Transient Magnetic Field of Energized Buried Grid

Moussa Lefouili, Bachir Nekhoul, Kamal Kerroum, and Khalil El Khamlichi Drissi

Abstract: **A new approach is adopted in this paper for modeling the transient magnetic field, radiated by buried grid under lightning strokes. This approach summarizes each of three methods: analytical formula, based on electrical dipole theory for determining radiated magnetic field in infinite conductive medium, modified images theory for taking into account the interface in the half space, and transmission line approach for determining the longitudinal and leakage currents. The model can be used to predict the transient characteristic of grounding systems because, it can calculate magnetic field in any points of interest, it is sufficiently accurate, time efficient, and easy to apply.**

Index terms: **Buried grid, Transient, Magnetic field, Modified images theory.**

I. INTRODUCTION

The numerical modeling methods for grounding systems under lightning strokes developed since the early eighties can be classified as follows:

-Transmission line approach;
-Circuit approach;
-E.M. field approach;
-Hybrid approach.

A. Transmission line approach

The transmission line approach was the first method that was used for simulating transient behaviour of grounding system. The lossy transmission line concept was applied on the horizontal grounding wire by Verma et al. [1], Mazzeti et al. [2], and Velasquez et al. [3], which was described by telegrapher's equations.

Recently the conventional transmission line approach has been extended from simple grounding wire to grounding grid [4], and has been improved from uniform per-unit parameters to non uniform per-unit parameters [5].

This approach can be either in time and in frequency domain, it can include all the mutual coupling between the grounding wires; it can also include the soil ionization. Moreover this approach can predict surge propagation delay. Further the computation time require by transmission line approach is extremely less compared with the electromagnetic approach.

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B. Circuit approach

The circuit approach for the transient analysis of grounding systems was developed by Meliopoulos et al. [6]. The main steps involved in this method are as follows:

-Divide the grounding system into many finite segments

-Create the equivalent lumped circuit for each segment and calculate its parameters

-Solve the nodal equation of the equivalent circuit that represents the whole grounding system based on Kirchoff's laws.

Meliopoulos used frequency independent parameters, such as self and mutual inductance (ΔL), capacitance (ΔC), conductance (ΔG) and internal resistance (ΔR) of each segment. Later, Ramamoorty et al. [7] developed a simplified circuit approach for the grounding grid. In their approach, each segment was only represented by a lumped circuit with self and mutual inductance (ΔL) and self earth leakage conductance (ΔG). Even though this model neglected the capacitive coupling and internal resistance, it is still reasonably accurate in low resistivity soils.

Circuit approach is easy to understand, can easy incorporate the non-linear soil ionisation phenomena, can include all the mutual coupling between the grounding wires. The main drawback of this approach is that it cannot predict the surge propagation delay.

C. Electromagnetic field approach

Electromagnetic field approach is the most rigorous method for modeling the transient behaviour of grounding systems, because it solves full Maxwell's equations with minimum approximations. This approach can be implemented either by:

- Method of Moment (MoM);
- Finite Elements Method (FEM).

The model for the transient behaviour of grounding system based on MoM was first developed by Grcev et al. [8-11]. This model aims to transform the associated electric field Maxwell's equations to a system of linear algebraic equations with minimum assumptions. However, this model is too complex to be implemented. Further, when the grounding structure is large, the computation time is very large. Another disadvantage of electromagnetic field approach is that, because of its frequency domain solution procedure, it cannot be easily modified to include non-linearity due to soil ionization.

The electromagnetic field approach for the transient analysis of grounding systems based on FEM was developed by Biro et Preis [12] and Nekhoul et al. [13-14]. This model starts from electric or magnetic energy equation, which involves partial differential Maxwell's equations.

The difficulty in this approach is to transform the open boundaries of both air and earth environment into a closed boundary problem using spatial transformation [15], which will reduce the size of the problem. The main advantage of this electromagnetic field approach based on FEM is that the descritization of the domain (geometry of the medium) of the problem can be highly flexible non-uniform patches or elements that can easily describe complex shapes. That is the reason why the soil ionization can be easily included into this model. However, this method is more complicated to understand, because it is not directly solving the Maxwell's equations.

D. Hybrid approach

Hybrid approach for the transient analysis of grounding system was first initiated by Dawalibi [16-17]. This model is the combination of both electromagnetic field approach and circuit approach. This approach was later modified by Andolfato et al. [18]. In this method, the methodology is to divide the whole grounding system into "n" small segments. The electric field at any point is given by: $E = -\nabla V - \frac{\partial A}{\partial t}$ This equation was derived from Maxwell's equations, A is the vector potential and V is scalar potential.

This method includes the frequency influence on series internal impedances, inductive components and capacitive-inductive components which makes this method more accurate than the conventional circuit approach, especially when the injection source frequency is high.

E. Our approach

In this work, we propose a new hybrid approach [19-20], where three methods are summarized; analytical formula for determining electromagnetic fields radiated by electrical dipole in infinite conductive medium, modified images theory for taking in account the interface in the half space instead Sommerfeld's integrals, and transmission line theory for determining the longitudinal and leakage current.

In infinite medium, the total electromagnetic fields are the sum of the contributions from each dipole. In semi infinite medium, two cases can be considered, the first case is the current source (dipole) and observation point in the same medium, the electromagnetic fields can be evaluated as a sum of the field of the current source and its image; the second case is the current source in medium.1 and observation point in medium.2, the electromagnetic fields can be evaluated as the field due only to the modified current source.

Our method can be either in time and in frequency domain, it's very easy to understand, reasonably accurate and time efficient.

II. Exact Expressions of Magnetic Field in a Conducting Medium

Let us consider an electric dipole of length (Δl) immersed in a conducting medium characterized by constitutive constants: conductivity (σ), permeability (μ), and permittivity (ε), and excited by an impulse current.

When the dipole is located in the origin of a Cartesian coordinate system, and oriented in the z direction, the vector potential in the frequency domain is as follows:

$$\vec{A}(r,s) = \frac{\mu}{4\pi}\int \frac{I\, e^{-\gamma r}}{r}\, dz\, \vec{k} \qquad (1)$$

With $$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} \qquad (2)$$

Where: r = distance between the source and observation point.

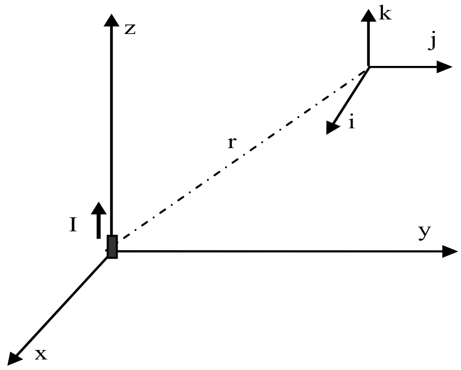


Fig.1. Electric dipole in conducting medium

From the tables of Laplace transforms [21], the inverse transformer of $e^{-\gamma r}$ is as follows:

$$e^{\frac{-r\alpha}{2}}\,\delta\left(t - r/v\right) + \frac{\alpha\, r}{2}\, e^{\frac{-t}{2\tau_0}}\, I_1(m)\frac{u\left(t - r/v\right)}{\sqrt{t^2 - r^2/v^2}} \qquad (3)$$

With $$m = \frac{\sqrt{t^2 - r^2/v^2}}{2\tau_0}$$

$\delta(t - r/v)$ is the Dirac function;

$u(t - r/v)$ is the Heaviside step function;

I_1 (m) is the first order modified Bessel function.

We also define the attenuation constant, the wave velocity and the relaxation time, respectively:

$$\alpha = \sigma\sqrt{\mu/\varepsilon}\,, \quad v = 1/\sqrt{\varepsilon\mu} \quad \text{and} \quad \tau_0 = \varepsilon/\sigma$$

Using equation (3), we take the expression of potential vector in time domain:

$$\vec{A}(r,t) = \frac{\mu\, I\Delta l}{4\pi\, r}\left[e^{-\alpha r/2}\,\delta(t - r/v) + \frac{\alpha\, r}{2}\, e^{-t/2\tau_0}\, I_1(m)\frac{u(t - r/v)}{\sqrt{t^2 - r^2/v^2}}\right]\vec{k} \qquad (4)$$

Using: $$\vec{H}(r,t) = \frac{1}{\mu}\nabla \wedge \vec{A}(r,t) \qquad (5)$$

We take the magnetic field components in the time domain:

$$dh_x(r,t) = \frac{-yI\Delta l}{4\pi r^3}\left\{\left[\frac{r}{v}\frac{\partial}{\partial t}\delta\left(t-r/v\right) + \left(1+\frac{\alpha r}{2}+\frac{\alpha^2 r^2}{8}\right)\delta\left(t-r/v\right)\right] e^{\frac{-\alpha r}{2}} + e^{\frac{-t}{2\tau_0}}\frac{\alpha^2 r^3\, I_2(m)\, u\left(t-r/v\right)}{4v\left(t^2-r^2/v^2\right)}\right\} \tag{6}$$

$$dh_y(r,t) = \frac{xI\Delta l}{4\pi r^3}\left\{\left[\frac{r}{v}\frac{\partial}{\partial t}\delta\left(t-r/v\right) + \left(1+\frac{\alpha r}{2}+\frac{\alpha^2 r^2}{8}\right)\delta\left(t-r/v\right)\right] e^{\frac{-\alpha r}{2}} + e^{\frac{-t}{2\tau_0}}\frac{\alpha^2 r^3\, I_2(m)\, u\left(t-r/v\right)}{4v\left(t^2-r^2/v^2\right)}\right\} \tag{7}$$

$$dh_z(r,t) = 0 \tag{8}$$

$I_2(m)$ is the second order modified Bessel function.

The expressions given in equations (6) and (7) are considered exact because up to here, no approximation has been made.

III. Modified Images Theory

In the semi-infinite medium, the interface is taken into account using modified images theory. This method was developed by Takashima et al. [22], to calculate the complex field in conducting media; the authors show that there exist dual relationships between a complex field due to an alternating current source in a conducting medium and an electrostatic field due to a charge in a dielectric medium.

A. Homogeneous conducting medium

The complex field at "M", due to an alternating current point source, located in a homogeneous medium with conductivity (σ) and permittivity (ε), as show in Fig.2 is given by equation (10).

$$I = I_0 e^{j\omega t} \tag{9}$$

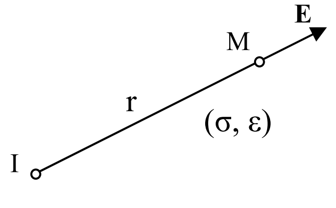


Fig.2. Alternating current in homogeneous medium

$$E = \frac{I}{4\pi r^2(\sigma + j\omega\varepsilon)} \tag{10}$$

And the potential at point "M" is given by equation (11).

$$V = -\int_{-\infty}^{r} E\, dr = \frac{I}{4\pi(\sigma + j\omega\varepsilon)r} \tag{11}$$

B. Semi infinite medium

Let us consider two conducting mediums (σ_1, ε_1), (σ_2, ε_2) and an alternating current point source located in medium.1, at a distance "h" from a plane separating boundary, as show in Fig.3. The method of images replaces the semi-infinite medium (two mediums) by only observation point medium.

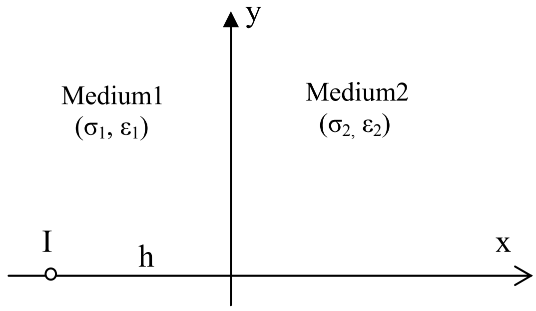


Fig.3. Two conducting mediums

In medium.1 the potential at point "M" (Fig.4), can be evaluated as sum of the current source I and its image I' (equation 12), the current source image is placed at a distance "h" from separating boundary.

$$V_1 = \frac{1}{4\pi(\sigma_1 + j\omega\varepsilon_1)}\left(\frac{I}{r}+\frac{I'}{r'}\right) \tag{12}$$

In medium.2 the potential at point M' (Fig.5), can be evaluated as potential due to the modified current source I", it given by equation (13).

$$V_2 = \frac{1}{4\pi(\sigma_2 + j\omega\varepsilon_2)}\frac{I''}{r''} \tag{13}$$

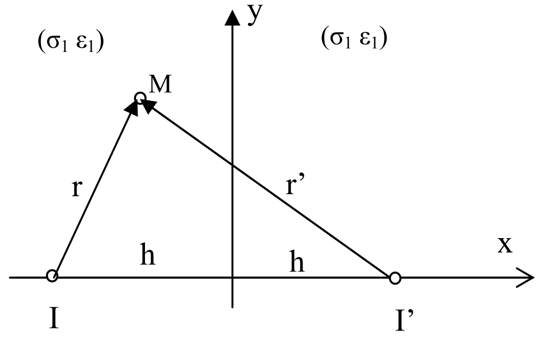


Fig.4. The current source I and its image I'

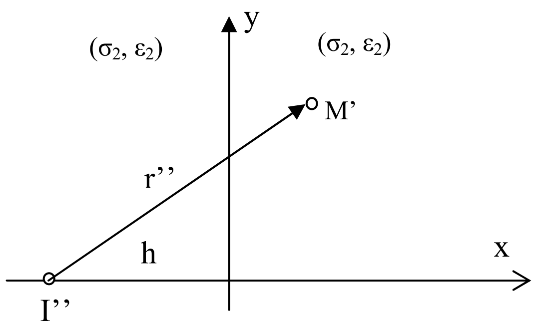


Fig.5. Modified current source I"

To determine I' and I" the following boundary conditions must hold. On the boundary plane (x=0).

$$V_1 = V_2 \tag{14}$$

And

$$\left(\sigma_1 + j\omega\varepsilon_1\right)\frac{\partial V_1}{\partial x} = \left(\sigma_2 + j\omega\varepsilon_2\right)\frac{\partial V_2}{\partial x} \tag{15}$$

From equations (11) to (15), we have

$$I' = \frac{\left(\sigma_2 + j\omega\varepsilon_2\right) - \left(\sigma_1 + j\omega\varepsilon_1\right)}{\left(\sigma_1 + j\omega\varepsilon_1\right) + \left(\sigma_2 + j\omega\varepsilon_2\right)} I = \mathrm{R}(\omega)\,\mathrm{I} \tag{16}$$

$$I'' = \frac{2(\sigma_1 + j\omega\varepsilon_1)}{\left(\sigma_1 + j\omega\varepsilon_1\right) + \left(\sigma_2 + j\omega\varepsilon_2\right)} I = T(\omega)\,\mathrm{I} \tag{17}$$

The dual relationships can be used to calculate complex fields in more complicated configurations. For buried grid (current source in soil), two cases can be considered for the position of the observation point.

C. Current source and observation point in soil

The semi infinite medium, soil and air (Fig.6.a) is replaced by observation point medium, soil in this case (Fig.6.b), and electromagnetic fields can be evaluated as a sum of the field of the current source and its image I' as follows:

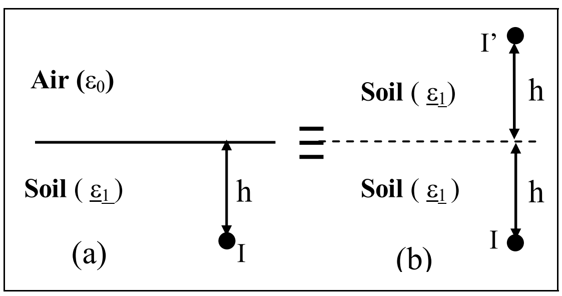


Fig.6. a) Configuration of media and source.
b) Images representing the field in soil

$$I' = \frac{\underline{\varepsilon}_1 - \varepsilon_0}{\underline{\varepsilon}_1 + \varepsilon_0} I \tag{18}$$

With $$\underline{\varepsilon}_1 = \varepsilon_1 + \frac{\sigma_1}{j\omega} \tag{19}$$

D. Current source in soil and observation point in air

The semi infinite medium, soil and air (Fig.7.a) is replaced by observation point medium, air in this case (Fig.7.b), and the electromagnetic fields can be evaluated as the field due to the modified current source (I'')*:*

$$I'' = \frac{2\varepsilon_0}{\underline{\varepsilon}_1 + \varepsilon_0} I \tag{20}$$

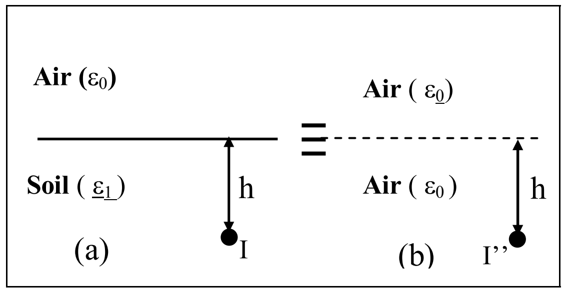


Fig.7. a) Configuration of media and source.
b) Images representing the field in air

IV. Longitudinal and Leakage Currents

The transmission lines approach for the transient analysis of buried grid based on FDTD method was developed by Nekhoul & al. [23].

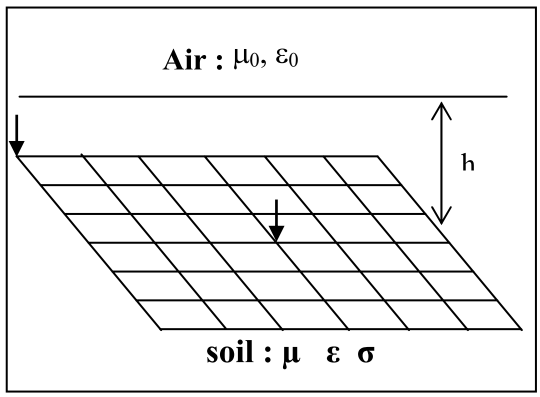


Fig.8. Buried grid

To determine the longitudinal and leakage currents in the ground conductor, we propose the direct resolution of the propagation equation in time domain, by the finite differences time domain method (FDTD).

Transmission line equations in potential and current in time domain for one dimension are given by:

$$\begin{cases} \dfrac{\partial U}{\partial \chi} = -RI - L\,\dfrac{\partial I}{\partial t} \\ \dfrac{\partial I}{\partial \chi} = -GU - C\,\dfrac{\partial U}{\partial t} \end{cases} \quad \chi = \mathrm{x \ or \ y} \tag{21}$$

R, L, C and G are the per unit length parameters of the buried conductor [24].

The propagation equation is obtained by combination of two equations in system (21)

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}-2(RC+LG)\frac{\partial U}{\partial t}$$
$$2RGU-2LC\frac{\partial^2 U}{\partial t^2}=0 \qquad (22)$$

The partial derivatives can be approximated by finite differences at point of coordinates (i, j, n), the subscripts i, j, and n, are respectively associated to variables x, y, and time. Substituting the partial derivatives by their approximations into equation (22), we obtain:

$$\begin{aligned}&\frac{1}{\Delta x^2}U(i-1,j,n))+\frac{1}{\Delta y^2}U(i,j-1,n))\\&+\frac{1}{\Delta x^2}U(i+1,j,n))+\frac{1}{\Delta y^2}U(i,j+1,n))\\&-\left[\frac{2}{\Delta x^2}+\frac{2}{\Delta y^2}+2RG+\frac{2(RC+LG)}{\Delta t}+\frac{2LC}{\Delta t^2}\right]U(i,j,n)\\&=\frac{2LG}{\Delta t^2}U(i,j,n-2)-\left[\frac{2(RC+LG)}{\Delta t}+\frac{2LC}{\Delta t^2}\right]U(i,j,n-1)\end{aligned} \qquad (23)$$

By writing this equation on all points of the buried grid, we can generate the following linear matrix equation.

$$[A][U]=[B] \qquad (24)$$

The resolution of this system gives the node voltage on the buried grid. This resolution requires the knowledge of suitable conditions in extremities of the grid. Then, the voltage at the injection point and at the extremities (on borders of the grid) must be fixed.

Once the transient voltages responses are computed, the currents in different branches of grounding grid are obtained by numerical integration of the following current line equation:

$$\frac{\partial U}{\partial \chi}=-RI-L\frac{\partial I}{\partial t} \qquad \chi = \text{x or y} \qquad (25)$$

V. Computation Procedure

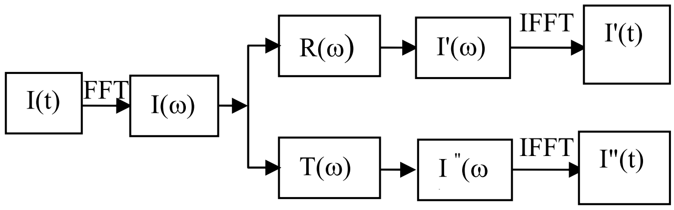
Computation results are obtained as follows:

-The resolution of the system (24) gives the node voltage on the grid;

-The currents in different branches (dipoles) of grounding grid are obtained by numerical integration of the current line equation (25);

-Once the transient currents I(t) responses are computed, we use the following syntaxes for determining the modified current source I"(t) and current source image I'(t) for each dipole, were FFT, IFFT are Fast Fourier Transform and Inverse Fast Fourier Transform respectively.

Using the current distribution, the components in time domain of radiated magnetic field are calculated by analytical formula (equations 6 and 7) for each dipole. The total radiated magnetic field is the sum of the contributions from each constituent dipoles.



VI. Application and Validation

For analysis we take the same example treated by Grcev et al.[10], a 60 m by 60 m square ground grid with 10 m by 10 m meshes, made of copper conductor with 1.4 cm diameter, and buried at a depth of 0.5 m under the earth's surface. The soil is assumed to be homogenous with a resistivity 1000 Ωm, a relative permittivity 9 and a relative permeability 1.

In the following applications, we use the typical double exponential lightning current impulse given by:

$$I(t)=I_0\left(e^{-\alpha t}-e^{-\beta t}\right) \qquad (26)$$

With

$$I_0=1.635KA;\ \alpha=0.142\,1/\mu s\ ;\ \beta=1.073\ 1/\mu s$$

A. Injection at the corner point of the grid

In the first application, the lightning stroke is fed at the corner point of the grid (Fig.9). The profile.1 is directly above the interface from (0,-5, 0.5) to (0, 65, 0.5).

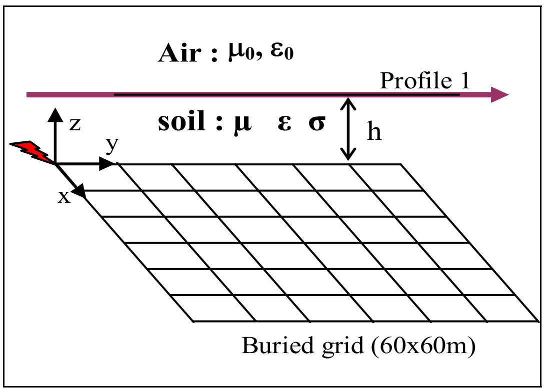


Fig.9. Grid under the interface and profile.1

Fig.10 illustrates the magnetic field along profile.1 (70 m) at the soil surface, parallel to and centred on the conductor, as depicted on Fig. 9, at t =10 μs.

Fig.11 shows the spatial distribution form 3D of the magnetic field, to remote ground at the soil surface (70m x 70m) parallel to and centred on the grid, at t =10 μs.

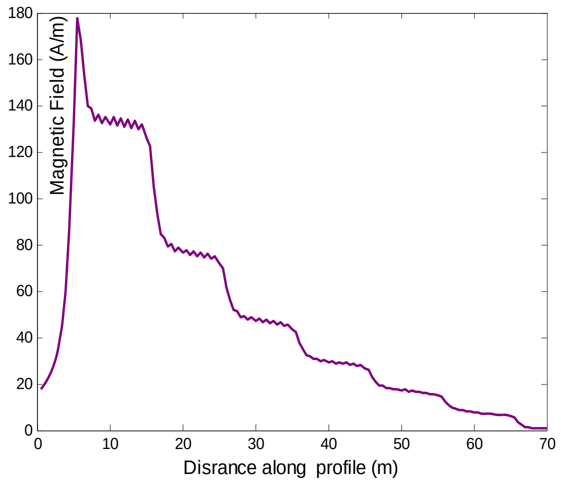


Fig.10. Magnetic field along profile.1 (t=10µs)

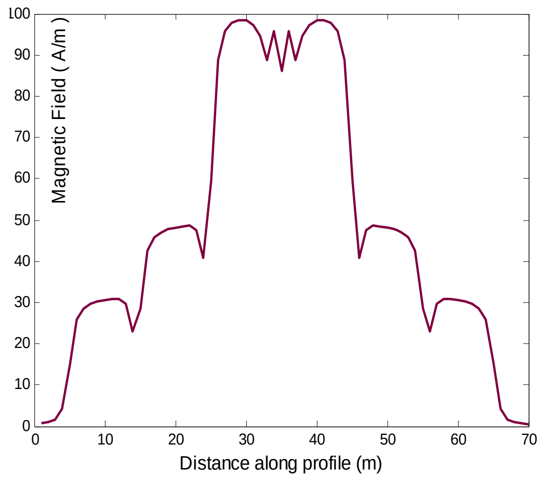


Fig.13. Magnetic field along profile.1 (t=10µs)

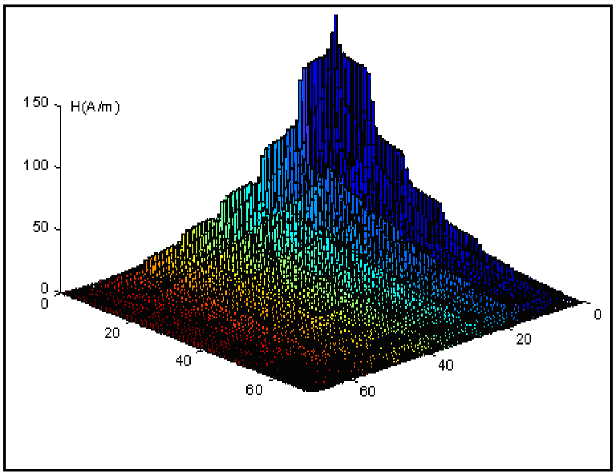


Fig.11. Magnetic field 3D (t=10µs)

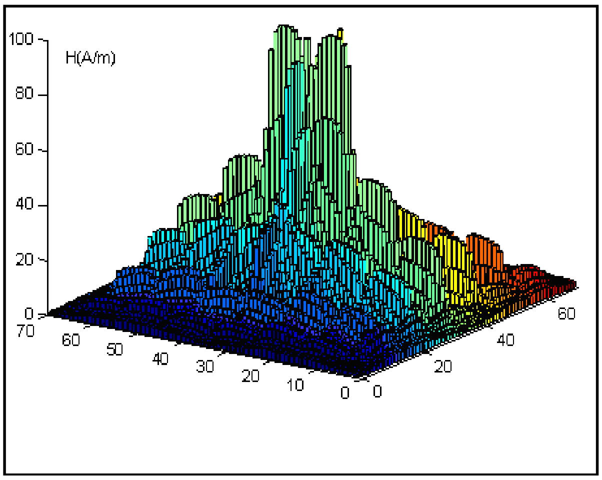


Fig.14. Magnetic field 3D (t=10µs) middle injection

B. *Injection at the middle point of the grid*

In the second application, the lightning stroke is fed at the middle point of the grid. The profile.2 is directly above the interface from (30,-5, 0.5) to (30, 65, 0.5).

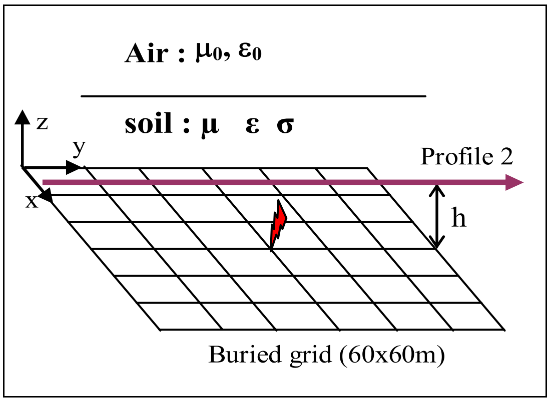


Fig.12. Grid under the interface and profile.2

Fig.13 illustrates the magnetic field along profile.2 (70 m) at the soil surface parallel to and centred on the conductor, as depicted on Fig.12, at t =10 µs.

Fig.14 shows the spatial distribution form 3D of the magnetic field to remote ground at the soil surface (70 m x 70m) parallel to and centred on the grid, at t =10 µs.

Presented results show large differences of the magnetic field to remote ground between points at the interface. High values of the magnetic field occur near the injecting point and are further spreading toward the rest of the ground surface while the values are decreasing.

The different locations of feed point are shown in figures 9 and 12. The curves in figures 10 and 13 compare the magnitude of magnetic field, for the feed point at one corner and the center of the grid with the same current injection.

For the same grounding grid, the maximal magnitude of magnetic field, for feed point at the center is much smaller than that for feed point at the corner. The location of feed point at the center is strongly recommended, instead of at the corner.

C. Comparison with other results

For comparison with the result published by Dawalibi et al. [25], we use the same physical situation. The grid depicted in figure 12 is buried in soil how is assumed to be homogenous with a resistivity 100 Ωm, a relative permittivity 36 and a relative permeability 1.

Fig.15 shows the spatial distribution form of the magnetic field to remote ground at the soil surface (70 m x 70 m) parallel to and centred on the grid at t = 20 μS.

Fig.16 shows the same spatial distribution form of the magnetic field obtained, at low frequency, by Dawalibi et al. [24] using electromagnetic field approach.

Figures 14 and 15 show that there are significant differences between the static (t=20 μs) and the quasi-static (t=10 μs) cases, and they show that our computation results were successfully compared to those obtained by Dawalibi et al. [25].

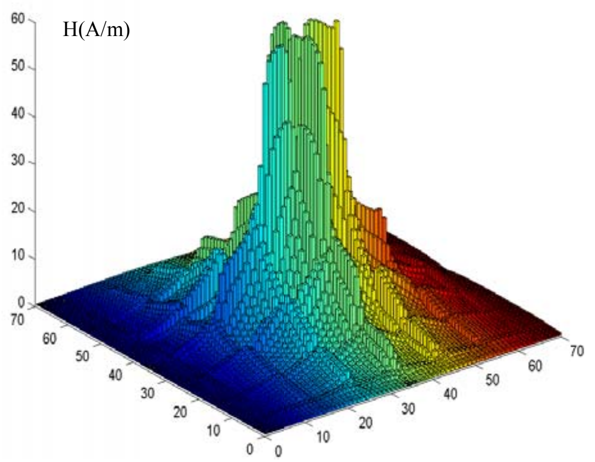


Fig.15. Magnetic field 3D (t=20μS) middle injection

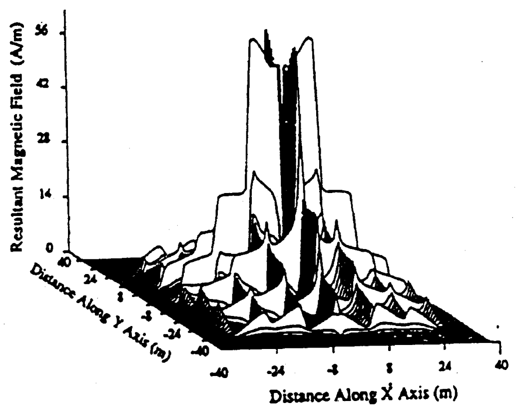


Fig.16. Magnetic field 3D middle injection [25]

VII. Conclusion

In this work, a hybrid approach for analysis transient magnetic field behaviour of grounding grid under lightning stroke is presented. This study is based on: transmission line approach, electrical dipole theory and modified images theory. In this formalism, the computation is carried out in two steps: one numerical, for determining the current distribution on the grid by direct resolution of the propagation equation in the temporal space, using the finite differences time domain method (FDTD) and the other, analytical, for calculating magnetic field's components. The interface between earth and air is taken into account using modified image theory instead Sommerfeld's integrals.

The computation results are based on a general formulation, in time domain, which permit the observation point in air or in soil, and are in good agreement with that based on electromagnetic fields approach. The location of feed point at the center is strongly recommended, instead of at the corner**.** The model can be used to predict the transient characteristic of grounding systems because, it can calculate magnetic field in any points of interest; it is sufficiently accurate, time efficient, and easy to apply.

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