Transient Analysis of Grounding Systems Associated to Substation Structures under Lightning Strokes

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Original scientific paper

Abstract: **In this paper we propose a new formalism for analyzing the transient behavior of grounding systems associated to substation structures (Faraday-cage) under lightning strokes in unsettled regime. The protective device to study is formed of a guard filet connected to a grounding grid by simple conductors called down conductors. Our formalism is based on the resolution of the propagation equation in potential on 3D. The purpose of our proposition is the direct analyzing in time domain and simple implementation. We compare the results obtained by this new approach to results published in literature.**

Index terms: **Faraday-cage, 3D, grounding grid, propagation equation, FDTD.**

I. Introduction

In order to achieve a good protection of VHV and HV substations against the lightning effects, it is indispensable to use guard filets and grounding grids. A guard filet bonded to a grounding grid is identified by a faraday-cage.

The analysis of grounding systems behaviour in unsettled regime stay among the principal preoccupations of industries in electrotechnics, electronics, telecommunications, computer science, etc. When lightning strikes a substation or transmission lines, high currents generated by the stroke will flow into the grounding systems and dissipate in the soil. Lightning-induced currents flowing out in the earth of an aerial station can generate radiated perturbations susceptible to disrupt the electromagnetic environment of local electric systems (auto pollution), and may be dangerous to personnel working nearby.

Traditionally, in the literature, the problem of a grounding grid is treated by using antenna theory and moments method [1] in case of direct injection of a lightning stroke on grounding grid. The purpose of our work is to show that problem of grounding systems associated to substation structures can be treated by simpler numeric tools to implement.

In our work, we propose a new formulation which consists in the direct resolution by FDTD (finite difference time domain) of differential equation in potential spatio-temporal on 3D, while taking into account the semi-infinite environments and the conditions at extremities.

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This proposed model allows computation of the voltage which is the node state variable (continue in each node) of the whole set (buried grid, guard filet and down conductors), then we deduct the currents in different branches.

II. Propagation Equation in Nodal Scalar Potential

The system (aerial guard filet-buried grounding grid) under study is represented in Fig. 1:

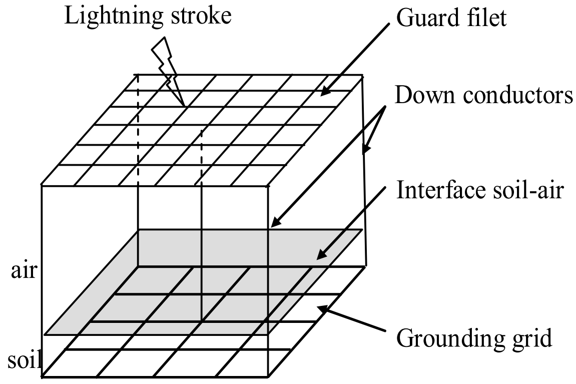

Fig. 1. Grounding grid in substation.

Temporal lines equations in potential and in current when the propagation is one-dimensional (1D) are given by:

$$\begin{cases} \dfrac{\partial U}{\partial \eta} + R\,I + L\,\dfrac{\partial I}{\partial t} = 0 \\ \dfrac{\partial I}{\partial \eta} + G\,U + C\,\dfrac{\partial U}{\partial t} = 0 \end{cases} \qquad \eta = x, y\ or\ z \quad (1)$$

Combining the two equations of system (1) to eliminate one of the two variables, we get the wave equation in potential, called telegrapher's equation:

- If the propagation is in three-directions x, y and z (3D):

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} - 3RGU - 3(RC + LG)\frac{\partial U}{\partial t} - 3LC\frac{\partial^2 U}{\partial t^2} = 0 \quad (2)$$

- If the propagation is in two-directions x and y (2D):

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}-2RGU-2(RC+LG)\frac{\partial U}{\partial t} -2LC\frac{\partial^2 U}{\partial t^2}=0 \quad (3)$$

- If the propagation is in one-direction (1D):

$$\frac{\partial^2 U}{\partial \eta^2}-RGU-(RC+LG)\frac{\partial U}{\partial t} -LC\frac{\partial^2 U}{\partial t^2}=0 \qquad \eta = x, y \; or \; z \quad (4)$$

R, L, C and G: per unit length parameters of the conductors, defined by the propagation direction.

Our system is constituted of several types of conductors, the resolution of the propagation equation requires the knowledge of the per unit length parameters of the buried grid, the down conductors and the guard filet, these parameters can be calculated as follows:

- For the buried part, the per unit lines parameters of buried vertical and horizontal electrodes can be calculated with two manners: E.D. Sunde [2] formulas or Y. Liu [3] formulas,

- For the aerial part, E.J.Rogers formulas [4], [5] permit to calculate the pert unit length parameters of finite length vertical and horizontal conductors.

III. Discretization of Propagation Equation in Potential by the Finite Differences

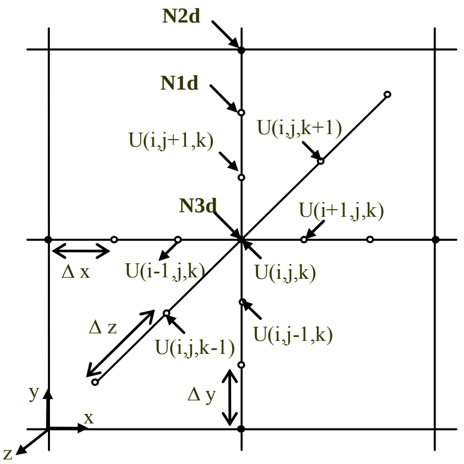

Fig. 2. Spatial discretization.

- If the node is a crossing point of two metallic bars of the grid or of the guard filet, the spatial discretization is in 2D (N2d),

- If the node is a crossing point of two metallic bars of the grid or of the guard filet with down conductors, the spatial discretization is in 3D (N3d),

- Otherwise, in all other points of the grid, of the guard filet or of the down conductors, the spatial discretization is in 1D (N1d).

The spatial and temporal derivative approximation at point of coordinates (i, j, k) while using simple finite differences permit us to write:

$$\frac{\partial^2 U}{\partial x^2}=\frac{1}{\Delta x^2}\left(U^n_{i+1,j,k}-2U^n_{i,j,k}+U^n_{i-1,j,k}\right) \quad (5)$$

$$\frac{\partial^2 U}{\partial y^2}=\frac{1}{\Delta y^2}\left(U^n_{i,j+1,k}-2U^n_{i,j,k}+U^n_{i,j-1,k}\right) \quad (6)$$

$$\frac{\partial^2 U}{\partial z^2}=\frac{1}{\Delta z^2}\left(U^n_{i,j,k+1}-2U^n_{i,j,k}+U^n_{i,j,k-1}\right) \quad (7)$$

$$\frac{\partial U}{\partial t}=\frac{1}{\Delta t}\left(U^n_{i,j,k}-U^{n-1}_{i,j,k}\right) \quad (8)$$

$$\frac{\partial^2 U}{\partial t^2}=\frac{1}{\Delta t^2}\left(U^n_{i,j,k}-2U^{n-1}_{i,j,k}+U^{n-2}_{i,j,k}\right) \quad (9)$$

Substituting the partial derivatives by their approximations into equation (2) of propagation in potential on 3D, we obtain:

$$\begin{aligned}&\left[-\frac{2}{(\Delta x)^2}-\frac{2}{(\Delta y)^2}-\frac{2}{(\Delta z)^2}-3RG -\frac{3(LG+RC)}{\Delta t}-\frac{3LC}{(\Delta t)^2}\right]U^n_{i,j,k}\\ &+\left[\frac{1}{\Delta x}\right]U^n_{i+1,j,k}+\left[\frac{1}{\Delta x}\right]U^n_{i-1,j,k}+\left[\frac{1}{\Delta y}\right]U^n_{i,j+1,k}\\ &+\left[\frac{1}{\Delta y}\right]U^n_{i,j-1,k}+\left[\frac{1}{\Delta z}\right]U^n_{i,j,k+1}+\left[\frac{1}{\Delta z}\right]U^n_{i,j,k-1}\\ &=\left(-\frac{3(RC+LG)}{\Delta t}-\frac{6LC}{(\Delta t)^2}\right)U^{n-1}_{i,j,k}+\frac{3LC}{(\Delta t)^2}U^{n-2}_{i,j,k}\end{aligned} \quad (10)$$

The equation (10) gotten thus after is discretization by FDTD, permits us to generate a system of linear equations of the type [A][U]=[B]:

$$\begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1k} & \cdots & A_{1l} & \cdots & A_{1N}\\ A_{21} & A_{22} & \cdots & A_{2k} & \cdots & A_{2l} & \cdots & A_{2N}\\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots\\ A_{1k} & A_{2k} & \cdots & A_{kk} & \cdots & A_{kl} & \cdots & A_{kN}\\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots\\ A_{l1} & A_{l2} & \cdots & A_{lk} & \cdots & A_{ll} & \cdots & A_{lN}\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots\\ A_{N1} & A_{N2} & \cdots & A_{Nk} & \cdots & A_{Nl} & \cdots & A_{NN}\end{bmatrix}\begin{bmatrix}U_1\\U_2\\ \vdots\\U_k\\ \vdots\\U_l\\ \vdots\\U_N\end{bmatrix}=\begin{bmatrix}B_1\\B_2\\ \vdots\\B_k\\ \vdots\\B_l\\ \vdots\\B_N\end{bmatrix} \quad (11)$$

[A]: matrix of coefficients,
[U]: node voltage vector representing the unknown variables including the aerial nodes, buried nodes and the nodes of air-soil interface,
[B]: the second member of the equation,
N: total number of nodes.

The elements of matrix [A] and vector [B] are defined as follows:

- The diagonal elements of matrix [A]:

$$A_{kk} = -\frac{2}{(\Delta x)^2} - \frac{2}{(\Delta y)^2} - \frac{2}{(\Delta z)^2} - 3RG - \frac{3(LG+RC)}{\Delta t} - \frac{3LC}{(\Delta t)^2} \qquad (12)$$

- Elements outside of the diagonal of matrix [A]:

$$A_{kl} = \frac{1}{(\Delta x)^2} \quad \text{if l is the adjacent node to node k in x direction} \qquad (13)$$

$$A_{kl} = \frac{1}{(\Delta y)^2} \quad \text{if l is the adjacent node to node k in y direction} \qquad (14)$$

$$A_{kl} = \frac{1}{(\Delta z)^2} \quad \text{if l is the adjacent node to node k in z direction} \qquad (15)$$

$$A_{kl} = 0 \quad \text{else where} \qquad (16)$$

- Elements of vector [B]:

$$B_k = \left(-\frac{3(RC+LG)}{\Delta t} - \frac{6LC}{(\Delta t)^2} \right) U_{i,j,k}^{n-1} + \frac{3LC}{(\Delta t)^2} U_{i,j,k}^{n-2} \qquad (17)$$

Once equation (11) is generated, its' resolution allows the determination of the node voltage. The numerical discretization by FDTD requires the use of suitable conditions at extremities of the buried grid and the guard filet.

IV. Branch Currents

At every step of calculation, once all the transient voltage responses have been computed, the currents in different branches of grounding grid, of down conductors and of the guard fillet are obtained by numerical integration of current line equation (18).

$$\frac{\partial U}{\partial \eta} + R\,I + L\,\frac{\partial I}{\partial t} = 0 \qquad \eta = x, y \text{ or } z \qquad (18)$$

V. Imposition of Conditions

A. Hold in Account of Interface Nodes

Our proposed mathematical analysis uses the voltage as the basis variable which is a nodal quantity, its' continuity on the soil-air interface is naturally insured.

B. Open Boundary Problem

Lines Equations are obtained directly from the general theory of electromagnetic field and its properties, it is therefore imperative to hold in account the two semi-infinite environments (air and soil).

The proposed formalism allows us to deduce the distribution of currents and voltages only. The notion of open boundary and ground-air interface is already taken in account when we calculate the per unit length parameters of the electrical circuit of the grounding electrode [2], [3].

This holding in account of the semi-infinite environments with plane interface is identical to the case of transmission line with ground return.

C. Imposition of Conditions in Extremity

The resolution of the propagation equation (2) requires the knowledge of conditions at the extremities. Then, the voltages at the injection point and at the extremities (on borders of the grid or the guard filet) must be fixed [6].

V. Validations and Application

In order to validate our theoretical work, we propose to confront our calculation results to those achieved for applications already published in the literature and treated by the antennas formalism [1], [8].

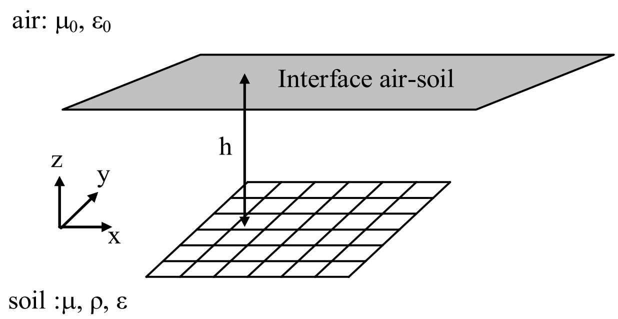

Fig. 3. Buried grid.

In this validation, we propose to treat the example achieved by L.Grcev [1] while using the system presented in Fig. 4.

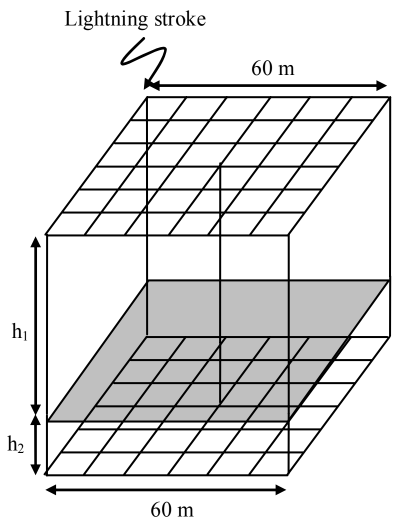

Fig. 4. Grounding grid in substation.

A. First Application

To get the same application treated by L.Grcev [1], we block the passage of the current in conductors of guard filet and we let it pass only in one down conductor bonded to grounding grid, then we consider in a first time a very short down conductor. We notice that the problem is treated in 3D.

Table I shows the numerical values of the electrical and physical parameters of the first application.

TABLE I
PARAMETER OF THE FIRST APPLICATION

Lightning stroke generator	Electrode	Soil
$I(t) = I_0 (e^{-\alpha t} - e^{-\beta t})$ $I_0 = 1.63\, kA$ $\alpha = 0.0142\, \mu s^{-1}$ $\beta = 1.073\, \mu s^{-1}$	l_f = 60 m l_g = 60 m Ø = 1.4 cm h1 = 0.5m h2 = 0.5m	$\rho = 100\, \Omega.m$ $\varepsilon r = 36$

In this application, the lightning stroke is injected at the middle point of the guard filet (Fig. 4).

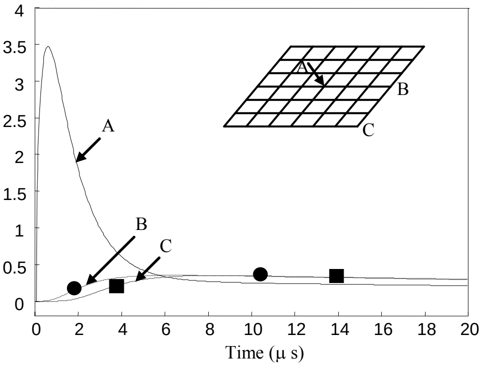

Fig. 5. a. Transient voltages at points A, B and C.

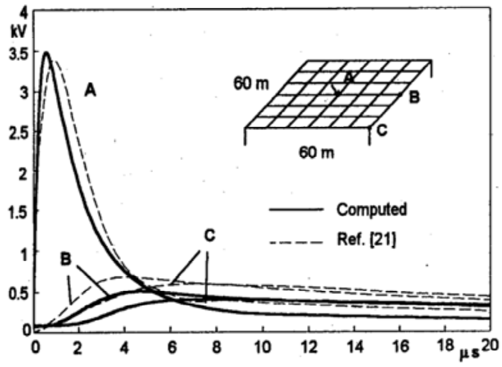

Fig. 5. b. Transient voltages at points A, B and C [1].

In the following applications, we use a double-exponential current impulse given by:

$$I(t) = I_0 (e^{-\alpha t} - e^{-\beta t})$$
$$I_0 = 1.0167\, kA,\ \alpha = 0.0142\, \mu s^{-1},\ \beta = 5.073\, \mu s^{-1} \quad (19)$$

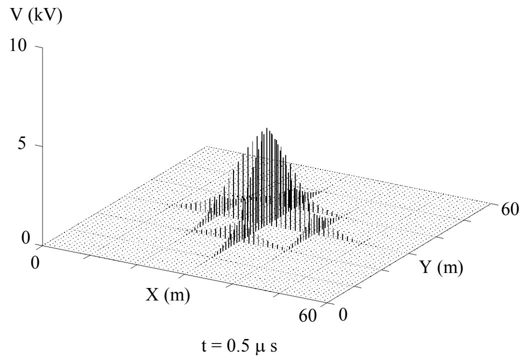

Fig. 6. a. Transient voltages response at the surface of the grid at t = 0.5μs.

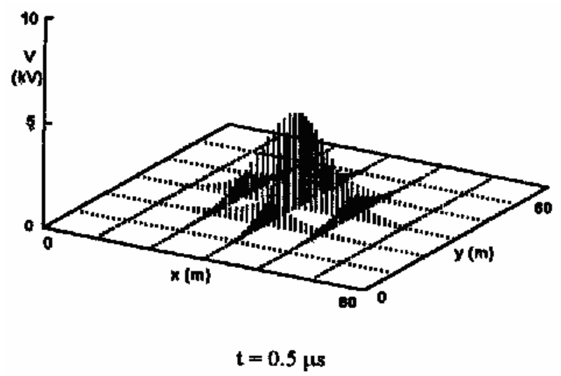

Fig. 6. b. Transient voltages response at the surface of the grid at t = 0.5μs [1].

L.Grcev [1] treats the example while injecting the lightning surge current directly on the grounding grid (fig. 3), while in our work, we inject the lightning stroke on the top of a down conductor situated in air at a height of 0.5 m. The results (fig. 5.a and 6.b) are practically the same in shape and in magnitude. Our simulation is nearer to the reality.

B. Second application

In this application, we let the passage of the currents in different conductors of the device (see fig. 4) and we take in a first time a very short down conductor. The lightning stroke is injected at the middle point of the guard filet.

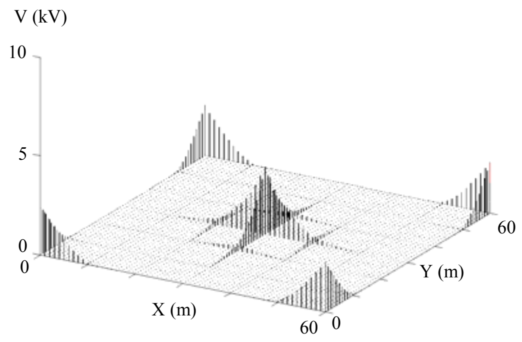

Fig. 7. Transient voltages response at the surface of the grid at t = 0.5μs.

In the second time, we vary the length of the down conductors above the soil. We begin by very short down conductors, and then we increase their lengths. The lightning stroke is injected at the corner of the guard filet.

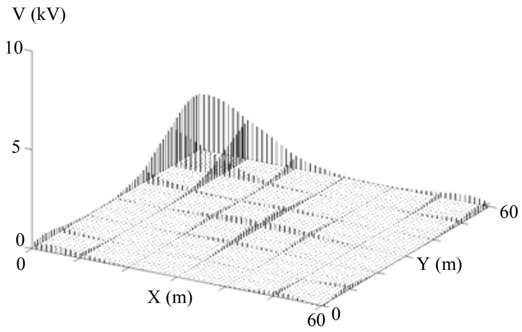

Fig. 8. a. Transient voltages response at the surface of the grid at t =1μs (h1=0.5 m).

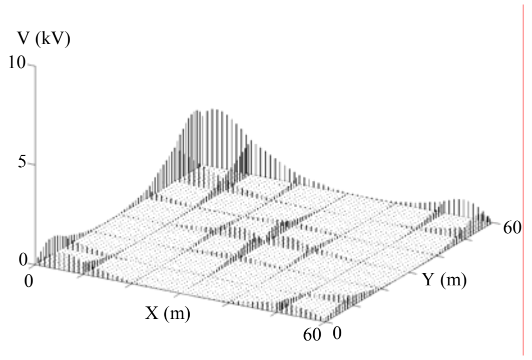

Fig. 8. b. Transient voltages response at the surface of the grid at t =1μs (h1=10 m).

The use of guard filet allows a better evacuation of the stroke discharge, indeed, the transient voltages magnitudes decrease at the surface of the grid (fig. 7) comparatively to the first application when the current is injected in a single point of the grounding grid (fig. 6.a).

While increasing the length of the down conductors, the propagation appears in potential relief undulations. This result is confirmed by the measure results achieved in [7].

C. Third application

In this application we propose to treat the example achieved by F. Dawalibi [8] while the lightning surge current is injecting on the top of an above-ground metallic structure bonded to the grounding grid and located at the corner of the substation (Fig. 9). We note that our formalism can only treat the nodal electric quantities localized on the metallic structure.

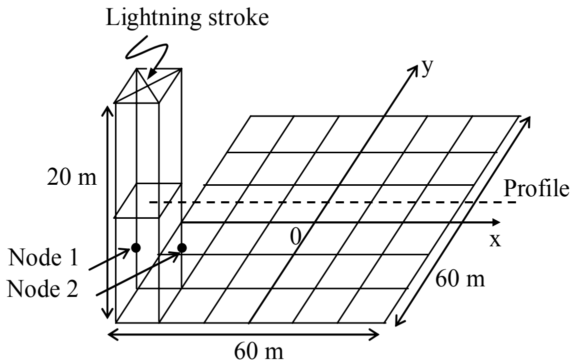

Fig. 9. Grounding grid in substation.

The computations of F. Dawalibi [8] were carried out at the various observation points located on the earth surface along X-direction profile. In our work, we treat this application but the calculations profile is located on the ground depth (i.e., at 0.5 m) (Fig. 9).

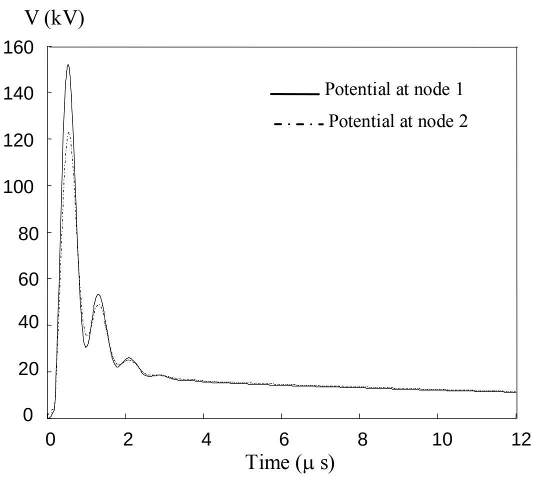

Fig. 10. Transient voltages at nodes 1 and 2.

In Fig. 10, we present the potential variation in the nodes 1, 2 as indicated in Fig. 9. The nodes 1 and 2 are situated on the soil-air interface on down conductors (fig. 9).

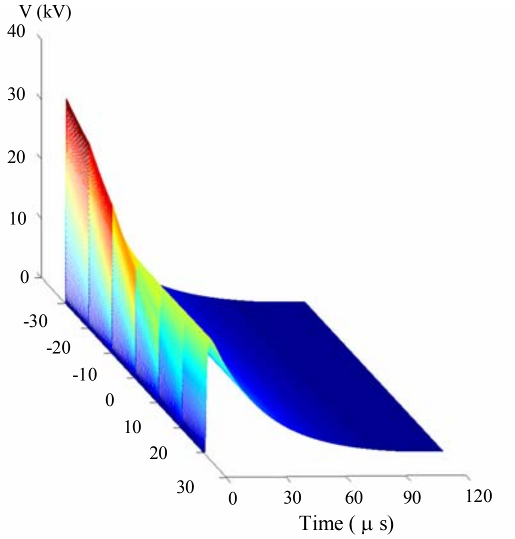

Fig. 11. Transient voltages along the profile.

Fig. 11 presents our calculation result for the same example published by F. Dawalibi [8] along profile that presented in Fig. 9. We notice that the general shape is conserved. For the amplitude, it is logical that the potentials on the soil-air interface are more elevated because the grounding grid conductivity is more important then the soil conductivity.

VI. CONCLUSION

In this paper, we propose a new formalism for studying the transient behavior of a three dimensional device (guard filet-grounding grid) subjected to a lightning stroke.

We have realized some examples treated in the literature [1] when the current stroke is injected at the top of an above-ground structure (guard filet bonded to the grounding grid). Using our model, we have obtained results with the same precisions to those obtained by antennas theory [1]. Then we can say that our model based on the resolution of the propagation equation in 3D by FDTD constitutes an important advantage by comparison to antenna theory. The advantage of our mathematical model is the simplicity of practice implementation as well as the less calculation time which conduct to the same results published by L.Grcev [1]. We have also proposed some applications for a Faraday-cage.

The weakness of our formalism is that it considers the per unit length parameters frequency-independents, which is not the case for the antennas theory.

Our formalism, doesn't take in account interactions between all elements of the device (guard filet-grounding grid). This second weakness is probably less important because the frequency spectrum of a lightning wave does' not exceed a few MHz.

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