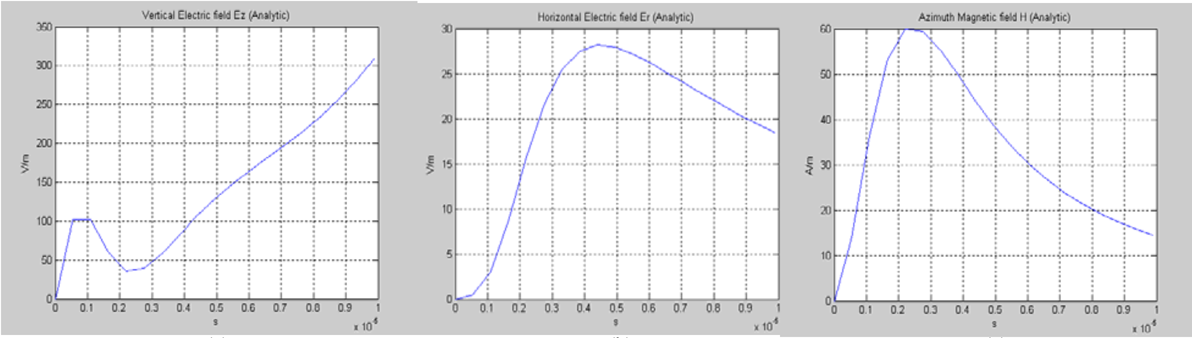
$$\int_0^t i(z',t-\frac{R}{C})d\tau=\frac{I_o}{\alpha}\left(1-e^{\alpha t}\right)exp\left[\frac{\alpha R}{c}+\left(\frac{\alpha}{v}-\frac{1}{\lambda}\right)z'\right]-\frac{I_o}{\beta}\left(1-e^{\beta t}\right)exp\left[\frac{\beta R}{c}+\left(\frac{\beta}{v}-\frac{1}{\lambda}\right)z'\right] \tag{7}$$

$$\frac{\partial i}{\partial t}=I_o\left\{-\alpha e^{-\alpha t}\exp\left[\frac{\alpha R}{c}+\left(\frac{\alpha}{v}-\frac{1}{\lambda}\right)z'\right]+\beta e^{-\beta t}\exp\left[\frac{\beta R}{c}+\left(\frac{\beta}{v}-\frac{1}{\lambda}\right)z'\right]\right\} \tag{8}$$

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

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

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



(a) (b) (c)

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

V. VERVOLTAGES 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.

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.

$$\vec{E}^e = \vec{E}^{inc} + \vec{E}^{ref} \quad \text{and} \quad \vec{B}^e = \vec{B}^{inc} + \vec{B}^{ref}$$

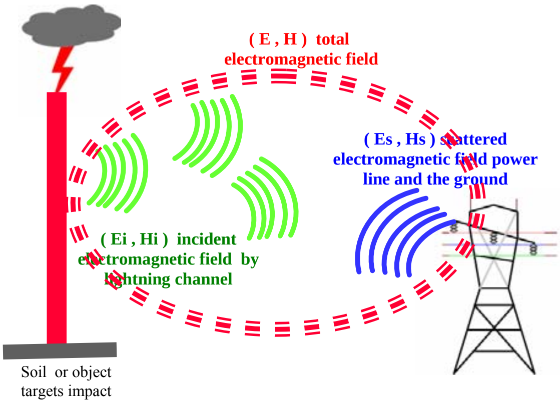


Fig. 7 Coupling phenomenon between lightning electromagnetic field and electric power line

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

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

$$\frac{dU(x)}{dx} + j\omega L' I(x) = -j\omega\int_0^h B_y^e(x,z)dz$$
$$\frac{dI(x)}{dx} + j\omega C' U(x) = -j\omega C'\int_0^h E_z^e(x,z)dz \quad (15)$$

Boundary conditions:

$U(0) = -Z_A I(0)$ et $U(L) = Z_B I(L)$

Equivalent circuit of coupling model:

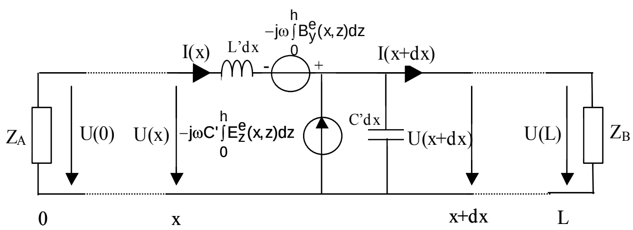


Fig. 8 Equivalent circuit of coupling model of Taylor

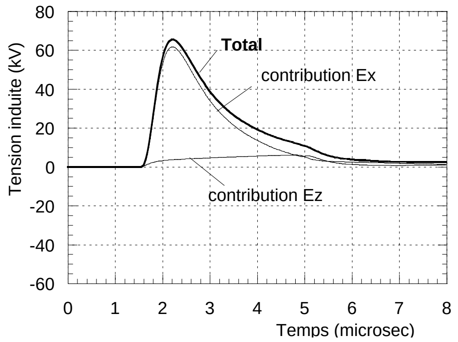


Fig. 9 Induced over voltages calculated by Taylor model

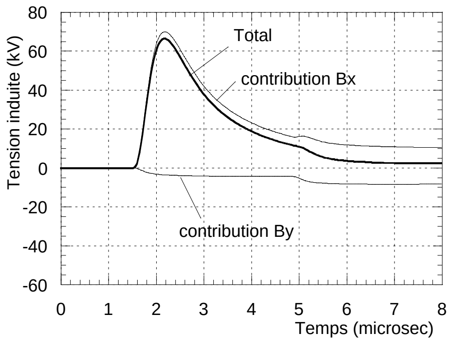


Fig. 10 Induced over voltages calculated by Rachidi Model

VI. Results and Discussion

The most significant result in this paper is the validation of our formula suggested of the electromagnetic field radiated by the lightning: owing to the fact that for the particular case where the distance R from the point of observation is constant, we obtained very close fields that those obtained by experimental measurements and simulations establish by [3,4,6,7,11].

We tested our expressions for the horizontal field on the ground (z=0) which was null this evaluation approves moreover our steps for a possible general procedure.

For model MTLE of the current of the lightning is adopted for its effectiveness compared to the other models in the calculation of the electromagnetic field and consequently the overpressures induced consequently, this last analysis was also results published by several authors [4,5,6].

VII. 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-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.

From the selected model MTLE and the electromagnetic field equations radiated by the lightning of Master and Uman, we tried to reformulate a new analytical expression. But the instability, the speed and the variation between several parameters defining the phenomenon (geometrical, physical and electric) implied us in a very complicated calculation.

After using a technique of approximation in particular for the observation distance R, we could establish for this particular case where R is fixed, a new analytical expression of the three components of the electromagnetic field. A comparison between those and those which exist in the literature us led to a result adjacent and encouraging. In this type of research domain, the situation is always fertile and requires more work for a protection more reassuring of the electric and electronic systems.

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