EMC ASPECTS IN A STEEL STRUCTURE STRUCK BY LIGHTNING

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Abstract - The EMC analysis of a complex steel structure struck by a direct lightning, based on a simulation model developed by the authors, is here presented. For this proposal, simulations of the resulted magnetic field, as a function of the time, in the places where the higher susceptibility equipment will be installed, considering different lightning struck points, are carried out and these results are compared with some established limits. Some conclusions are presented, pointing out the advantages of the considered EMI prediction model during the design of the electrical and electronic installations, when lightning effects should be considered.

INTRODUCTION

Beyond the safety aspects, the resulted effects from lightning have been assuming a special concern since high susceptibility equipment have been used in almost all branches of activities of our society.

When a building is struck by lightning, the resulted current and voltages transients can cause effects that can be dangerous from various point of view. The current that flows in the columns and beams of a building produces electromagnetic fields that couple with components of electrical and electronic systems and it can result in material damages, malfunction of equipment, alteration of information ...

Thus, from the EMC point of view, it is possible to conclude that it is very important to analyze the behavior of buildings when they are struck by lightning, so as to determine the best solutions for the lightning protection system and for the lay-out of equipment, improving the aspects related to the EMC level of all electrical and electronic systems.

A simulation model, suitable for determining the lightning current distribution in the lightning protection system and the magnetic field at ~~in~~ any point of the space, has already been developed by the authors [6,7,8]. In this work is presented a brief description of this model and as an application a prediction of the resulted magnetic field, as a function of time, in a complex steel structure where high susceptibility equipment will be installed, considering different lightning struck points.

THE MODEL

The methodology, here used, consists in dividing the considered structure in cells. Each cell corresponds to a junction of transmission lines, like in fig.1, where the length of them is chosen to be much smaller then the minimum wave length of the transient wave.

The response of the cells are determined based on transmission line and wave propagation theory to calculate the current distribution [1] and on infinitesimal time-varying dipole theory and method of images to calculate the magnetic field [2].

The total magnetic field as a function of the time, at ~~in~~ any point of the space, is determined by superposition.

This model differs from others, presented up to this moment in the scientific literature, due to their intrinsic aspects. In this model it is not necessary to solve any equation system and thanks to the direct methodology there is not problems related to the convergence of the solution, this method is unconditionally stable.

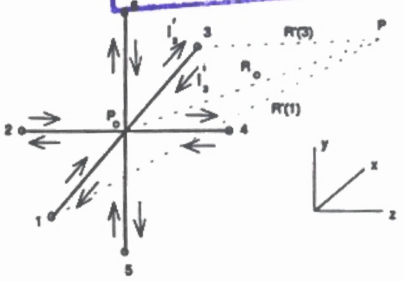


Fig. 1: Proposed Three-dimensional Element

Another characteristic, to be mentioned about this method, is the determination of magnetic field considering the incident and reflected current, not the current resulted from the sum of them. It is important because the validation time should be follow during the calculation of the magnetic field.

It is assumed in the present model some simplifications that could be reduced in the future, without damage to the general philosophy adopted up to this moment.

Among these simplifications are the simulation of the lightning stroke by a unidirectional current source, the consideration of the impulses propagation velocity equal to the speed of light and the calculation of transmission line parameters through traditional formulas, not taking into account the non-linear ionization phenomena. However, the non-linearities, necessary to a realistic representation, can be handled separately thus resulting in a simplified procedure.

Lightning Model

The lightning stroke is simulated by an ideal unidirectional current source injected in the struck point, not taking into account the lightning channel.

For mathematical convenience, the current waveshape can be expressed by functions like the double exponential function or by the sum of two simple ramp functions.

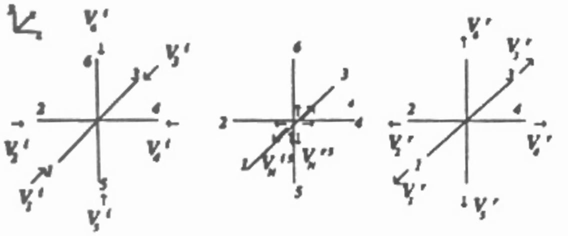
The second one is the function adopted in the present study.

Impulse Response of the Cell

The impulse response of the cell at instants k, k+1and k+2 is illustrated by fig.2.

If at time $t=(k-2)\Delta l\ 2c$, voltage impulses $_{k-2}V^{i}_{n}$ on lines 1 to n are incident on any series node of the cell, then, the reflected voltages on these lines at time $t=k\,\Delta l/2c$ will be represented by (01).

$$_{K}\left[V^{r}_{n}(z,x,y)\right]=\left[\sigma(I,J)\right]_{K-2}\left[V^{i}_{n}(z,x,y)\right] \qquad (01)$$



(K) (K+1) (K+2)

Fig. 2: Impulse response of the cell at instants k, k+1and k+2

The parameter Δl is the length between two series nodes of the cell, $\Delta l/2c$ is the propagation time along each segment of transmission line, which is taken as the time step of the calculation, and $[\sigma(I,J)]$ is the transmission coefficients matrix, where the coefficients σ_h and σ_v, that are used in the following relation (02), are the transmission coefficients of lines 1-4 and 5-6 respectively.

$$[\sigma(I,J)] = \begin{bmatrix} (\sigma_h-1) & \sigma_h & \sigma_h & \sigma_h & \sigma_v & \sigma_v \\ \sigma_h & (\sigma_h-1) & \sigma_h & \sigma_h & \sigma_v & \sigma_v \\ \sigma_h & \sigma_h & (\sigma_h-1) & \sigma_h & \sigma_v & \sigma_v \\ \sigma_h & \sigma_h & \sigma_h & (\sigma_h-1) & \sigma_v & \sigma_v \\ \sigma_h & \sigma_h & \sigma_h & \sigma_h & (\sigma_v-1) & \sigma_v \\ \sigma_h & \sigma_h & \sigma_h & \sigma_h & \sigma_v & (\sigma_v-1) \end{bmatrix} \quad (02)$$

Equation (03) shows us how reflected impulses, from neighboring cells, becomes incident impulses on the cell (z,x,y) :

$$\begin{bmatrix} {}_K V_1^i(z,x,y) \\ {}_K V_2^i(z,x,y) \\ {}_K V_3^i(z,x,y) \\ {}_K V_4^i(z,x,y) \\ {}_K V_5^i(z,x,y) \\ {}_K V_6^i(z,x,y) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} {}_K V_1^r(z,x+\Delta l,y) \\ {}_K V_2^r(z+\Delta l,x,y) \\ {}_K V_3^r(z,x-\Delta l,y) \\ {}_K V_4^r(z-\Delta l,x,y) \\ {}_K V_5^r(z,x,y+\Delta l) \\ {}_K V_6^r(z,x,y-\Delta l) \end{bmatrix} \quad (03)$$

The Boundary Conditions

The boundary condition for series nodes of cells connected to earth can be expressed by (03) and (04), where in (04) R_{at} is the earth resistance and z_v the characteristic impedance of the vertical lines.

$${}_K V_6^r(z,x,y-\Delta l) = {}_K V_5^i(z,x,y) = \frac{R_{at}-Z_v}{R_{at}+Z_v} {}_K V_5^r(z,x,y) \quad (04)$$

Current Distribution

The reflected and incident current along line "n", at instant "k", is expressed respectively by (05) and (06), where z_n is the characteristic impedance of line "n" and the value of SR^D depends on the position and direction of the wave propagation :

$${}_K[I_n^r(z,x,y)] = \left[\frac{1}{Z_n}\right] SR^D \, {}_K[V_n^r(z,x,y)] \quad (05)$$

$${}_K[I_n^i(z,x,y)] = \left[\frac{1}{Z_n}\right] [C(I,J)] SR^D \, {}_{K-1}[V_n^r(z,x,y,\Delta l)] \quad (06)$$

Table I shows the values of SR^D, when z,x,y are positive (0) or negative (1) coordinates of the cell.

TABLE I

VALUE OF SR^D AS A FUNCTION OF THE COORDINATES OF CELLS

Z	X	Y	I/n	1	2	3	4	5	6
0	0	0	1	-1	-1	1	1	-1	1
0	0	1	2	-1	-1	1	1	1	-1
0	1	0	3	1	-1	-1	1	-1	1
0	1	1	4	1	-1	-1	1	1	-1
1	0	0	5	-1	1	1	-1	-1	1
1	0	1	6	-1	1	1	-1	1	-1
1	1	0	7	1	1	-1	-1	-1	1
1	1	1	8	1	1	-1	-1	1	-1

If the point (z,x,y) is the node struck by lightning, then SR^D assumes the value 1, i. e. the direction of the wave propagation is always the same of the reflected impulses on the lines of this cell.

Grounding System

In this work, the simulation of the grounding system is carried out connecting a resistance, the earth resistance R_{at}, to each down-conductor of the lightning protection system. This value is handled separately before introducing it in the configuration of the system.

Characteristic Impedance

Horizontal and vertical characteristic impedance of the transmission lines can be calculated through traditional formulas given by literature. For example, these parameters can be calculated by the following relations, where h is the height and Dc is the diameter of the conductor [9,10]:

$$Z_h = 138\log(4h/Dc) \quad (07)$$

$$Z_v = 60\ln(2h/Dc) + 90(2h/Dc) - 60 \quad (08)$$

Magnetic Field Calculation

Rubinstein and Uman [02] have derived the equation for the magnetic field generated by a elemental dipole of current propagating along y axis with speed v, where the geometrical factors are shown in the fig. 3 :

$$dB_\phi(r,\phi,y,t) = \frac{\mu_0 dy'}{4\pi}\left(\frac{r}{R^3} i(y',t-\frac{R}{c}) + \frac{r}{cR^2}\frac{\partial i(y',t-\frac{R}{c})}{\partial t}\right) \quad (06)$$

In order to obtain the magnetic field, the spatial-temporal distribution of the current in each radiating dipole is considered as a step function in this work :

$$i(y',t) = I_0 u(t - \frac{y'}{v}), \text{ where } u(\xi) = \begin{matrix} 0, \xi \langle 0 \\ 1, \xi \geq 0 \end{matrix} \qquad (07)$$

Therefore, from the knowledge of the reflected and incident currents along lines 5 or 6 of the cell, the magnetic field as a function of the time can be found by using the method of images after integrating properly (8) plus (9).

$$\frac{\mu_0 I_0 r}{4\pi R^3} dy', t\rangle {}^{R}\!/_{c} + {}^{y'}\!/_{v} \qquad (08)$$

$$\frac{\mu_0 I_0 r}{4\pi c[(y-y')^2 + r^2]} \frac{1}{[\frac{1}{v} - \frac{(y-y')}{c\sqrt{(y-y')^2 + r^2}}]} dy', t\rangle {}^{R}\!/_{c} + {}^{y'}\!/_{v} \qquad (09)$$

The time $(R/c + y'/v)$ is named retarded time or validation time.

The same thought can be used to obtain the magnetic field due to the distribution of currents along lines 1,3 and 2,4 of the cell.

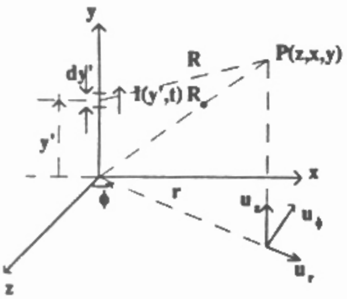


Fig. 3: Definition of geometrical factors used in the field computation.

The total field at time t in any point P of the space is then obtained by superposition. In order to simplify this approach, authors has adopted Cartesian coordinate system to sum the fields due to all radiating dipole elements of the cell [6].

APPLICATION

The complex steel structure shown in fig. 4 is taken in consideration. Each columns and beams of the structure is considered as part of the lightning protection system, constituting the conductors of this system, like the downconductors and the roof-grid conductors.

General Criteria

Considering the great number and different kinds of beams and columns used in the building (fig. 4), some simplifications are adopted in this study :

- The structure is divided in identical cells;
- Each conductor of the lightning protection system is assumed as characterized by a circular cross-section through the equivalent cylindrical conductors and
- It is taken an average value for the vertical and for the horizontal characteristic impedance of beams and columns.

The three-dimensional cell has been chosen based on the length of beams and columns and on the dimensions of the building. In this application the length between two series nodes of the cells is 4m.

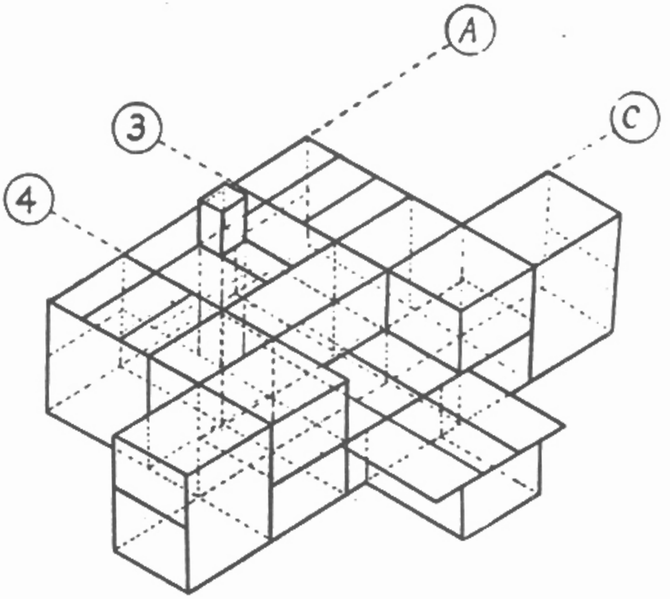


Fig. 4 : Sketch of the building, steel structure, which average dimensions are (44 x 24 x 14) m.

The average values of the characteristic impedance of vertical and horizontal lines are 219Ω and 353Ω. They have been determined by traditional relations presented in this work, taking into account the dimensions and frequency of utilization of each columns and beams in the structure. The lightning stroke is represented by (10) :

I = 8.3t (kA) for t≤1.2 μs and

I = 10[0.83 t - 0.84 (t - 1.2)] (kA) for t⟩ 1.2μs (10)

The lightning struck points have been chosen applying the electrogeometric model around the region where the higher susceptibility equipment will be installed.

According to this model the striking distance R_c(m) is determined by (11), where I (kA) is the peak value of the lightning stroke current, resulted to be 44 m.

$$R_c = 9.4 I^{2/3} \qquad (11)$$

Therefore, the lightning struck points, around the interested region, have been determined.

One of the lightning struck points considered in the EMC analysis of the building is represented in fig. 5. The earth resistance (Rat) is assumed as 5Ω.

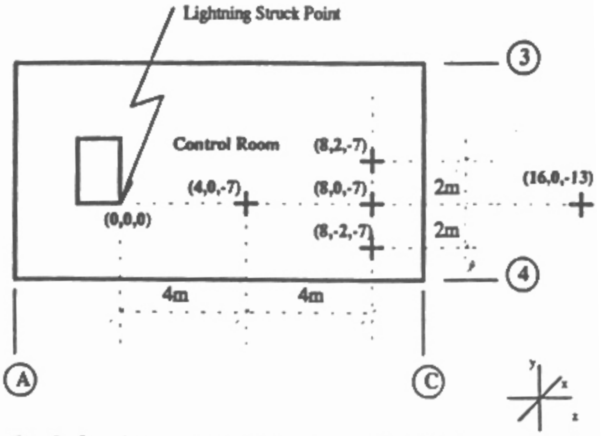


Fig. 5 : Sketch of the considered region and the lightning struck point.

RESULTS

The behavior of the magnetic field has been analyzed taken into consideration the maximum value and the front steepness of the field waveform and different lightning struck points.

The struck point, represented by the intersection of axis 4 and C in the fig. 5, is the point that defines the magnetic environment of the interested region of the building.

This is the worse situation, where the maximum value of the magnetic field can reach values up to 500 µT. The comparison with the established limit (~100 µT) has shown the best lay-out, where is stressed that the corner, given by the intersection of axis 4 and C represented in the fig. 5, should be avoided.

As an example, fig. 6 up to fig. 10 shows the profile of the magnetic field as a function of time, at the points represented in fig.5, due to current distribution in the structure (fig. 4) in the case of a direct strike at point (0,0,0).

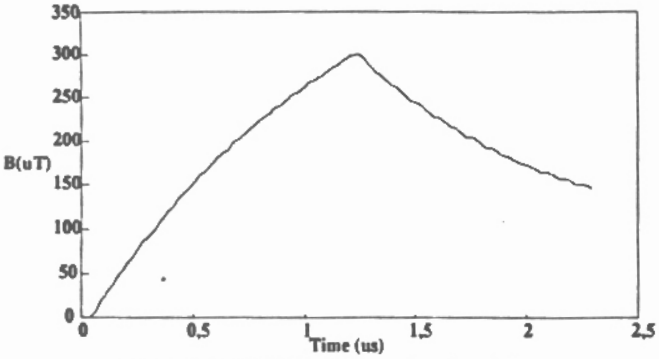


Fig. 6 : Magnetic field B (µT) as a function of time (µs) at point (4,0,-7) m.

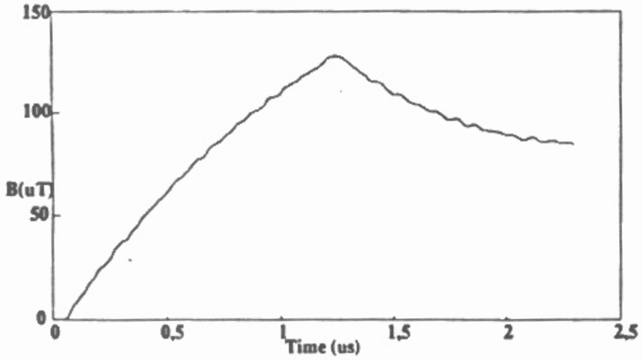


Fig. 7 : Magnetic field B (µT) as a function of time (µs) at point (8,0,-7) m.

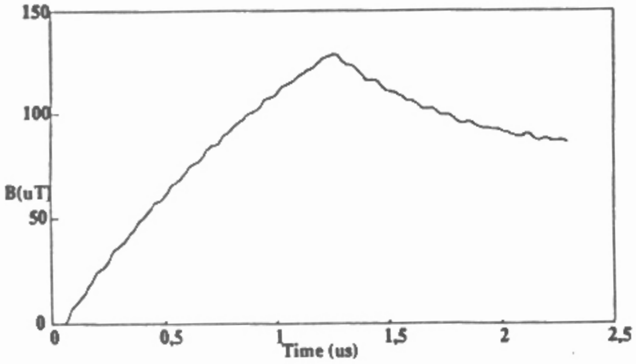


Fig. 8 : Magnetic field B (µT) as a function of time (µs) at point (8, 2,-7) m.

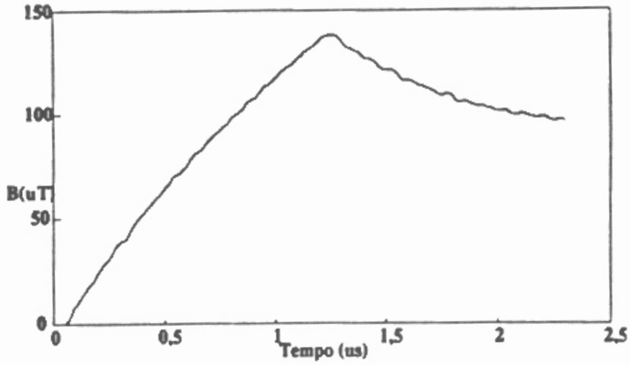


Fig. 9 : Magnetic field B (µT) as a function of time (µs) at point (8,-2,-7) m.

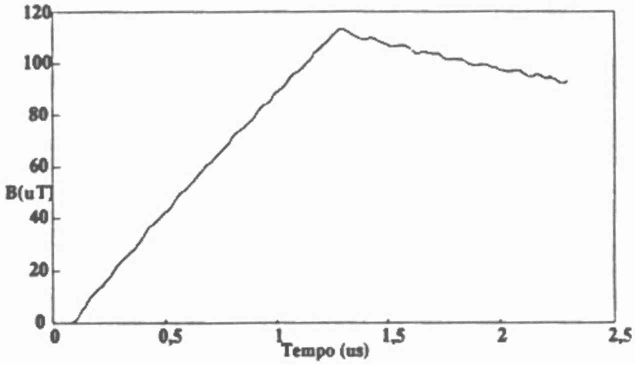


Fig. 10 : Magnetic field B (µT) as a function of time (µs) at point (16,0,-13) m.

CONCLUSIONS

A numerical model, based on transmission line and wave propagation theory to calculate the current distribution in a structure, struck by a direct lightning, and on infinitesimal time-varying dipole theory and method of images to calculate the magnetic field around it, has been presented.

With this model an EMC analyses has been carried out and some results has been presented. It has been shown, that the proposed methodology is simple but it is a suitable numerical method for electromagnetic compatibility studies.

Some of the advantages of this methodology are :

. It is a fast and direct method, when computational aspects are considered;
. It is possible to represent almost all kinds of configuration by appropriate composition of the elementary cell and
. The magnetic field can be predicted, helping the designer to take best decisions during a EMC study, when many parameters are involved.

This method will be improved in the future, when the nonlinearities and the lightning channel effect will be directly considered in the computational scheme.

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