Transient Performance of 3D Substation Systems Subjected to Lightning Stroke

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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 transient regime. The protective device to study is formed of an aerial wire mesh connected to a grounding grid by simple conductors called down conductors. Our formalism is based on the resolution of the propagation equation in potential in 3D. The purpose of our proposition is the direct analysis in time domain and the simplicity of the implementation. We compare the results obtained by this new approach to results published in literature.

Introduction

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

The analysis of grounding systems behaviour in transient 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 electrical 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 moment method [1] in case of direct injection of a lightning stroke on grounding grid. The purpose of our work is to show that the problem of grounding systems associated to substation structures can be treated by numerical tools simpler to implement.

In our work, we propose a new formulation consisting in the direct resolution by FDTD (finite difference time domain) of differential equation in potential spatio-temporal in 3D, while taking into account the semi-infinite environments and the conditions in extremities. This proposed model allows the computation of the voltage which is the node state variable (continue in each node) of the whole set (buried grid, aerial wire mesh and down conductors), then we deduce the currents in different branches.

Propagation Equation in Nodal Scalar Potential

The system (aerial wire mesh-buried grounding grid) under study is represented in figure 1:

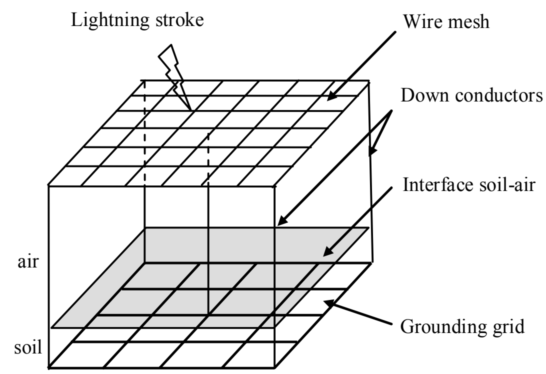

Figure 1: Grounding grid in substation.

Lines equations in potential and current in temporal domain for a one-dimensional (1D) propagation are given by:

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

Combination of the two equations in system (1) eliminates one of the two variables and gives the wave equation (telegraphers equation):

- In case of tree-directional (3D) propagation (x, y and z) we get:

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

- 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 direction of propagation.

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 both of the buried grid, the down conductors and the aerial wire mesh, these parameters can be calculated as follows:
- for the aerial part, E.J.Rogers formulas [4-5] allows the calculation of the pert unit length parameters of finite length vertical and horizontal conductors,
- for the buried part, the per unit lines parameters of buried vertical and horizontal electrodes can be calculated either by E.D. Sunde [2] formulas or by Y. Liu [3] formulas.

Discretization of Propagation Equation in Potential by the Finite Differences

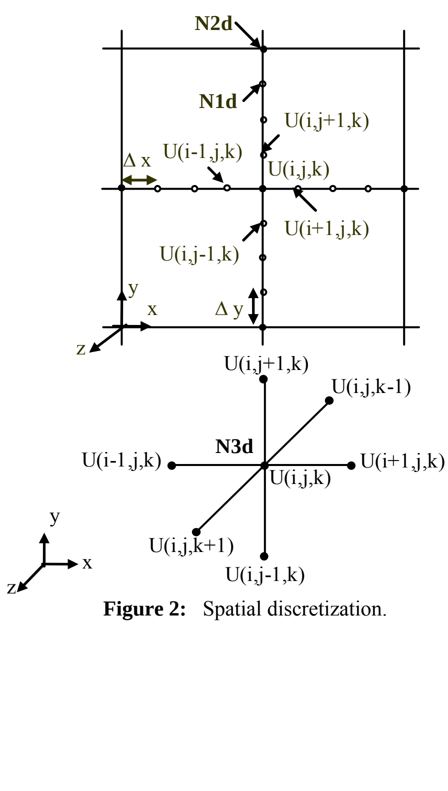

Figure 2: Spatial discretization.

- If the node is the crossing point of two metallic bars of the grid or the aerial wire mesh, the spatial discretization is in 2D (N2d),
- If the node is the crossing point of two metallic bars of the grid or the aerial wire mesh with down conductors, the spatial discretization is in 3D (N3d),
- otherwise in all other point of the grid, the aerial wire mesh and the down conductors, spatial discretization is in 1D (N1d).

The spatial and temporal derivative approximation at point of coordinates (i, j, k) while using simple finites differences allows 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 in 3D, we obtain

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

We notice that the obtained equation (10) is discretized by FDTD. It permits us to generate the following system of linear equations of the type [A][U]=[B]:

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

[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 nods.

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

- the diagonal elements of matrix [A]:

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

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

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

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

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

$$A_{kl} = 0 \quad \text{else where} \tag{16}$$

- element of vector [B]:

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

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 in extremities of the buried grid and the aerial wire mesh.

Branch Currents

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

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

Boundary Conditions

Take into Account of Interface Nodes

The mathematical analysis that we propose uses the voltage as the basis variable which is a nodal quantity, its continuity on the soil-air interface is naturally insured.

Open Boundary Problem

Lines equations are obtained directly from the general theory of electromagnetic field and its properties, it is therefore imperative to take into 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 linear parameters of the electrical circuit of the grounding electrode [2-3].

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

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 aerial wire mesh) must be fixed [6].

Validations

With no measured and calculated results already published for analyzing the transient performances of such a system (aerial wire mesh + grounding grid) we propose to realize some examples treated in the literature by using our model, the treated problem is illustrated in figure 3 [1].

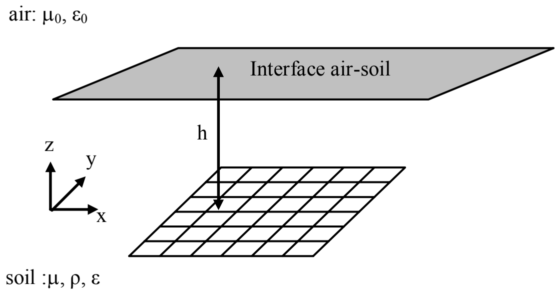

Figure 3: Buried grid.

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

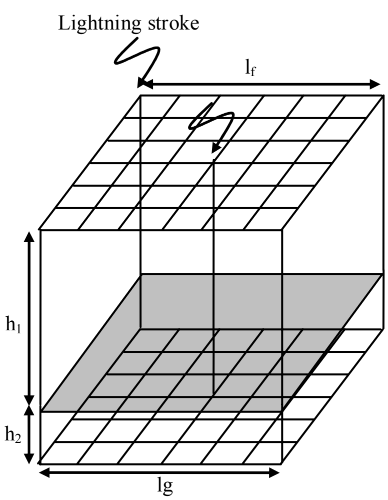

Figure 4: Grounding grid in substation.

The First Application

To get the same application treated by L.Grcev [1], we block the passage of the current in conductors of wire mesh 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 1 shows the numerical values of the electrical and physical parameters of the first application.

Table 1: 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 aerial wire mesh (figure 4).

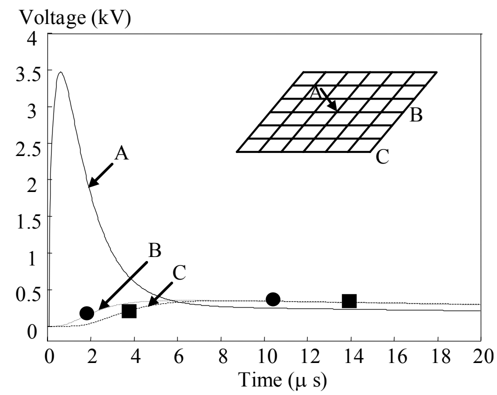

Figure 5.a: Transient voltages at points A, B and C.

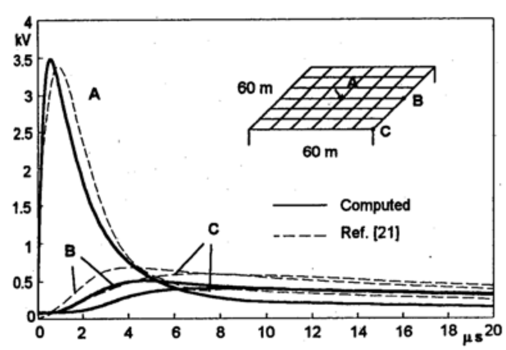

Figure 5.b: Transient voltages at points A, B and C [1].

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

$$I(t) = I_0 (e^{-\alpha t} - e^{-\beta t})$$

$$I_0 = 1.0167\, kA,\ \alpha = 0.0142\, \mu s^{-1},\ \beta = 5.073\, \mu s^{-1}$$

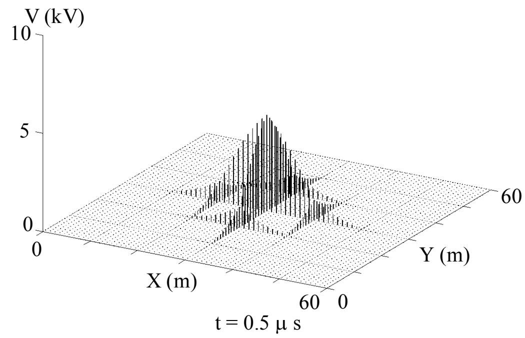

Figure 6.a: Transient voltages response at the surface of the grid at t = 0.5μs.

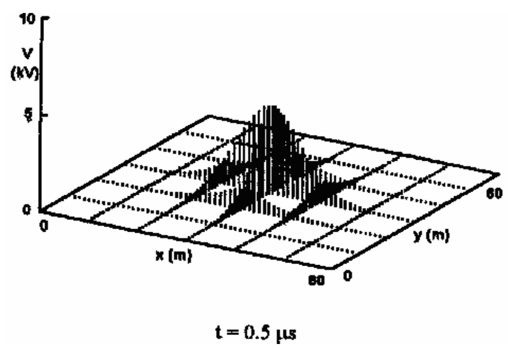

Figure 6.b: Transient voltages response at the surface of the grid at t = 0.5μs [1].

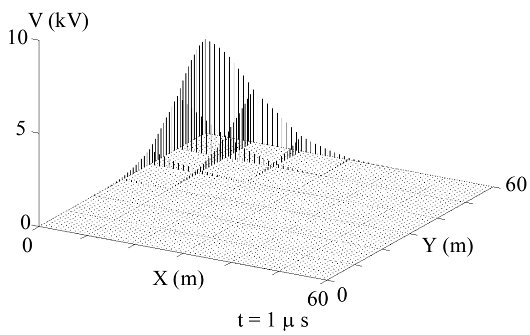

Figure 7.a: Transient voltages response at the surface of the grid at t = 1μs (h1=0.5 m).

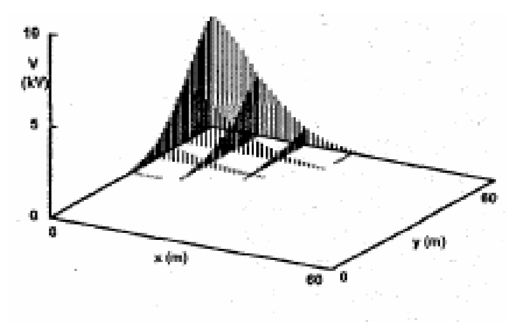

Figure 7.b: Transient voltages response at the surface of the grid at t = 1μs [1].

L.Grcev [1] treats the example while injecting the lightning surge current directly on the grounding grid (figure 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 (figure 5.a to 7.b) are practically the same in shape and in magnitude. Our simulation is nearer to the reality.

The second application

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

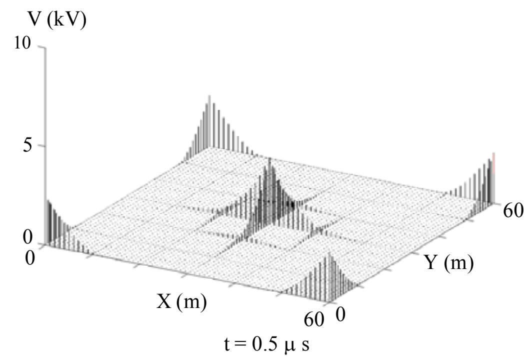

Figure 8: Transient voltages response at the surface of the grid at t = 0.5μs.

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 aerial wire mesh.

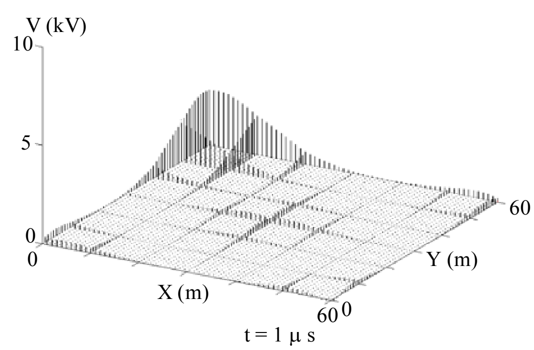

Figure 9.a: Transient voltages response at the surface of the grid at t = 0.5 μs (h1=0.5 m).

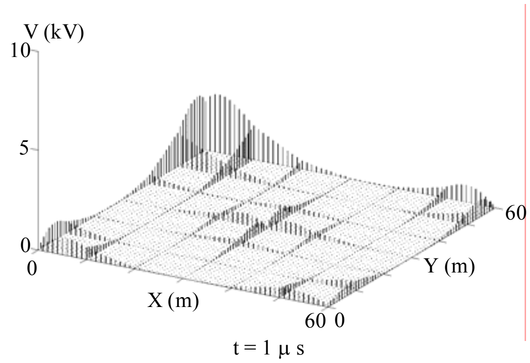

Figure 9.b: Transient voltages response at the surface of the grid at t = 0.5 µs (h1=10 m).

The use of the aerial wire mesh allows a better evacuation of the stroke discharge indeed the transient voltages magnitudes decrease at the surface of the grid (figure 8) comparatively to the first application when the current is injected in a single point of the grounding grid (figure 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].

Conclusion

In this paper, we have studied the transient behaviour of a three dimensional device (aerial wire mesh-grounding grid) subjected to a lightning stroke. This analysis has been described in the case of a current stroke injection at the top of an above-ground structure (wire mesh) bounded to the grounding grid.

In the first time, in the absence of measured and calculated results already published for the analysis of such a system (aerial wire mesh-grounding grid), we have realized some examples treated in the literature [1]. Using our model, we have obtained results with the same precisions to those obtain by antennas theory [1]. Then we can say that our model based on the resolution of the diffusion equation in 3D by FDTD constitutes a big 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 (aerial wire mesh-grounding grid). This second weakness is probably less important because frequency spectrum of a lightning wave does' not exceed few MHz.

References

[1] L. D. Grcev, "*Computer Analysis of Transient Voltages in Large Grounding Systems*", IEEE Transactions on Power Delivery, Vol.11, N° 2, April 1996, pp. 815-823.

[2] E. D. Sunde, *Earth Conducting Effects in Transmission Systems*, New York, N. Y. Dover publications, Inc 1968.

[3] Y. Liu, N.Theethayi, and R. Thottappillil, "*An Engineering Model for Transient Analysis of Grounding Systems Under Lightning Strikes: Nonuniform Transmission-Line Approach*", IEEE, Trans. On Power Delivery, Vol.20, No, 2, April 2005, pp. 722-730.

[4] E. J. Rogers, and J. F. White, "*Mutual Coupling Between Finite Lengths of Parallel or Angled Horizontal Earth Return Conductors*", IEEE, Trans. On Power Delivery, Vol.4, No, 1, January 1989, pp. 103-113.

[5] E. J. Rogers, and J. F. White, "*Mutual Coupling Between Horizontal Earth Return Conductors Using Actual Routing Parameters*", IEEE, Trans. On Power Delivery, Vol.5, No, 3, July 1990, pp. 1266-1274.

[6] B. Nekhoul, B. Harrat, K. Kerroum, K. el Khamlichi Drissi, *Caractérisation d'une grille de mise à la terre par résolution d'une équation de propagation*, Revue International de Génie électrique, 8 N° 3-4/2005, pp.407-423.

[7] M. Akke, T.Biro, "*Measurements of the Frequency Dependent Impedance of a Thin Wire with Ground Return*", IEEE, Trans. On Power Delivery, Vol.20, No, 2, April 2005, pp. 1748-1752.

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