ANALYSIS OF RADIATED-LIGHTNING ELECTROMAGNETIC FIELDS ABOVE IMPERFECT GROUND USING A QUASI-FDTD HYBRID METHOD

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ABSTRACT

In this paper, our purpose is to compute radiated lightning electromagnetic fields using the hybrid method principle. The proposed method called the quasi-FDTD method is a new version of the classical hybrid method which is based partially on the use of the finite difference method in time domain (FDTD) for the calculation of the electric field components after the evaluation of the magnetic flux density using the images theory. However, the particularity of the proposed method is to take into account the finite conductivity of the ground in the lightning electromagnetic field calculations. This is obtained by a modification brought to the formulation of the classical hybrid method presented by Sartori and al in [2]. Furthermore, in the proposed method, the representation of the lightning current distribution is achieved by the use of engineering models typically the MTLE and MTLD models since they have showed reasonable agreement with measurements. Finally the simulation results are compared with those obtained using numerical approximate methods taken from literature. This comparison has shown that the proposed hybrid approach, taking into account the finite ground conductivity, is completely valid since it reproduces similar wave shapes for the electric and the magnetic fields above the ground.

Keywords: *Electromagnetic compatibility (EMC), Lightning Electromagnetic Fields, Engineering models, Finite time domain (F.D.T.D), finite ground conductivity.*

1. INTRODUCTION

The modern society is highly dependent on complex and sensitive electronic and communication systems, which have a low damage threshold level. Indeed, these high susceptibility equipments are used in almost all domains of activities.

Electric power networks constitute the most powerful and complex interconnected systems including power equipments and control-command systems which are a virtually parallel telecommunications networks.

The increase demand of a best quality of electric energy and the requirement of best service continuity necessitate a good protection against disturbing phenomena such as the lightning phenomenon. This latest interferes with power networks and their control-command circuits generating malfunction or even destruction of these critical installations. Thus, the evaluation of lightning electromagnetic fields assumes a special and important concern for designers and industrial managers whose the task is to establish an adequate lightning protection system. This task is complicated by the fact that a transient coming into the sensitive equipments will have many coupling paths.

To accurately represent the interaction of lightning electromagnetic fields with electrical networks, it is necessary to have mathematical models that are able to reproduce the electromagnetic field signatures generated by a lightning flash.

For that purpose, many models has been developed in order to reproduce as well as possible the various lightning aspects, namely, lightning return strokes, radiated electromagnetic fields, coupling mechanisms between lightning stroke and the system to be protected and finally the behaviour of various devices to incident lightning transients propagating within the system

The present work has as special focus to calculate the lightning electromagnetic field using a special proposed hybrid method, called the quasi-FDTD method. This latest, combines the finite difference time domain (FDTD) method and the images method adapted for the case of imperfect conducting ground.

2. INTEREST OF THE QUASI-FDTD HYBRID METHOD

According to literature there is a general agreement for the magnetic field results. In return, this literature shows quite different results concerning the intensity and the wave shape of the near electric field [1], [2].

Among the electromagnetic fields calculation methods, the FDTD method constitutes a simple and efficient tool. This efficiency is particularly interesting in the treatment of electromagnetic environment relative to complex structures subjected to radiation of lightning electromagnetic fields [3]. However this technique involves some disadvantages such as the difficulty in the analysis of low-frequency transients, in which the space-discretization step is several hundreds or thousands times smaller than the minimum wavelength associated to the maximum frequency excited by the source such as the interaction of lightning phenomenon with complex structures like overhead lines in power networks. To outline this major difficulty, the hybrid method has been proposed and successfully tested by *Sartori and al*. [2]. Nevertheless, for the magnetic flux density calculation, these authors have considered the current distribution in each radiating dipole as a step function. Furthermore, only the case of a perfect ground has been considered in this method.

For these reasons, in this paper, our contribution deals with firstly the consideration of a current distribution along the lightning channel close to the reality given by the models MTLE and MTLD. Indeed, these models have been ranked in the literature among the best engineering models [1], [4]. The second contribution concerns the introduction of the finite conductivity ground. This is obtained by a modification brought to the original formulation of the classical hybrid method. This modification rest on *Wang and Zhou* works [5].

3. ANALYSIS OF RADIATED-LIGHTNING ELECTROMAGNETIC FIELDS

3.1. Case of a perfectly conducting ground

Figure 1 shows a schematic representation of the lightning channel's assumed geometry and indicates the observation point "P" where the magnetic flux density is calculated. Generally, the calculation of the electric and magnetic fields associated with lightning return stroke is based on certain assumptions [6], namely:

- The lightning channel is represented by a straight vertical antenna along which the return stroke front propagates upward at the return stroke speed;
- The ground is assumed flat, homogenous and characterized by its conductivity and its relative permittivity.

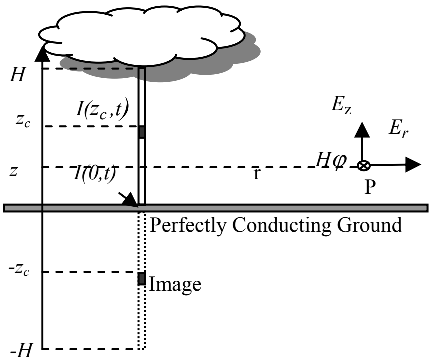

Fig. 1 Lightning channel geometry

- Magnetic field calculation

The magnetic field components at the location P(r,φ, z) produced by a short vertical section of infinitesimal channel *dz'* at height *z'* carrying a time-varying current *i(z',t)* can be computed in the time domain using the flowing relation :

$$H\varphi(x,y,z,t) = \frac{1}{4\pi\mu_0} \cdot \int_{-H}^{H} [(\frac{r}{R^3} \cdot i(z_c, t-R/c)) + (\frac{r}{cR^2}\frac{\partial i}{\partial t}(z_c, \tau - R/c))]\, dz \quad (1)$$

With:

$$R = \sqrt{\left(x^2+y^2\right)^2 + (z-z_c)^2} \quad (2)$$

i(z',t) is the current carried by the *dz'* dipole at time t; μ_0 the vacuum permeability, c the speed of light in vacuum., *R* the distance from the dipole to the observation point, and r the horizontal distance between the channel and the observation point.

In the literature several return stroke models are used in the L.E.M.P. calculations. In this section the M.T.L.E. (Modified Transmission Line-exponential) model was adopted [1], [7] for the lightning current distribution expressed by the following equations:

$$z_c < v.t \quad i(z_c,t) = e^{-z/\lambda}.\, i(0, t - z_c/v) \quad (3)$$

$$z_c > v.t \quad i(z_c,t) = 0 \quad (4)$$

$$z_c > H \quad i(z_c,t) = 0 \quad (5)$$

The λ factor is the decay constant and v is the speed of propagating of the return stroke.

For the representation of the channel-base current, a sum of two functions has been chosen in order to better reproduce the overall wave shape of the current as observed in typical experimental results. The formulation of this sum is given by the equations (6)-(9).

$$i(0,t) = i_1(t) + i_2(t) \quad (6)$$

$$i_1(t) = \frac{I_1}{\eta_1}.[\frac{(t/\tau_{11})^{n1}}{1+(t/\tau_{11})}].\exp(t/\tau_{12}) \quad (7)$$

$$i_2(t) = \frac{I_2}{\eta_2}.[\frac{(t/\tau_{21})^{n1}}{1+(t/\tau_{21})}].\exp(t/\tau_{22}) \quad (8)$$

$$\eta_1 = \exp[(\tau_{11}/\tau_{12}).(n1.\tau_{11}/\tau_{12})^{1/n1}] \quad (9)$$

I_1(1,2) is the amplitude of $i_1(i_2)$, $\tau_{11}(\tau_{21})$ the front time constant of $i_1(i_2)$, $\tau_{12}(\tau_{22})$ the decay time constant of $i_1(i_2)$, $\eta_{1,2}$ the amplitude correction factor, and $n_{1,2}$ is an exponent having values between 2 to 10.

- Electric field calculation

The electric field computation is performed using the FDTD method. It is based on the direct solution of the difference form of Maxwell's equations by means of the Yee discretization scheme. The technique has the advantage of being very flexible, and it is easy to implement it in a computer code [8]. In this procedure the electric field is numerically evaluated by a simplified F.D.T.D. approach applied to the basic Maxwell equation given in (10):

$$\nabla\times\vec{B} = \mu(\vec{J} + \frac{\partial\vec{D}}{\partial t}) = \mu(\sigma\vec{E} + \varepsilon\frac{\partial\vec{E}}{\partial t}) \quad (10)$$

Where, μ is the permeability; σ is the conductivity; ε is the permittivity; $\vec{J}$ is the current density vector, and $\vec{D}$ is the electric flux density vector.

The vector equation (10) represents a system of three scalar equations, which can be expressed in a rectangular coordinate system through their (x, y, z) components as:

$$\frac{\partial E_z}{\partial t}=\frac{1}{\mu\varepsilon}\left(\frac{\partial B_y}{\partial x}-\frac{\partial B_x}{\partial y}-\mu\sigma E_z\right) \quad (11)$$

$$\frac{\partial E_x}{\partial t}=\frac{1}{\mu\varepsilon}\left(\frac{\partial B_z}{\partial y}-\frac{\partial B_y}{\partial z}-\mu\sigma E_x\right) \quad (12)$$

$$\frac{\partial E_y}{\partial t}=\frac{1}{\mu\varepsilon}\left(\frac{\partial B_x}{\partial z}-\frac{\partial B_z}{\partial x}-\mu\sigma E_y\right) \quad (13)$$

Thus, the F.D.T.D. method is applied in the solution of equations (11) to (13). This calculating method consists of a space and time approximation derivatives by a central finite differences scheme [9].This approximation can be written as,

$$\frac{\partial F(n,p,m,k)}{\partial z}=\frac{F(n,p,m+1,k)-F(n,p,m-1,k)}{\Delta l} \quad (14)$$

$$\frac{\partial F(n,p,m,k)}{\partial t}=\frac{F(n,p,m,k+1/2)-F(n,p,m,k-1/2)}{\Delta t} \quad (15)$$

The notation *F(n, p, m, k)* is the grid point of the space, the variable Δl is the length between two series nodes, and Δt the propagation time (assumed to be the time step related to the magnetic flux density values).

We can rewrite equations (11)-(13) with applying (14)-(15). The electric field components E_X, E_y, and E_Z can be calculated as:

$$E_x(n,p,m,k+1/2)=E_x(n,p,m,k-1/2)+\frac{c^2\Delta t}{\Delta l}[B_z(n,p+1,m,k)-B_z(n,p-1,m,k)+B_y(n,p,m-1,k)-B_y(n,p,m+1,k)] \quad (16)$$

$$E_y(n,p,m,k+1/2)=E_y(n,p,m,k-1/2)+\frac{c^2\Delta t}{\Delta l}[B_x(n,p,m+1,k)-B_x(n,p,m-1,k)+B_z(n-1,p,m,k)-B_z(n+1,p,m,k)] \quad (17)$$

$$E_z(n,p,m,k+1/2)=E_z(n,p,m,k-1/2)+\frac{c^2\Delta t}{\Delta l}[B_y(n+1,p,m,k)-B_y(n-1,p,m,k)+B_x(n,p-1,m,k)-B_x(n,p+1,m,k)] \quad (18)$$

The implementation procedure consists in first of evaluating the magnetic flux density, by integrating the equation (1), at six points around the point where the electric field will be calculated. The electric field is computed with the approach described below in (16)-(18). The F.D.T.D. algorithm requires specific considerations. Thus the grid size Δl should be a fraction of wavelength. In addition, to avoid numerical instabilities the time increment should be bounded by the grid size values. The typical choice is refried to the following equation:

$$\Delta t \leq \Delta l/2c \quad (19)$$

Finally, the hybrid procedure has the particularity that the electromagnetic field can be evaluated without meshing the entire of the configuration. It is an important feature which can be translated in term of memory space reducing

- Results

The lightning channel current parameters considered in this study are: λ= 1.5 km and v =1.10^{8}m/s.
The lightning channel base current parameters are reported in Table 1 Its variations in step with the time are presented in Fig. 2. In Fig. 3 the magnetic field density waveshape obtained by integration of equation (1), is drawn in step with time. In this figure, experimental measures of the same field taken from [10] are also plotted. It is easy to show the satisfactory agreement, between the calculated values and the measured one.
Plots of the calculated vertical electric field at 9km from the striking point, and of the measured one [10] are found in Fig. 4.

Table 1 Lightning Channel base current parameters [10]

I_1	τ_{11}	τ_{12}	n_1	I_2	τ_{21}	τ_{22}	n_2
19.5kA	1μs	2μs	2	12kA	8μs	30μs	2

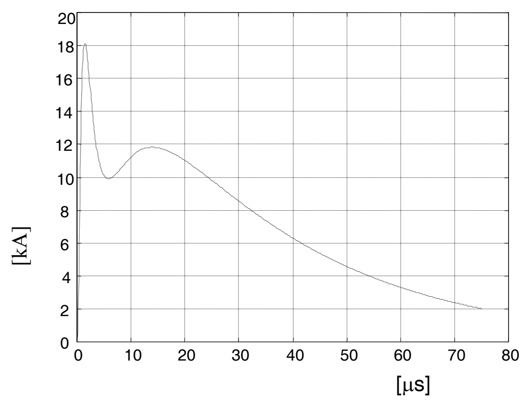

Fig. 2 Lightning channel base current waveshape

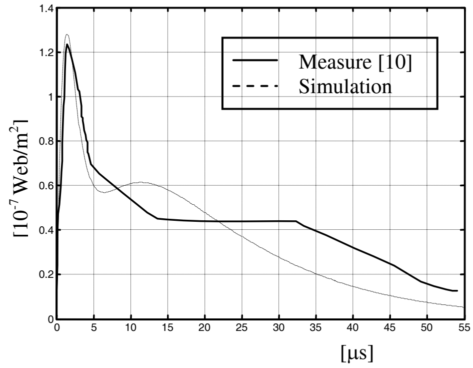

Fig. 3 Calculated and measured magnetic flux densities

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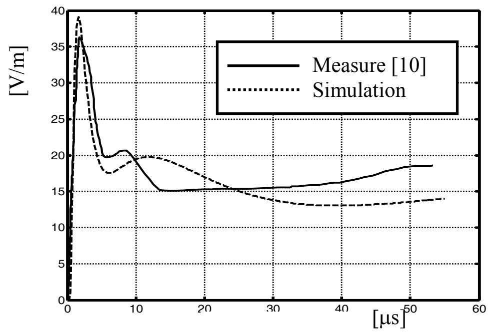


Fig. 4 Calculated and measured vertical electric field

It can be seen from Fig. 3 and Fig. 4 that a good agreement is obtained between the simulation and experimental results. In return some differences in the peak values, of the magnetic flux density and the vertical electric field wave shapes, reaching about ten percent in the worst case are observed. The hybrid approach as well as the program developed by authors for this purpose is then validated. However, it is known [11] that for close ranges, the approximation of the ground as a perfect conducting medium becomes no more realistic in calculating the horizontal electric field and even in evaluating the distortion of the vertical one because of the dominated effect of the earth's properties on the electric field behaviour. For that reason, an extension of the hybrid method is proposed in this work to take into account the ground's conductivity in calculating the horizontal electric field.

3.2. Case of a finitely conducting ground

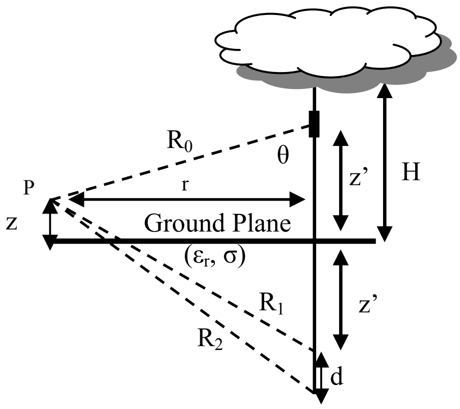


Fig. 5 Geometry of the problem

- Magnetic field calculation

The lightning electromagnetic fields expressions associated to engineering models are completely defined by the numerical resolution of *Sommerfeld's* integrals
The exact lightning electromagnetic field formula generated by subsequent return strokes is given by the combination of *Sommerfeld*'s integrals formulations with the subsequent return stroke current distribution. However, the numerical implementation of this procedure is difficult. And the latest is characterized by a great time consummation. For these reasons several approximate formulations allowing the resolution of the *Sommerfeld* equations have been developed by a lot of researchers. Among these approximate formulations the *Norton*'s method is known as the best one. Nevertheless in electromagnetic fields calculations relative to very close to lightning channel, the validity of this method especially for poorly conducting ground has not been proved [5]. According to *Yang and Zhou* [5], the complete problem relative to a dipole electromagnetic radiation over a finitely conducting half-space has been treated by *Baños* and *Wait*. This treatment has been achieved by determining the solution of Maxwell's equations for both media in accordance with the boundary conditions on the air-ground interface.

The exact expression for the vector potential set up by a vertical dipole over a flat and non-ferromagnetic ground is given in [5] which authors have simplified the expression given by *Sommerfeld* in the frequency domain as following:

$$dA_{z0} = \frac{\mu_0 I(z')\,dz'}{4\pi}\left(\frac{\exp(-jk_0R_0)}{R_0} + A\frac{\exp(-jk_0R_1)}{R_1} - B\frac{\exp(-jk_0R_2)}{R_2}\right) \quad (20)$$

Where:

$$R_0^2 = r^2 + (z-z')^2, R_1^2 = r^2 + (z+z')^2, R_2^2 = r^2 + (z+z'+d)^2$$

$$A = \frac{n^2-1}{n^2+1}, B = \frac{2n^2}{n^2+1}, d = \frac{n^2+1}{\alpha}, n^2 = \frac{k_1^2}{k_0^2},$$

$$\alpha^2 = k_0^2 - k_1^2, k_0^2 = \omega^2\mu_0\varepsilon_0, k_1^2 = -j\omega\mu_0(\sigma + j\omega\varepsilon)$$

In this same reference, authors have presented the modified quasi-images formula where the magnetic field is calculated above a lossy ground by adding a term characterizing the finite ground conductivity. The azimuthal magnetic field expression, in this case, is given by the following expression:

$$dH_{\varphi}(j\omega, r, z) = -\frac{I(z')\,dz'}{4\pi}\frac{\partial}{\partial r}\left[\frac{\exp(-jk_0R_0)}{R_0} + A\frac{\exp(-jk_0R_1)}{R_1} - B\frac{\exp(-jk_0R_2)}{R_2}\right] \quad (21)$$

Where, the variable B characterize the lossy term.

In this paper we propose the introduction of this modified Quasi-Images formula in the hybrid method for the magnetic field calculation in other to take into account the finite ground conductivity. The magnetic field in the time domain is determined numerically by integrating the previous expression over the lightning channel and by using the inverse Fourier transform.

- Electric field calculation

The FDTD technique is used to compute the electric field components. In this procedure the electric field is numerically evaluated by an F.D.T.D. approach applied to the basic Maxwell equation given in (22):

$$\vec{\nabla}\times\vec{H}=\sigma\vec{E}+\varepsilon\frac{\partial\vec{E}}{\partial t} \quad (22)$$

For lightning engineering models, the two-dimensional (2D) cylindrical coordinates can be adopted [5], fig. 7.

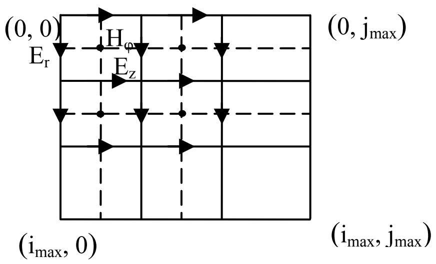


Fig. 7 2D-FDTD Meshes of cylindrical coordinates

The vector equation (22) can be written as:

$$\begin{cases}\sigma E_r+\varepsilon\dfrac{\partial E_r}{\partial t}=-\dfrac{\partial H_\varphi}{\partial z}\\ \sigma E_z+\varepsilon\dfrac{\partial E_z}{\partial t}=\dfrac{1}{r}\dfrac{\partial}{\partial r}(rH_\varphi)\end{cases} \quad (23)$$

The F.D.T.D. method is applied in the solution of this system. This calculating method consists of a space and time approximation derivatives by a central finite differences scheme:

$$\left.\frac{\partial f(r,z,t)}{\partial r}\right|_{r=i\Delta r}=\frac{f^n(i+\frac{1}{2},j)-f^n(i-\frac{1}{2},j)}{\Delta r} \quad (24)$$

$$\left.\frac{\partial f(r,z,t)}{\partial z}\right|_{z=j\Delta z}=\frac{f^n(i,j+\frac{1}{2})-f^n(i,j-\frac{1}{2})}{\Delta z} \quad (25)$$

$$\left.\frac{\partial f(r,z,t)}{\partial t}\right|_{t=n\Delta t}=\frac{f^{n+\frac{1}{2}}(i,j)-f^{n-\frac{1}{2}}(i,j)}{\Delta t} \quad (26)$$

We can rewrite the equations of the system (23) with applying (24)-(26). The electric field components E_r, E_z can be calculated as:

$$E_z^{n+1}\left(i,j+\frac{1}{2}\right)=\frac{2\varepsilon-\sigma\Delta t}{2\varepsilon+\sigma\Delta t}E_z^n\left(i,j+\frac{1}{2}\right)+\frac{2\Delta t}{(2\varepsilon+\sigma\Delta t)r_i\Delta r}\Bigg[r_{i+(1/2)}\cdot$$
$$H_\varphi^{n+(1/2)}\left(i+\frac{1}{2},j+\frac{1}{2}\right)-r_{i-(1/2)}H_\varphi^{n+(1/2)}\left(i-\frac{1}{2},j+\frac{1}{2}\right)\Bigg] \quad (27)$$

$$E_r^{n+1}\left(i+\frac{1}{2},j\right)=\frac{2\varepsilon-\sigma\Delta t}{2\varepsilon+\sigma\Delta t}E_r^n\left(i+\frac{1}{2},j\right)-\frac{2\Delta t}{(2\varepsilon+\sigma\Delta t)\Delta z}$$
$$\cdot\left[H_\varphi^{n+(1/2)}\left(i+\frac{1}{2},j+\frac{1}{2}\right)-H_\varphi^{n+(1/2)}\left(i+\frac{1}{2},j-\frac{1}{2}\right)\right] \quad (28)$$

Also to avoid numerical instabilities the time increment is given by the following equation:

$$\Delta t \le min(\Delta r, \Delta z)/2c \quad (29)$$

- Implementation procedure

The implementation procedure is divided into two parts:

- The first one consisting of the magnetic flux density evaluation. This evaluation is performed by integrating the equation (21), at points around the point where the electric field will be calculated and the use of the inverse Fourier transform to obtain the magnetic field in time domain.

- The second one consists in the computation of the electric field using the approach described in (27)-(28).

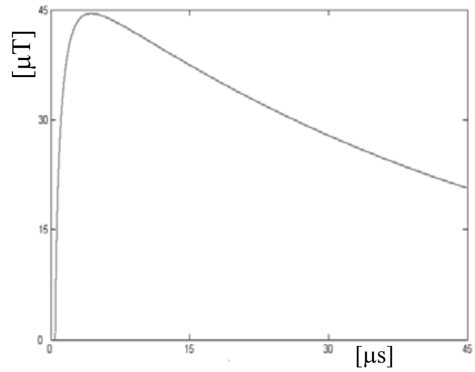
Thus, the electric field at instant "n+1" is calculated, taking into account the electric field at instant "n", i.e., the value obtained on the previous step and the pre-calculated magnetic field at instant "n+1/2".

- Results

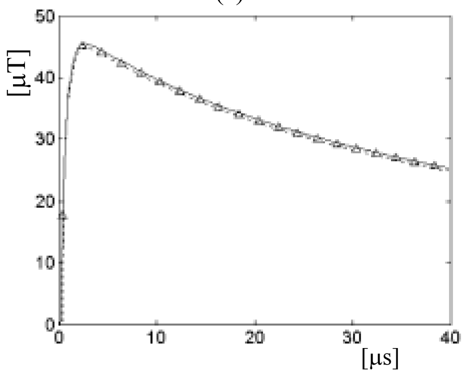
The validity of the proposed method is tested through several comparisons with results taken from literature. The first comparison concern the azimuthal magnetic field where the wave shape form obtained with the proposed method is compared to the same greatness presented in [5]. However, in other to make a good comparison we have chosen in our simulation the same data considered in [5]. It is question of the channel-base current waveform and the lightning current model in this case the $MTLD_2$ model with a return stroke speed having a value equal to 150 m/µs. The azimuthal magnetic field is computed at 50 m from the lightning channel for ground conductivity equal to $2{,}5.10^{-4}$ S/m and a permittivity equal to 10. Plots of the azimuthal magnetic field obtained respectively by the proposed method and by *Wang and Zhou* [5] are found in Fig.8.

It can be seen that the two results are virtually identical for the early time response. At later times, the agreement between the two approaches, although still reasonable, is less good.

For the horizontal electric field, the accuracy of the proposed method is tested by comparison between our results and those obtained by the *Cooray-Rubinstein* approximation [11] and the modified *Cooray* formula [12]. Thus, for the example given by *Rubinstein in* [11], we choose the same channel base current and speed, and the same return stroke model. The horizontal electric field is calculated at r = 100m from the lightning discharge and at 6m above the ground for ground conductivity of 0.01 S/m. Fig. 9 gives the two results namely the horizontal electric field variations in step of the time.

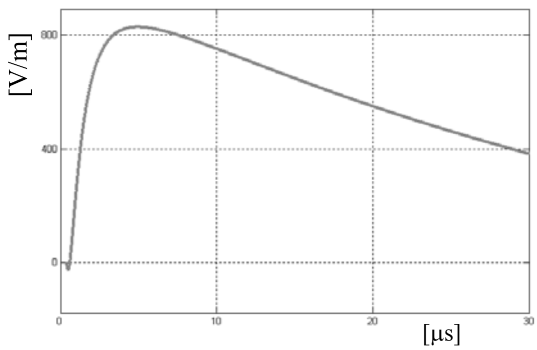


(a)

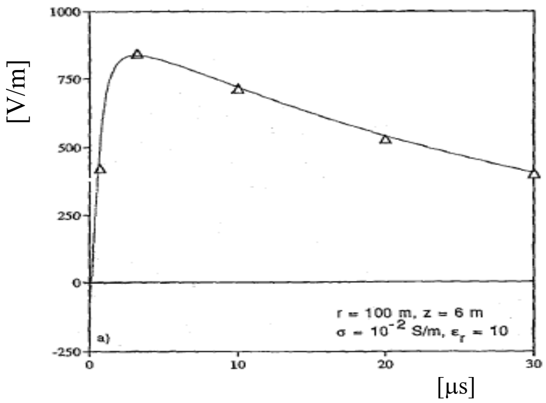


(b)

Fig. 8 Azimuthal magnetic field (a): computed using the quasi-FDTD method (b) Adopted from [5].



(a)

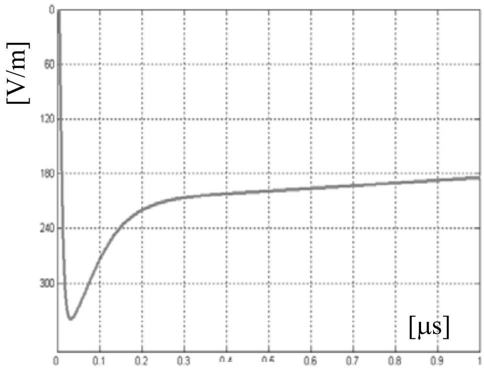


(b)

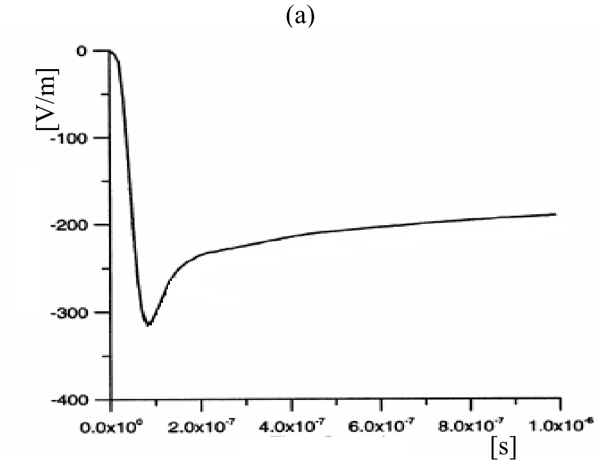
Fig. 9 Horizontal electric field (a) Using the quasi-FDTD method, (b) Adopted from [12]

A reasonable agreement between the two results can be viewed.

Figures 10 to 12 present waveforms of the horizontal electric field at a distance of 100m and 200m from the channel, and considering different heights above the ground (0, 5 or 20 m) and different ground conductivity (0.01 and 0.001 S/m). For that, a 13 KA channel base current will be injected in a $MTLD_1$ return stroke model with a speed of 130m/μs. In the same figures, we have also plotted the results obtained using the *Cooray's* formula [12].



(a)



(b)

Fig. 10 Computed horizontal electric field at ground level and distance of 100 m. (σ=0.01 S/m)
(a) Using the quasi-FDTD method,
(b) Adopted from [12]

It can be seen, that we can reproduce the same form of the horizontal electric field with the proposed hybrid method. Nevertheless, some discrepancies are observed which can be explained by the simple difference between the channel-base current and the return stroke models used in [12] which are developed by *Cooray*, and the *Nucci et al* current waveform and the $MTLD_1$ return stroke model used in this study.

According to *Cooray* [12], the change in the field wave shape and the increase in rise time of the horizontal electric field shown in fig. 9-12 are due to the effect of the ground conductivity, because when the electromagnetic field is propagating over a finite conducting ground plane, the soil will selectively attenuate the higher frequency components of radiated electric and magnetic fields, which results in an increase in the rise time and a decrease in the magnitude.

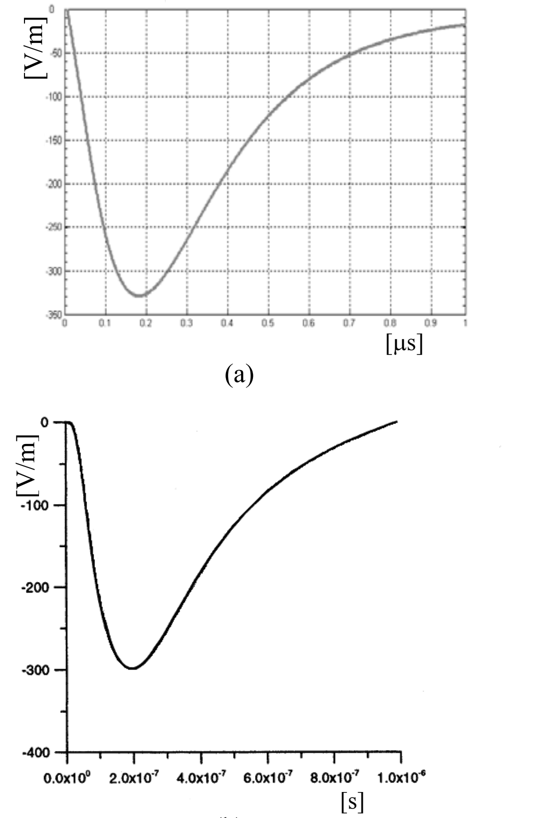


Fig. 11 Computed horizontal electric field at level of 5 m and distance of 200 m (σ=0.001 S/m) (a) Using the quasi-FDTD method,(b) Adopted from [12]

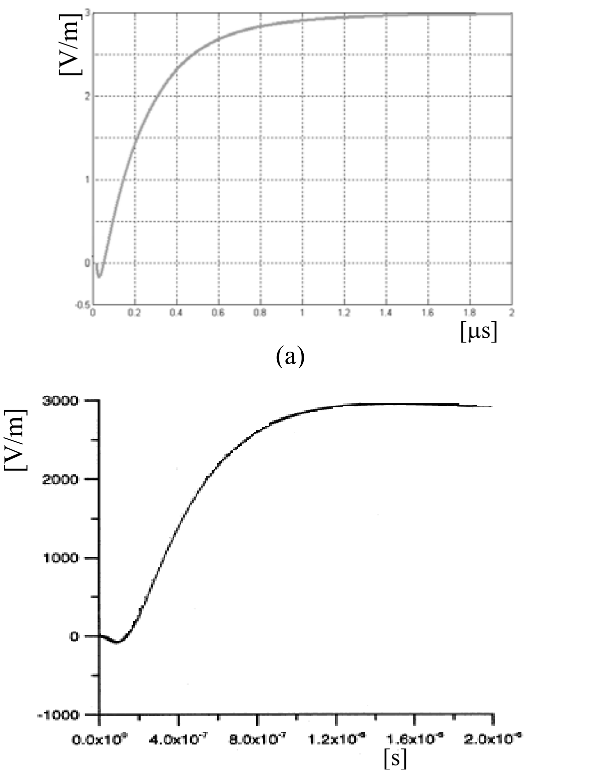


Fig. 12 Computed horizontal electric field at level of 20 m and distance of 100 m. (σ=0.001 S/m)
(a) Using the quasi-FDTD method,(b) Adopted from [12]

4. CONCLUSION

In this paper, we have presented a numerical approach for the calculation of radiated lightning electromagnetic fields in presence of an imperfect ground. This approach allowed the obtaining of simulation results validated by comparisons with theoretical and experimental results taken from literature. The numerical implementation of the proposed approach represents a good alternative in studies of lightning electromagnetic pulses (L.E.M.P.) interaction with complex electrical structures because it is very adapted to such structures. Indeed, the electromagnetic field is evaluated without meshing the entire region of the configuration. It is an important feature which can be translated in term of memory space reducing. Furthermore, another feature of the proposed approach is the introduction of lightning distribution current models reproducing some lightning characteristics observed in reality.

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