Frequency Analysis of the Induced Effects Due to the Lightning Stroke Radiated Electromagnetic Field

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***Abstract*— A lightning stroke to the protection system of the control building of an industrial plant can produce various effects such as transient voltages induced in feed cables, in measuring, protection and control cables, and in components of electrical equipment within the building, as well as transient voltages between down conductors and metal bodies often characterized by high peak values. These effects can give rise to operating anomalies in the equipment which may sometimes be damaged, and can also constitute a hazard to human life. This paper reports the results of a frequency-analysis study of effects connected with point values of the electromagnetic field generated within the building (e.g., the impact on field-effect transistor, etc.) or due to the presence of radiation fields, namely fields whose harmonic components, characterized by small wavelengths compared to the dimensions of the "victim" circuit, assume not negligible values. The best way of calculating these effects is through a procedure based on a field approach [1]–[3]. Characterization of the electromagnetic field is therefore ensured by a numerical procedure that permits simultaneous simulation of the protection system and analysis of the electromagnetic field by means of the Method of Moments used by various authors [5]–[8] for the study of direct lightning strokes into thin-wire structures. Two distinct points of impact of the lightning stroke to the protection system are considered and the ensuing results are compared.**

I. Introduction

The need for adequate protection of electrical and electronics systems from radiated and/or conducted electromagnetic disturbances is becoming increasingly important with the introduction in the power plants of static-type protection and control equipment incorporating microprocessors capable of assuring the most complex control functions.

Such equipment is very sensitive to electromagnetic disturbances and vulnerable to damage which may occur. The result may be the erroneous operation of the protection and control systems and, in the most serious cases, impairment thereof, owing to the high transient voltages induced in the measuring, protection, and control cables and also in the equipment to which they are connected.

A stroke to the lightning protection system (LPS) of the control building of an industrial plant may cause conducted disturbance to electrical equipment in the plant, or radiated disturbance perhaps involving frequencies amounting to several MHz, and even, in some cases, constitute a hazard for the people working inside the plant.

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It is not easy to evaluate these effects because of the presence of different conducting materials forming the various parts of the building, each of which carrying induced currents which cause electromagnetic fields.

The lightning protection system is designed to receive the stroke and lead the current to the grounding grid of the protected structure. The LPS generally consists of a set of straight interconnected conductors forming a cage which is either located outside the structure to be protected or incorporated within it [9].

This paper presents a procedure for calculation and analysis in the frequency domain of the electromagnetic field generated in the points inside the industrial plant whose LPS receives a lightning stroke. The procedure is based on the Method of Moments (MOM) [10]. It permits account to be taken of the field radiated by the various conductor elements forming the LPS, through which the lightning current flows, and of the field radiated by the lightning channel.

The lightning channel is simulated by a radiated vertical antenna affected by the lightning current, while the ground is assumed to be perfectly conducting.

The electromagnetic field generated is characterized by reference to two different points of impact between the lightning stroke and the LPS. These two different systems give rise to diverse distributions of lightning current among the various conducting parts of the protection system and, consequently, to effects of diverse magnitude.

A qualitative analysis is performed, in conclusion, of the influence of the LPS size on the electromagnetic field inside the building. This analysis has shown a great influence of the down conductors distance and number on the electromagnetic field values.

The procedure developed can thus be a great help in optimizing LPS design.

II. Simulation Models

A. Lightning Protection System

Fig. 1 illustrates the geometry of the LPS considered. It consists of a network of straight conductors interconnected to form a roof-grid in the upper part of the building, connected to the grounding-grid by down conductors located at the corners of the building. In order to simplify the LPS model the following assumptions, known as the thin-wire approximations, are used with reference to the generic wire of the LPS:

1) transverse currents are neglected in comparison to the axial current of each wire;

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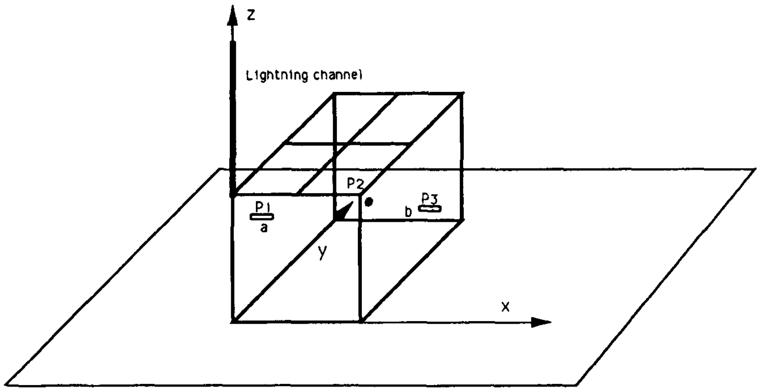


Fig. 1. Geometry of the lightning protection system.

2) the circumferential variation in the axial current is neglected;

3) the current flowing in each wire is represented by a filament on the wire axis.

These widely used and known approximations are valid as long as the wire radius is much less than both its length and the wavelength associated with the highest frequency applied by the exciting source.

Owing to the small transverse section of the conductors, skin and proximity effects are also neglected.

B. Lightning Channel

The lightning channel is simulated as a vertical radiating antenna in which flows the lightning current.

One of the most usual time-dependent expressions for the lightning current is a double exponential that in the frequency domain gives

$$I(\omega) = (\beta - \alpha) I_m / ((\alpha + j\omega)(\beta + j\omega)). \quad (1)$$

The amplitude of the induced EMF in the "victim" circuits is an inverse function of the crest time of the lightning current. In order to simulate therefore a stressful (even not frequent) electromagnetic situation, according to Singer *et al.* [8], the following values are assumed for α, β, and I_m:

$$I_m = 4600A, \qquad \alpha = 50 * 10^4 \ \text{sec}^{-1} \quad \text{and} \quad \beta = 55 * 10^6 \ \text{sec}^{-1}.$$

These values adopted for α and β give rise to a time variation of the lightning current whose characteristic parameters are a crest time (T_{cr}) of 100 ns and a half-value time (T_{hv}) of 5.0 μs.

Fig. 2 shows the frequency trend of the lightning-current amplitude, which is certainly anything but negligible in a range up to 10 MHZ where the values of $I(\omega)$ is about -28 dB. This observation prompted characterization of the electromagnetic field generated in the 150 kHz to 10 MHz frequency range.

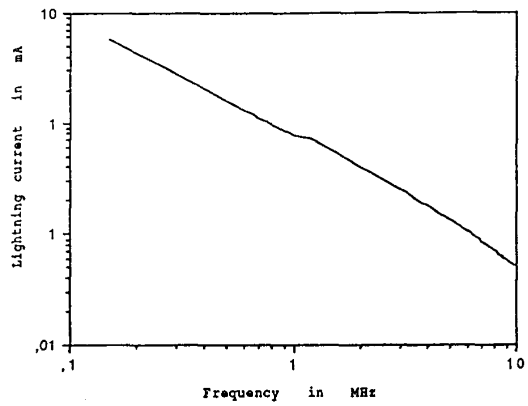


Fig. 2. Frequency spectrum of the lightning current.

III. The Field Approach

The well-known electric field integral equation (EFIE) is used to evaluate the electromagnetic field generated by the LPS excited by the lightning channel in which the lightning current flows. The rigorous derivation of this integral equation is given by Burke and Poggio in [11] and, for the sake of brevity, it is not reported here.

The thin-wire approximations introduced in Section II permit the EFIE to be reduced to a scalar integral equation such as:

$$-\boldsymbol{s}\boldsymbol{E}^i(r) = \frac{-j\eta}{4\pi k} \int_C I(s') \left(k^2 \boldsymbol{s}\boldsymbol{s}' - \frac{\partial^2}{\partial s \partial s'}\right) g(\boldsymbol{r}, \boldsymbol{r}')\, ds' \quad (2)$$

where

$$g(\boldsymbol{r}, \boldsymbol{r}') = \exp(-jkR)/R, \qquad R = \left[/\boldsymbol{r} - \boldsymbol{r}'/^2 + a^2(s)\right]^{1/2}$$
$$k = \omega(\mu_o \varepsilon_o)^{1/2}, \qquad \eta = (\mu_o/\varepsilon_o)^{1/2}. \quad (3)$$

In the preceding equation, I is the unknown induced current, $\boldsymbol{E}^i$ the exciting field, $\boldsymbol{s}$ and $\boldsymbol{s}'$ unit vectors tangent to the considered contour C at P and P', and $\boldsymbol{r}$ and $\boldsymbol{r}'$ are vectors to the points P and P' (see Fig. 3).

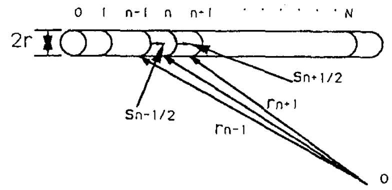


Fig. 3. Segmentation scheme for the generic wire.

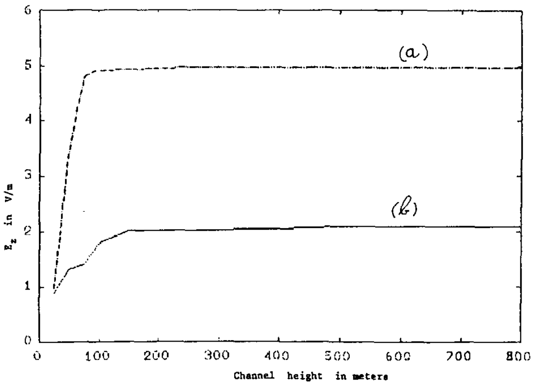


Fig. 4. Electric field vertical component as a function of the lightning channel height.

Equation (2) is solved numerically using the MOM. By means of an appropriate discretization of each conductive element in subsegments, the integral equation is enforced at specific points on the structure. The MOM needs to expand the unknowns (the currents in the conductors) in basic functions. Our approach uses a multiple-sine expansion, well suitable for electromagnetic field calculations:

$$
\begin{aligned}
I_j(s) = A_j &+ B_j[\sin k_s(s - s_j)] \\
&+ C_j[\cos k_s(s - s_j)], \\
&/s - s_j/ < \Delta_j/2
\end{aligned} \tag{4}
$$

where s_j is the value of the progressive s at the center of segment j, Δ_j is the length of segment j and k_s is the free space wave number.

Two of the three unknown constants A_j, B_j, and C_j are eliminated by local conditions on the currents and charges (currents and charges continuity at the segments' junctions, disappearance of the current at the free wire end) leaving one constant to be determined. In this way, a system of equations is obtained whose order is equal to the number of segments traversed by an unknown current. Resolution of this system permits identification of all the constants and hence of the currents through the various sides of the LPS and, successively, evaluation of the electromagnetic field generated in the individual point within the structure in question.

IV. Computational Results

The cubic geometry indicated in Fig. 1, where each individual side has a length of 24 m and a circular section of radius $r = 4$ mm, has been adopted for the LPS, according to the Italian Standards.

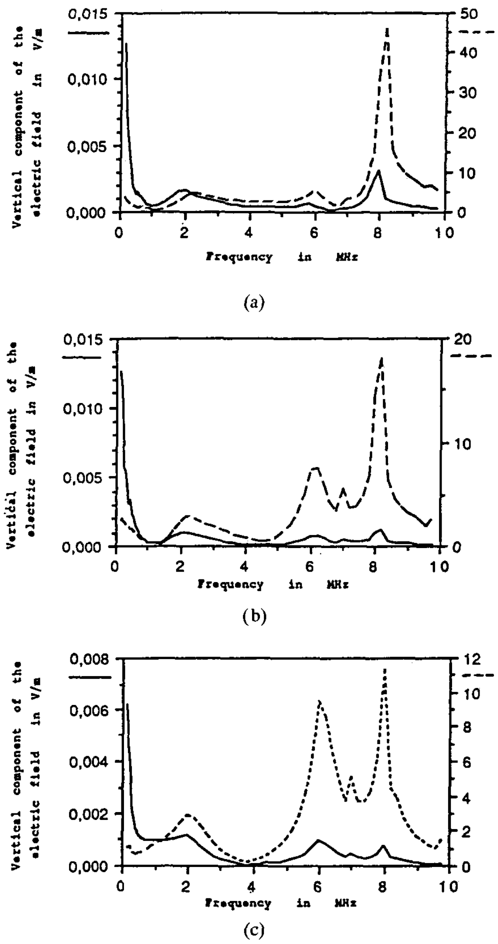


Fig. 5. Amplitude of the vertical component of the electric field in (a) P_1 (2,2,22) (b) P_2 (12,12,12), and (c) P_3 with reference to a lightning stroke on the roof-center.
---------- due to an unitary current impressed.
———— due to the lightning current impressed.

The lightning channel has been simulated by means of a 200 m long antenna. A previous study [5] had, in fact, indicated that in the internal points of the structure to be protected, the influence is felt of the electromagnetic field radiated solely by the lower elements of the lightning channel as it is shown in Fig. 4. This figure shows that for LCH's height greater than 200 m (about ten times the maximum dimension of the LPS) the electromagnetic field values in the generic point inside the building remain nearly constant. The propagation of the current along the LCH model is also neglected.

Each side of the LPS has been divided into six parts 4 m long; the calculation procedure adopted ensures accurate determination of the electromagnetic field generated within the installation if the length of the individual elements into which the structure has been discretized is less than one tenth the wavelength associated with the maximum significant

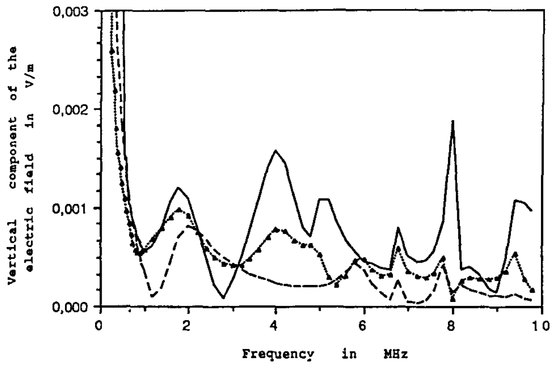
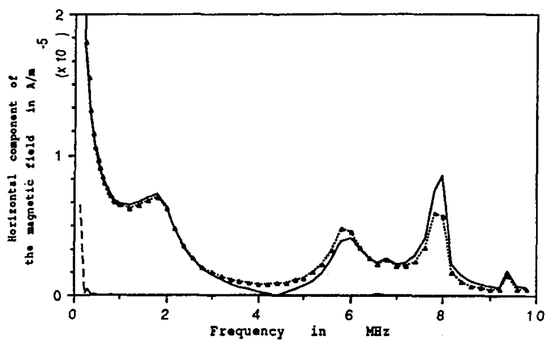
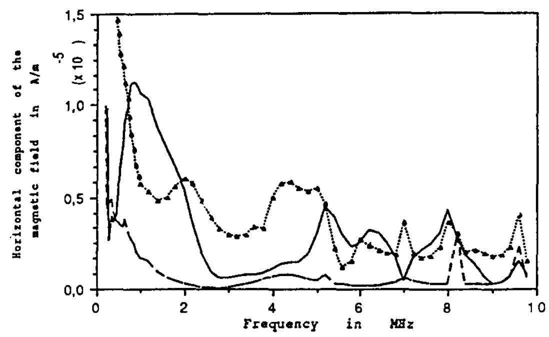


Fig. 6. Amplitude of the vertical component of the electric field with reference to a lightning stroke on the roof-corner. P_1 (2,2,22) ——— P_2 (12,12,12) ------ P_3 (22,22,2) ♦♦♦♦.



(a)



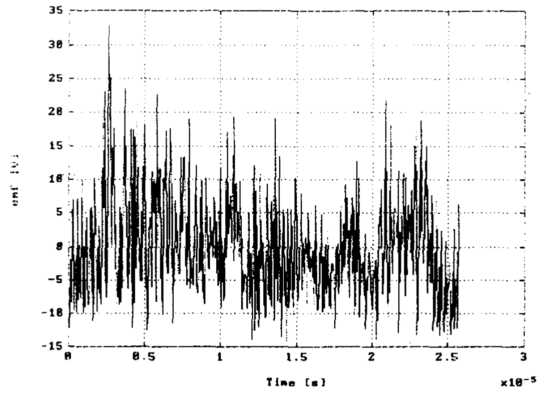
(b)

Fig. 7. Amplitude of the horizontal component of the magnetic field with reference to a lightning stroke on (a) the roof-center and (b) the roof-corner.

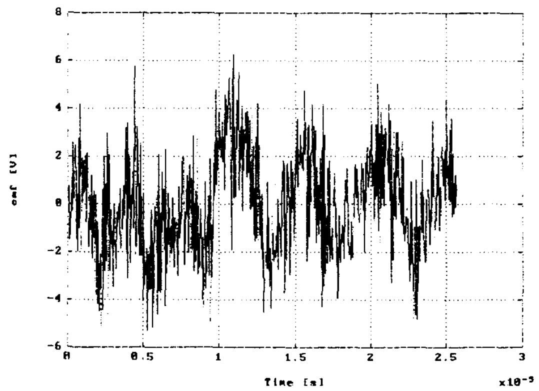
frequency of the phenomenon in question.

The lightning channel has, instead, been divided into parts whose length increases with height. In this way at the lower end of the channel, the shape of the current injected into the LPS approximates that of a step.

In the applications effected, two different points of impact of the lightning stroke to the LPS are considered: one in the center of the roof-grid and the other at a corner (points M and N in Fig. 1). The stroke to the center of the roof-grid gives rise to uniform distribution of the lightning current between



(a)



(b)

Fig. 8. Transient emf induced in square loops centered in (a) $P1$ and (b) $P2$ (see Fig. 1).

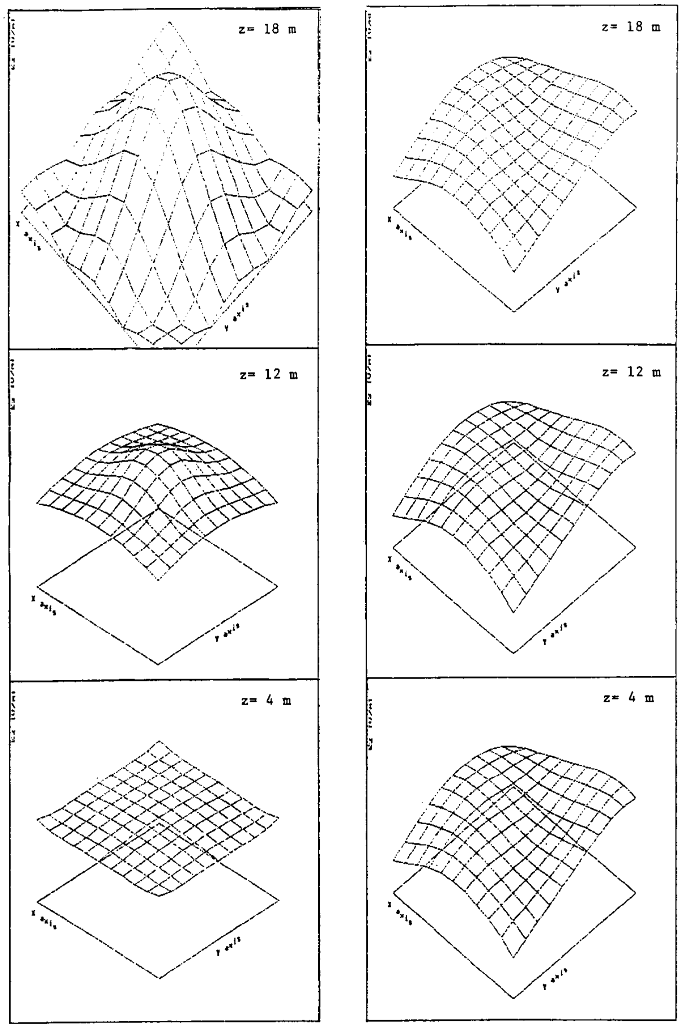
the four down conductors of the LPS. On the contrary, in the case of the stroke to the corner, the current flowing in the down conductor hit by the lightning is considerably greater than that in the other three.

The broken lines in Fig. 5 illustrate the trend of the amplitude of the frequency response of the vertical component of the electric field $E_z(\omega)$ in three points, coordinates $P_1[2, 2, 22]$, $P_2[12, 12, 12]$, and $P_3[22, 22, 2]$, respectively, namely, the values of the vertical component of the electric field due to an unitary current flowing through the lightning channel, for frequency values between 150 kHz and 10 MHz and with reference to the case of a stroke to the roof-grid. The continuous curves represent, on the contrary, the amplitude of the electric field vertical component due to the lightning channel current $E^{lch}(\omega)$ and given by the following relation:

$$E^{lch}(\omega) = E_z(\omega)I(\omega) \tag{5}$$

being $I(\omega)$ the frequency spectrum of the lightning channel current reported in Fig. 2.

Two resonances are revealed: one at low frequency (150–200 kHz) and one at a frequency between 5 and 7 MHz. It is possible to observe that the frequency response of the lightning channel current eliminates the resonances at frequency values higher than 5 MHz.



(a) (b)

Fig. 9. Spatial trends of the vertical component of the eletric field for different heights and a frequency value of 5 MHz. (a) Lightning stroke to the roof-center. (b) Lightning stroke to the roof-corner.

The trends of the preceding electrical parameters in the same points for a stroke to the corner are reported in Fig. 6.

Fig. 7 permit an analysis of the values of the horizontal component (according to axis x in Fig. 1) of the magnetic field $\boldsymbol{H}$ in the points previously defined for a stroke to the center (a) and to the corner (b) of the LPS roof-grid. In the case of a stroke to the center of the roof-grid, the values of the horizontal component of the magnetic field $\boldsymbol{H}$ in P_2, located in the central point of the cube schematizing the LPS, are very low. Values of practically the same order occur in the other two points.

A stroke to the corner gives rise to values little greater than those resulting from a stroke to the center of the roof-grid. Lesser effects occur at the central point P_2, while values of the same order are found at P_1 and P_3.

Fig. 8 shows the transients of the electromotive forces (EMF) induced in two metallic square-loops defining a surface of 100 mm^2 during a direct lightning strike to the corner of the building. The loops are, respectively, close and far to the struck corner. The former (a) (centered in P_1) lies in a vertical plane shifted of $\pi/4$ from the zx plane; the latter (b) (centered in P_3) lies on the zx plane.

In both cases, there is a fundamental harmonic component of period 6 μs, over which there are oscillations of greater frequency and amplitude in (a) and of lesser amplitude in (b).

The EMF induced in the loop close to the impact point present peak values of 35 V while the EMF induced in the farthest loop are about 6 V.

The Fig. 9 curves illustrate the spatial trends of the vertical component of the electric field in the points lying in planes parallel to the xy plane characterized by heights of 4, 12, and 18 m, respectively, for a stroke to the center (Curve a) and a stroke to the corner (Curve b), and for a frequency of 5 MHz.

The preceding curves permit identification of those zones

TABLE I
E_z AND H_x VALUES IN $P_1(2, 2, 22)$ FOR A STROKE ON THE LPS CORNER WITH REFERENCE TO THREE DIFFERENT LPS.

N. of downcond.	4		8		12	
Frequency MHz	E_z (V/m) $*10^{-3}$	H_x (A/m) $*10^{-5}$	E_z (V/m) $*10^{-3}$	H_x (A/m) $*10^{-5}$	E_z (V/m) $*10^{-3}$	H_x (A/m) $*10^{-5}$
0.5	2.511	2.490	1.729	0.931	1.362	0.274
1.0	3.002	1.708	1.738	0.176	1.242	0.108
1.5	2.988	2.555	1.969	0.199	1.182	0.089

TABLE II
E_z AND H_x VALUES IN $P_3(22, 22, 2)$ FOR A STROKE ON THE LPS CORNER WITH REFERENCE TO THREE DIFFERENT LPS.

N. of downcond.	4		8		12	
Frequency MHz	E_z (V/m) $*10^{-3}$	H_x (A/m) $*10^{-5}$	E_z (V/m) $*10^{-3}$	H_x (A/m) $*10^{-5}$	E_z (V/m) $*10^{-3}$	H_x (A/m) $*10^{-5}$
0.5	0.598	1.261	0.618	0.301	0.531	0.250
1.0	0.769	1.043	0.627	0.204	0.524	0.156
1.5	1.817	2.485	0.741	0.153	0.577	0.140

within the structure in which the intensity of the electromagnetic field produced is greater.

Finally, a qualitative analysis of the influence on the electromagnetic field inside the building of the distance between the down conductors was done. Both the number of downconductors and their reciprocal distances were varied. In addition to the LPS in Fig. 1, characterized by 4 downconductors each 24 m apart, there are considered two other types: one with 8 downconductors, each 12 m apart; and another with 12 conductors, each 8 m apart. Tables I and II show the values of $\boldsymbol{E}_z$ and $\boldsymbol{H}_x$ in P_1 and P_3 at three frequency value for a direct lightning strike on the corner. The tables' values show a decreasing of $\boldsymbol{E}_z$ and $\boldsymbol{H}_x$ when the number of down conductors increases pointing out a shielding effect of the LPS. This reduction it is most evident in P_1 (close to the struck corner) and less in P_3.

CONCLUSIONS

The design of a lightning protection system for a structure, which will ensure that there are only small effects on electrical and electronic components present within the structure, such as to prevent conditions that are hazardous for human life, calls for the characterization of the electromagnetic field produced within the structure when struck by lightning.

A calculation procedure for analysis in the frequency domain of the electromagnetic field produced by a lightning stroke is described and observations are made on the results of these analyses with reference to a stroke to different types of LPS in two different points. Analysis of the spatial distribution of the electric field is also performed in order to ascertain the points within the structure most highly stressed from the electromagnetic point of view. In the future, we plan to develop the analysis of the influence on the electromagnetic field inside the building of the dimensions and topology of the LPS. We will introduce the shielding effects of the metal structural part of the building, such as beams and reinforced concrete walls.

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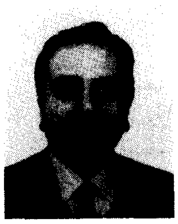

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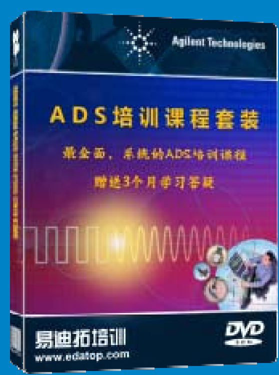

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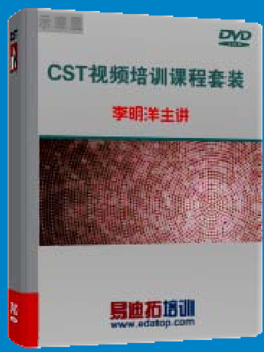
该套课程套装包含了本站全部 HFSS 培训课程，是迄今国内最全面、最专业的 HFSS 培训教程套装，可以帮助您从零开始，全面深入学习 HFSS 的各项功能和在多个方面的工程应用。购买套装，更可超值赠送 3 个月免费学习答疑，随时解答您学习过程中遇到的棘手问题，让您的 HFSS 学习更加轻松顺畅…

课程网址：http://www.edatop.com/peixun/hfss/11.html

CST 学习培训课程套装



该培训套装由易迪拓培训联合微波 EDA 网共同推出，是最全面、系统、专业的 CST 微波工作室培训课程套装，所有课程都由经验丰富的专家授课，视频教学，可以帮助您从零开始，全面系统地学习 CST 微波工作的各项功能及其在微波射频、天线设计等领域的设计应用。且购买该套装，还可超值赠送 3 个月免费学习答疑…

课程网址：http://www.edatop.com/peixun/cst/24.html

HFSS 天线设计培训课程套装

套装包含 6 门视频课程和 1 本图书，课程从基础讲起，内容由浅入深，理论介绍和实际操作讲解相结合，全面系统的讲解了 HFSS 天线设计的全过程。是国内最全面、最专业的 HFSS 天线设计课程，可以帮助您快速学习掌握如何使用 HFSS 设计天线，让天线设计不再难…

课程网址：http://www.edatop.com/peixun/hfss/122.html

13.56MHz NFC/RFID 线圈天线设计培训课程套装

套装包含 4 门视频培训课程，培训将 13.56MHz 线圈天线设计原理和仿真设计实践相结合，全面系统地讲解了 13.56MHz 线圈天线的工作原理、设计方法、设计考量以及使用 HFSS 和 CST 仿真分析线圈天线的具体操作，同时还介绍了 13.56MHz 线圈天线匹配电路的设计和调试。通过该套课程的学习，可以帮助您快速学习掌握 13.56MHz 线圈天线及其匹配电路的原理、设计和调试…

详情浏览：http://www.edatop.com/peixun/antenna/116.html

我们的课程优势：

※ 成立于 2004 年，10 多年丰富的行业经验，

※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求

※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

联系我们：

※ 易迪拓培训官网：http://www.edatop.com

※ 微波 EDA 网：http://www.mweda.com

※ 官方淘宝店：http://shop36920890.taobao.com