Artur NOGA, Andrzej KARWOWSKI, Tomasz TOPA
Silesian University of Technology, Institute of Electronics

doi:10.15199/48.2018.02.15

Evaluation of the Magnetic Field Inside Grid-Like Large Volume Shields For Protection Against LEMP

***Abstract**. In this paper, a computationally efficient broadband electromagnetic simulation of lightning protection system is presented. The approach employs a hardware accelerated implementation of the method of moments combined with the Stoer-Bulirsch algorithm and adaptive frequency sampling scheme to explore the frequency response of a large volume grid-like structures directly hit by lightning. Emphasis is placed on the evaluation of the lightning-induced magnetic field intensity and its derivative within the volume protected by single- and double-layer shields.*

***Streszczenie.** W referacie opisano efektywną obliczeniowo, opartą na metodzie momentów, technikę szerokopasmowej analizy dużych, ekranujących struktur siatkowych umożliwiających ochronę przed wyładowaniami atmosferycznymi. Skuteczność metody pokazano przy wyznaczaniu natężenia pól magnetycznych indukowanych w trakcie bezpośrednich wyładowań atmosferycznych w obszarach chronionych przez jedno- i dwuwarstwowe ekrany. (**Wyznaczanie pola magnetycznego indukowanego w trakcie wyładowań atmosferycznych w obszarach chronionych przez duże ekrany siatkowe**).*

Keywords: lightning protection; magnetic field shielding; frequency-domain analysis; method of moments.
Słowa kluczowe: ochrona odgromowa, ekranowanie pól magnetycznych, analiza w dziedzinie częstotliwości, metoda momentów.

Introduction

Lightning is a source of aggressive harmful high-intensity electromagnetic (EM) effects usually referred to as Lightning Electromagnetic Pulse (LEMP). The energy of LEMP may be sufficient to cause damage to sensitive electronics in electrical and electronic systems within structures. Therefore, protection measures to reduce the risk of failure of internal systems due to LEMP are vitally important [1]. This is particularly true for data processing, storage, and process control systems, radio systems, power electronic installations, telecommunication equipment, and similar. The principal source of potential damage is the lightning current and the associated magnetic field. This latter may be reduced to the acceptable level by employing magnetic shields. Large volume shields for protecting rooms and/or buildings are usually created by dedicated meshes of conductors combined with natural components of the structure such as the metal framework and the metal reinforcement in the walls, floors and ceilings. These elements taken together form three-dimensional grid-like spatial shields [1], and prediction of their response to lightning induced EM excitation is crucial for effective design of system protection (SPM) against LEMP. Perhaps the most suitable and accurate technique for EM analysis of grid-like shields composed of arbitrarily arranged conductors is the full-wave method of moments (MoM) formulated in the frequency domain (FD) [2]. Unfortunately, the direct MoM is considered computationally inefficient when a broadband response of a structure is required, since EM simulation must be performed repeatedly at many discrete frequencies and the computational cost can be prohibitive for complex structures.

In this paper, a computationally efficient CUDA-enabled heterogeneous CPU+GPU co-processing implementation of the method of moments is used for electromagnetic simulation of large volume grid-like spatial shields over a wide frequency band relevant to LEMP. The approach employs the technique described in [3,4] and [5]. Emphasis is placed on the evaluation of the lightning-induced magnetic field intensity and its derivative within the volume protected by single- and double-layer grid-like shields. Also, the effect of the presence of bonding network(s) on the magnetic field distribution in multi-storey and skeleton buildings is thoroughly investigated via numerical simulations. The potential of the approach is demonstrated by numerical examples involving, among others, canonical grid-like shields given in [1]. For consistence of presentation, partial concepts of the overall approach including adaptive frequency sampling supported by implicit rational interpolation and CUDA-based CPU+GPU implementation of the relevant computer program are briefly summarized follow

Method

The approach adopted for the study reported in this paper is based upon the mixed-potential electric field integral equation (EFIE) for the current excited on an arbitrary 3D wire structure. The equation is converted into a matrix equation by a conventional MoM procedure employing one-dimensional RWG-type functions for both expansion and testing. The MoM-generated matrix approximant to EFIE is frequency dependent and, therefore, the system matrix equation must be set up and then solved repeatedly for each individual frequency within a set of discrete frequencies of interest. The matrix equation is solved via LU decomposition [6], and the solution gives an approximation to the current excited on a structure. All other quantities of interest are derived from this current in a routine way.

To reduce the number of EM simulations needed for reconstruction of the system response and thus minimizing the overall processing time, we employ an adaptive frequency sampling (AFS) scheme based upon interval halving (bisection) in combination with the rational interpolation of the observed quantity (e.g. the magnetic field intensity at the selected point in space) implemented through Stoer-Bulirsch (SB) algorithm [7]. The details of the formulation are given in [3,4].

Further speedup of numerical MoM-based simulations is achieved by GPU hardware acceleration [8, 9, 10, 11]. The approach employs the technique described in detail in [5] for mapping CPU sequential MoM procedures to parallel GPU platform.

The key components of a hardware platform engaged in this study were the Intel Core i7-3820 Quad-Core Processor and GeForce GTX 680 graphics card. Software tools included Intel Fortran, PGI Fortran, CULA and Intel MKL libraries.

Results

The approach outlined in Section II is applied for exploring the frequency response of a large volume grid-like structure directly hit by lightning. The construction serving as a building shielding structure from the lightning electromagnetic pulse (LEMP) is modelled by the grounded wire-mesh cages (see Fig. 1). The perfectly electrically conducting (PEC) ground plane is assumed and taken into account by the method of images. The dimensions of the 'building' are (length x width x height) 10x10x50 m. The model corresponds to the type 3 grid-like large volume shield proposed in [1]. The building with its grid-like electromagnetic shield may be equipped with an external lightning protection system (LPS) as shown in Fig. 1b. In this case, the entire construction consists of two wire meshes: a coarse one representing the external LPS (rectangular mesh of 5.5 m x 5 m, except the top one forming the square mesh of 5.5 m x 5.5 m) and a fine one representing the internal grid-like shield (alternatively referred to as an internal LPS) with the width of a square grid equals to 1 m. The inner and outer meshes are interconnected at the four roof corners. Additional interconnections between the four vertical edges of the meshes are introduced at height z = 25 m. Both meshes are assu-med to be made of perfectly conducting wires of radius 4 mm.

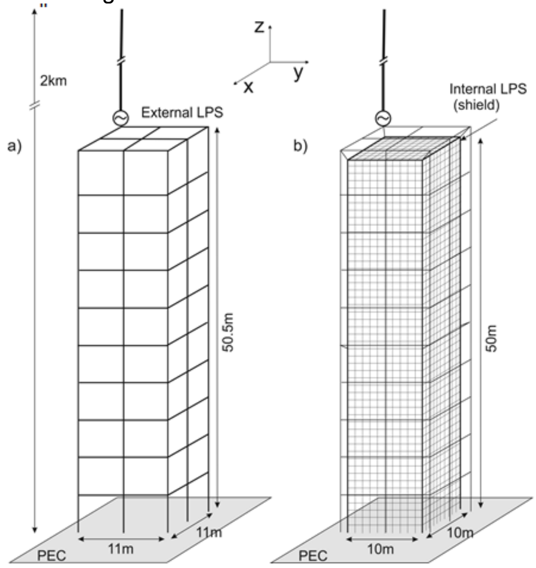

Fig. 1.Models of external LPS (a) and LPS integrated with internal wire-grid shield (b).

It is assumed that lightning strikes a corner of the building as depicted in Fig. 1. The lightning channel is represented by a vertical lossy monopole antenna with distributed loading. To be specific, the monopole of the height 2 km and radius 5 cm is uniformly loaded with series inductance of 4.5 μH/m and series resistance of 1 Ω/m [12]. The monopole is fed at its base by a delta-gap unit-voltage generator.

Following the subdomain-type basis/testing function MoM methodology, the complete structure, i.e. the external LPS, internal shield and lightning channel, is subdivided into segments. The total number of wire segments is 6794, and the number of unknowns (basis functions) associated with the structure is 8984. This is tantamount to saying that the size of the MoM-generated structure matrix is 8984 x 8984.

Within a general purpose of the study reported here, a partial goal has been to investigate, in the frequency domain, the effect of a double-layer protecting installation on the magnetic field/current transmittance $T_H/I_c(\omega)$

$$(1)\quad T_{H/I_C} = \frac{\sqrt{\left|H_x(j\omega)\right|^2 + \left|H_y(j\omega)\right|^2 + \left|H_z(j\omega)\right|^2}}{\left|I_C(j\omega)\right|}$$

where $T_{H/Ic}$ is understood as the absolute value of the magnetic field intensity $H(\omega)$ at the selected point in space within the protected volume normalized to the current amplitude $I_c(\omega)$ at the lightning channel base, i.e. T_H/I_c = $|H/I_c|$. Fig. 2 shows the requested transmittance computed in the frequency range from 1 kHz to 20 MHz. The magnetic field is observed at the center of the protected volume ($x = y$ = 5.5 m, z = 25 m). The results for the external LPS alone are compared in Fig. 2 with those obtained for the double-layer structure involving the grid-like internal shield integrated with the external LPS (see Fig.1b). The comparison clearly indicate that the use of the internal shield results in a noticeable reduction, by about 10 dB, of the low-frequency components of the magnetic field penetrating the protected volume compared to that observed for the external LPS alone. The results for the upper portion of the considered frequency range are less conclusive due to multi-resonant behaviour of the structures being compared.

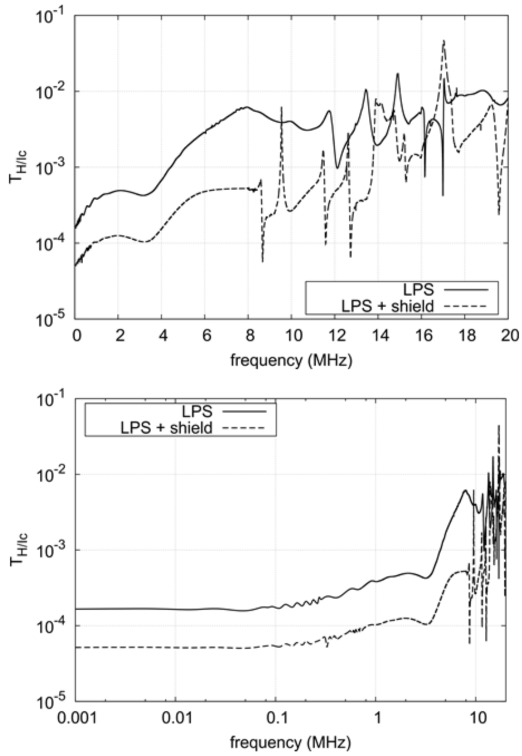

Fig. 2.Frequency runs of the magnetic field/current transmittance $T_{H/Ic}$.

It is well known that the magnetic induction effects are related to the raising front of the magnetic field. From this perspective, a quantity of particular interest is the time derivative of the magnetic field, dH/dt, within the protected volume. In the frequency domain, the spatially averaged effect of dH/dt can be examined by observing the induced electromotive force (emf) or open-circuit voltage in a loop immersed in the magnetic field under consideration. For the demonstration example, a square loop lying in the plane x - $y = 0$ with its center coinciding with the center of the protected volume ($x = y$ = 5.5 m, z = 25 m) is taken. The side length of the loop is 1 m, and its two sides are parallel to the vertical wires of spatial grids. The task was to examine the frequency behaviour of the open-circuit voltage $U(\omega)$ induced on the loop normalized to the current $I_c(\omega)$ at the lightning channel base. In other words, the observed quantity was the voltage/current transmittance T_U/I_c = $|U/Ic|$. Fig. 3 shows the frequency runs of T_U/I_c in the range from 1 kHz to 20 MHz. As in the previous case, the results for the external LPS alone are compared with those for LPS integrated with the grid-like internal shield. The comparison reveals that the use of internal shield has the effect similar to that previously observed for the magnetic field/current transmittance.

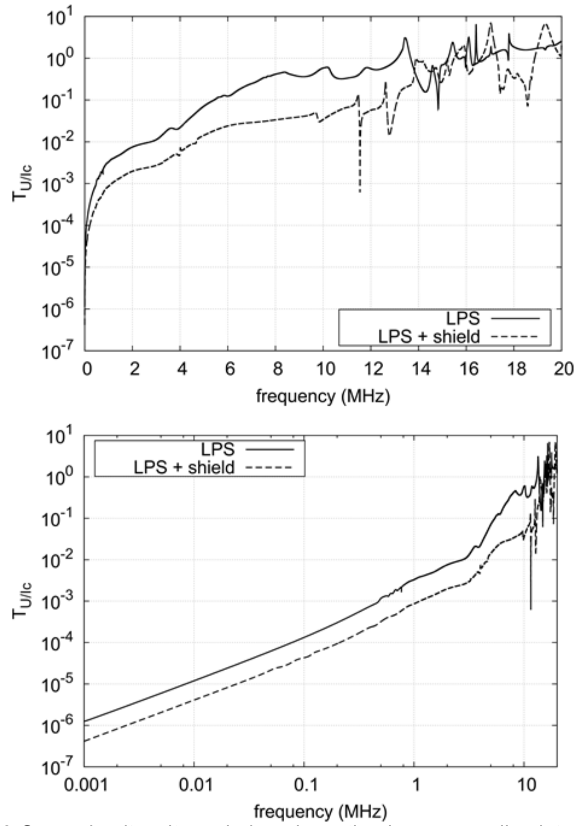

Fig. 3.Open-circuit voltage induced on the loop normalized to the current at the lightning channel base ($T_{U/Ic}$ transmittance).

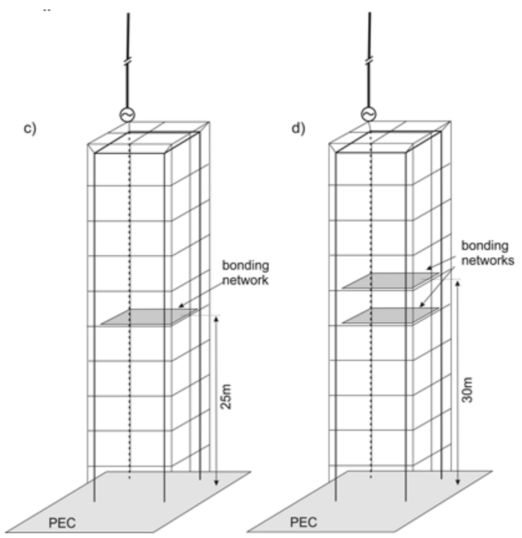

Fig. 4.Model of external LPS integrated with internal wire-grid shield with bonding networks.

The last and the most challenging example addresses the problem of the spatial distribution of the magnetic field inside the volume being protected. In this context, the role of the individual components of the protecting installation is also studied. For this purpose, the four geometries have been considered starting from the two depicted in Fig. 1. The LPS integrated with the internal shield has been expanded by bonding networks (BNs) placed at heights 25 m and 30 m yielding the two geometries shown in Fig. 4. The detailed structure of BNs is shown in Fig. 5.

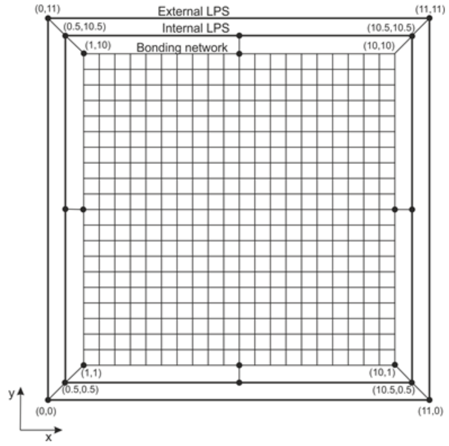

Fig. 5.Detailed structure of bonding network.

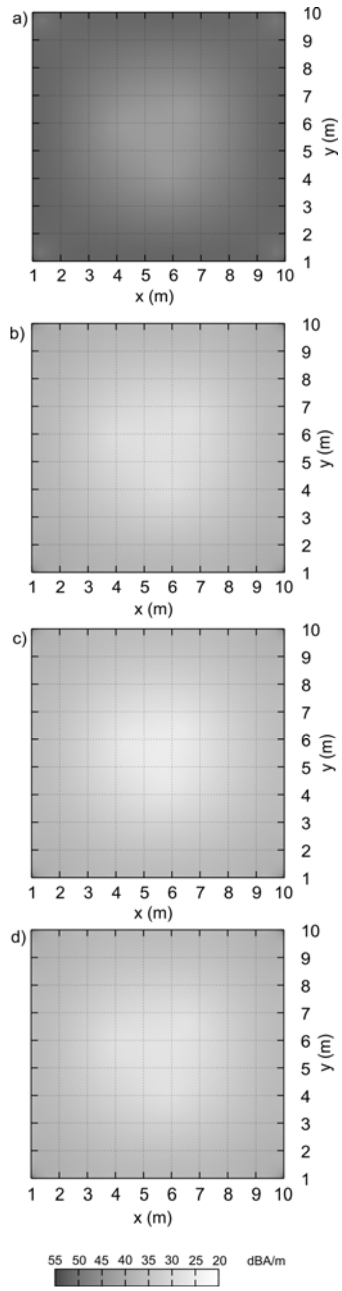

Fig. 6. Spatial distributions of the magnetic field magnitude in the horizontal plane z = 26 m for geometries shown in Figs. 1 and 4 (the frequency is 25 kHz).

Fig. 6 shows the computed spatial distributions of the magnetic field (H) magnitude in the horizontal plane 26 m above the ground plane. The computations were performed for the frequency 25 kHz that can be used to characterize the magnetic field of the first positive 100 kA lightning stroke (current for lightning protection level III based on 10/350 μs waveform). As can be easily seen from the Figure, the presence of the internal shield has a profound effect on the magnetic field intensity inside the protected volume, and a careful examination of the results indicates that the use of the shield results in decrease of the average value of the field by about 12 dB compared to the value without the shield. The use of BNs has little effect on both the average level of the field and its statistics, that is, the standard deviation and coefficient of variation.

Conclusion

The computationally efficient MoM-based approach has been used for full-wave frequency-domain broadband EM simulation of wire-grid shielding installations in the context of reduction of lightning-induced magnetic fields and voltages within large volume structures. The observed quantities comprise the magnetic fields, open-circuit voltages induced on electrically small loops and spatial distributions of the magnetic field magnitude on selected planes. The results for a typical single-layer LPS are compared to those for the two-layer structure in the form of a wire-grid spatial shield integrated with the external LPS. The expected additional reduction of the H field intensity inside the protected volume compared to that offered by a conventional LPS has been clearly demonstrated and characterized quantitatively.

This work is supported by the Polish Ministry of Science and Higher Education (decision no. 8686/E-367/S/2017).

***Authors**: dr inż. Artur Noga, dr hab. inż. Andrzej Karwowski, dr inż. Tomasz Topa, Politechnika Śląska, Instytut Elektroniki, ul. Akademicka 2A, 44-100 Gliwice, E-mail: anoga@polsl.pl, andrzej.karwowski@gmail.com, ttopa@polsl.pl.*

REFERENCES

[1] IEC 62305-4, Protection Against Lightning - Part 4: Electrical and electronic system within structures.

[2] Harrington R. F., Field Computation by Moment Methods, MacMillan, New York, 1968.

[3] Karwowski A., Noga A., Topa T., Computationally efficient technique for wide-band analysis of grid-like spatial shields for protection against LEMP effects, *ACES Journal*, vol. 32, no. 1, January 2017, pp. 87-92.

[4] Karwowski A., Noga A., Topa T., An efficient framework for analysis of wire-grid shielding structures over a broad frequency range, *Radioengineering*, vol. 25, no. 4, Dec. 2016, pp. 629-636.

[5] Topa T., Karwowski A., Noga A., Using GPU with CUDA to accelerate MoM-based electromagnetic simulation of wire-grid models, *IEEE Antennas Wireless Propag. Lett.*, vol. 10, 2011, pp. 342-345

[6] Golub G. H., van Loan C. F., Matrix Computations, Baltimore, MD, USA, The John Hopkins University Press, 1996.

[7] Stoer J., Bulirsch R., Introduction to Numerical Analysis, Springer-Verlag, New York, 1980.

[8] Peng S., Nie Z., Acceleration of the method of moments calculations by using graphics processing units, *IEEE Trans. Antennas Propag.*, vol. 56, no. 7, Jul. 2008, pp. 2130–2133.

[9] Lezar E., Davidson D., GPU acceleration of electromagnetic scattering analysis using the method of moments, in *Int. Conf. on Electromag. in Advanced Applic., ICEAA*, Torino, Italy, Sept. 2011, pp. 452–455.

[10] Kolundzija B., Zoric D., Efficient evaluation of MoM matrix elements using CPU and/or GPU, in *6th European Conf. on Antennas and Propagation, EuCAP*, Prague, Czech Rep., March 2012, pp. 702–706.

[11] De Donno D., Esposito A., Monti G., Tarricone L., Parallel efficient method of moments exploiting graphics processing units, *Microwave and Optical Technology Letters*, vol. 52, no. 11, Nov. 2010, pp. 2568-2572.

[12] Aniserowicz K., Maksimowicz T., Comparison of lightning induced current simulations in the time and frequency domains using different computer codes, *IEEE Trans. Electromagn. Compat.*, vol.53, no.2, May 2011, pp. 446-461.