INTERNATIONAL CONFERENCE ON LIGHTNING PROTECTION
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Electromagnetic Shielding Analysis of Buildings Under Power Lines Hit by Lightning

S. Ladan, A. Aghabarati, R. Moini, S. Fortin and F.P. Dawalibi
Safe Engineering Services and Technologies ltd.
Montreal, CANADA
www.sestech.com

***Abstract*—The shielding effectiveness of a metallic enclosure with multiple openings sited close to a transmission line tower hit by lightning is investigated, both in the frequency domain and in the time domain. Two scenarios are analyzed to define the possible sources of interference. First, the entire power network including the tower hit by lightning, shield wires and phase conductors is considered. Next, the simplified case of a single tower hit by lightning is investigated. The results reveal that for a better protection of equipment against lightning, the entire power network should be considered as source of interference for the study of shielding effectiveness.**

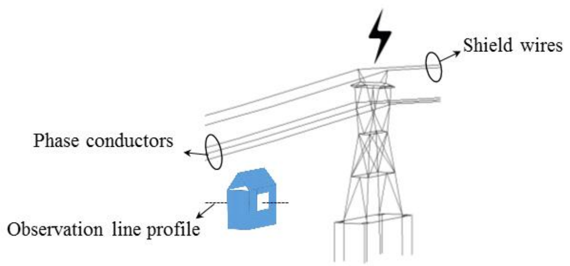
Keywords-Shielding Effectiveness (SE), Lightning, Electromagnetic Interference, Transmission Line, Transient Response.

I. INTRODUCTION

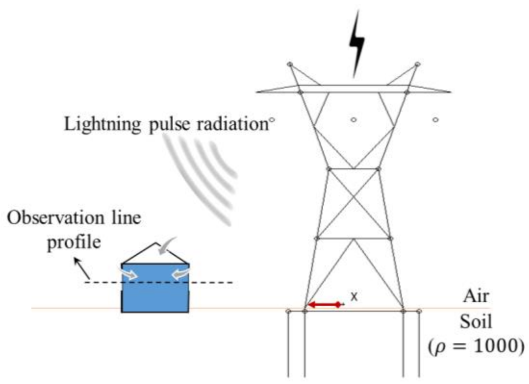
Lightning is a transient, high-current electric discharge whose path length extends over several kilometres. The consideration of cloud-to-ground (CG) lightning events is important in protection studies of electric and electronic equipment used in power systems, information technology systems, etc. Overhead lines in medium and high voltage transmission and distribution networks are susceptible to be hit by CG lightning. Therefore, huge lightning currents can be induced on structures located near their impact zone. Particularly, the maximum rate of change of a very small fraction of these currents circulating in grounding and bonding wires can cause irreversible damage to nearby electronic printed circuit boards [1]. Thus, in addition to physical damages and power interruptions caused by lightning strikes, the problem of electromagnetic interference caused by these currents has to be investigated carefully for a better protection of electronic equipment located in their vicinity. Nowadays, the number of buildings located under power lines in areas of high ground flash density is increasing, and the protection levels provided inside these buildings, with sensitive equipment installed, is of great interest.

Protection of power components against conducted interferences, for structures hit by lightning has been widely investigated in literature [2]-[4]. Usually, the use of optimized grounding network [5]-[7] and surge arresters limits the level of such threats for power components. However, the electromagnetic disturbance radiated by direct or indirect lightning is susceptible to damage electronic integrated circuits used in communication and control apparatus deployed in the surrounding area. Therefore during the last decades, a great deal of effort has been devoted to the analysis of the distribution of transient currents in lightning protection systems (LPS) and of the resulting transient electromagnetic interference inside buildings [8].

In order to determine the threat level to sensitive equipment, the electromagnetic field radiated by structures hit by lightning



(a)



(b)

Fig. 1. Sketch of the power network hit by lightning and the shielding enclosure close to it: (a): Considering the shield wires and the phase conductors, (b): Ignoring the shield wires and the phase conductors.

must be determined through an accurate model and the shielding properties of the enclosure should be expressed by means of appropriate shielding effectiveness parameters. The aim of this paper is to analyze the shielding effectiveness of a typical building located in the vicinity of a power transmission line tower, hit by a lightning strike. The paper is organized as follows. In Section II, the system under study is presented in detail. In Section III, the computation methodology and the lightning current waveforms used as a source of disturbance are presented. Sections IV and V are dedicated to the harmonic and transient analysis of the shielding effectiveness of the building, respectively.

II. SYSTEM NETWORK UNDER STUDY

A schematic of the network, including a tower hit by lightning, a grounding network system, the surrounding transmission lines and a building in its proximity, is shown in Fig. 1. The tower of the three-phase (525 kV) transmission line has a height of 35 m and its grounding system consists of a 16 m by 16 m loop buried at a depth of 0.5 m and four vertical ground rods which are driven to a depth of 10 m. The soil is assumed to be homogeneous with a 1000 Ω-m resistivity, relative permittivity of 1, and relative permeability of 1. As shown in Fig. 1, the tower is in the middle of the studied portion of the power network. The transmission line is modeled for 400 m on either side of the structure: this was found to be sufficiently accurate for the calculation of electromagnetic fields around the tower. The height of the transmission line conductors is about 27 m above the ground at the tower location, and the height drops to 17 m at the point of maximum sag. The building, located 15 m away from the center of the tower, is modeled by a 7 m × 8 m × 13 m enclosure with metallic walls. The building is a metallic enclosure with multiple openings. It has two 3 m × 3 m rectangular apertures located on opposite walls and two more triangular openings under the roof, as shown in Fig. 1-b. The walls, roof, and floor of the building are realized by means of metallic sheets and the bottom of the building is assigned to electrical ground and its potential is set to zero.

In order to examine the level of disturbance inside the building resulting from the transient electromagnetic fields generated by the tower hit by lightning, observation points are defined over a straight line passing through the window openings and covering the regions inside and outside the enclosure, as shown in Fig. 1. The building is studied under two scenarios:

- Scenario 1: The shield wire and phase conductors are included in the model and their radiation effects as sources of interference are considered.
- Scenario 2: The shield wires and the phase conductors are removed from the system under analysis.

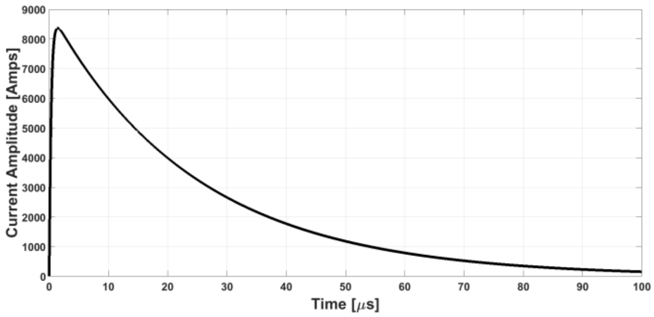


Fig. 2. Current waveform of the studied lightning signal.

III. COMPUTATION METHODOLOGY AND LIGHTNING WAVEFORM

The computation of the electromagnetic fields is performed in frequency domain, for each frequency component contained in the surge signal. In order to study the radiating effects of lightning and to characterize its interference level, a full-wave numerical modeling is conducted using the commercial software package, CDEGS (Current Distribution, Electromagnetic fields, Grounding and Soil structure analysis) [9]. The computation results for the described problem were obtained using the HIFREQ and FFTSES modules of CDEGS. The HIFREQ module provides a solution of the electric field integral equation by Method of Moment (MoM) for complex structures including networks of wires and metallic surfaces [10]. It should be noted, the conducted methodology takes into account computation of the vector potential and rise of scalar potential associated with any nearby metallic objects. The presence of a multilayer soil can also be taken account. The removal of low frequency instabilities, which typically affects such computation methods, permits the computation of inducing effects from 0 Hz to several MHz [11]. The latter allows an accurate analysis of lightning phenomena.

The lightning current is injected into the top of the tower. Its waveform is shown in Fig. 2. The time variation of the current used in the computations is represented by the sum of two double exponential functions as follows:

$$\mathbf{I(t) = 9000(e^{-40000t} - e^{-3000000t}) + 115(e^{-100000t} - e^{-22200t})} \quad (1)$$

The transient waveform has a rise time of 1.44 μs and a half-value time of 24 μs. A total number of 512 sample frequencies ranging from 0 Hz to 5.2 MHz are selected from the discrete Fast Fourier Transform (FFT) to represent the lightning surge in the frequency domain. First, the computation is performed at each frequency for a unitary current. Then the application of the Inverse Fast Fourier Transform (IFFT) to the superposition of the values computed in the frequency domain, modulated by the amplitude of the lightning current spectrum, provides the transient response of the system. Once the induced currents are obtained for the wires and surfaces of the entire network, the radiated electric and magnetic fields of the energized system are computed for the evaluation of the induced effects of the LEMP (lightning electromagnetic pulse) to the regions around the building.

IV. Frequency-Domain Evaluation of the Shielding Effectiveness

The Shielding Effectiveness (SE) of a shielding structure is an index used to assess the adequacy of the structure and to evaluate the protection level it affords against LEMP. Electromagnetic shielding problems in many case studies are analyzed in the frequency domain [12]. To calculate the electric and magnetic SE at any point in frequency-domain, the following equations are defined

$$\mathbf{SE_{dB}}\ (\mathbf{Electric}) = \mathbf{20log}\left(\frac{|\boldsymbol{E_{absence}}|}{|\boldsymbol{E_{presence}}|}\right) \quad (2)$$

$$\mathbf{SE_{dB}}\ (\mathbf{Magnetic}) = \mathbf{20log}\left(\frac{|\boldsymbol{H_{absence}}|}{|\boldsymbol{H_{presence}}|}\right) \quad (3)$$

in which $\boldsymbol{E_{absence}}$ and $\boldsymbol{H_{absence}}$ represent, respectively, the electric and magnetic fields when there is no shielding (without presence of the building) while $\boldsymbol{E_{presence}}$ and $\boldsymbol{H_{presence}}$ denote to the electric and magnetic fields in presence of the shielding

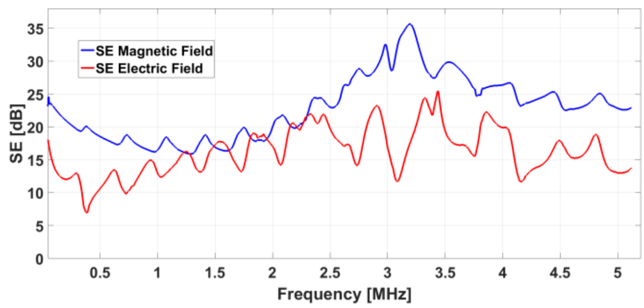


Fig. 3. Electric SE and Magnetic SE for the case considering the shield wires and phase conductors (Scenario 1).

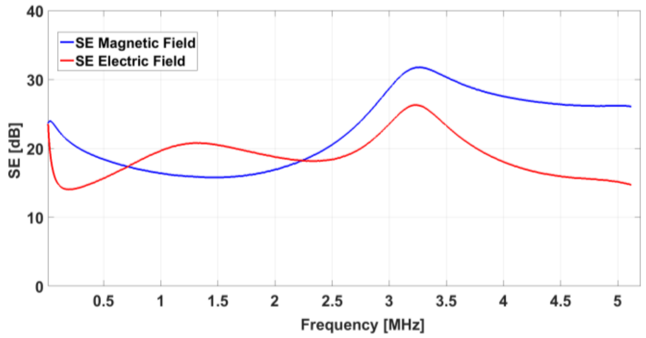


Fig. 4. Electric SE and Magnetic SE for the case ignoring the shield wires and phase conductors (Scenario 2).

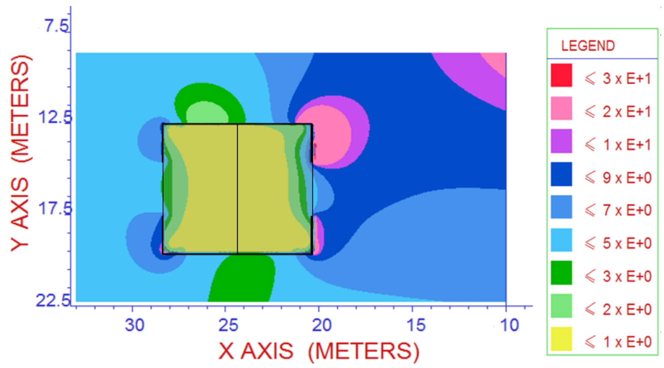


Fig. 5. The electric field distribution (V/m) at frequency of 3.2 MHz.

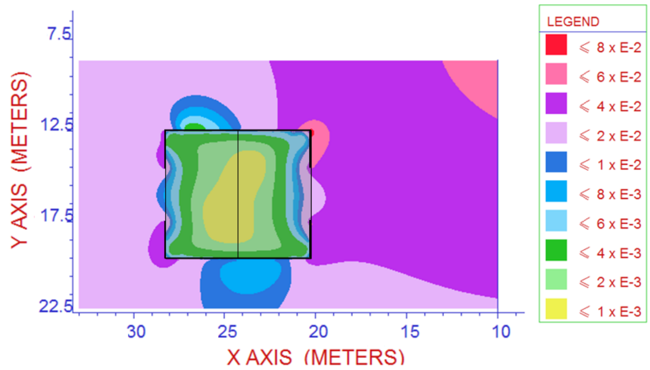


Fig. 6. The magnetic field distribution (A/m) at frequency of 3.2 MHz.

enclosure (the building). To calculate the SE in the frequency domain, simulations are performed for Scenario 1 and Scenario 2 described in Section II.

Fig. 3 and Fig. 4 depict the electric and magnetic shielding effectiveness at a point located in the middle of the observation profile (as shown in Fig. 1), for Scenarios 1 and 2, respectively. As shown in Fig. 3, the electric and magnetic shielding effectiveness over the frequency range from DC to 5.12 MHz for the observed point inside the building presents a highly oscillatory behavior. Indeed, these oscillations are related to the electromagnetic fields radiated by a fraction of the surge current propagating along the shield wires to the adjacent towers and the subsequent reflections from the termination points. The maximum magnetic SE occurs at 3.2 MHz while the maximum electric SE happens at 3.5 MHz.

It can be observed from Fig. 4 that the shielding effectiveness for the same point and over the same frequency range has fewer oscillations when removing the shield wires and phase conductors (second scenario). It is worth mentioning that, despite the unrealistic behavior in this scenario, the results can still be used to assess the general level of electromagnetic fields penetrating inside the enclosure when the network is hit by lightning.

A surface profile parallel to the ground and passing through the building is selected for the presentation of the spatial variation of the electromagnetic fields. Fig. 5 and Fig. 6 show the distribution of the electric and magnetic fields for the selected surface profile, respectively (top view of the building). The computation is performed for the frequency where magnetic SE is maximum (3.2 MHz). As seen in those two figures, the minimum level of magnetic field inside the building is in the range of 10^{-3} A/m while the level of electric field at the center is also reduced to 1 V/m. This shows that due to the presence of the metallic enclosure, the level of electric and magnetic field inside the building is decreased significantly compared to that in the exterior regions.

V. Time-Domain Evaluation of the Shielding Effectiveness

Electromagnetic shielding analyses are normally performed in the frequency domain [12]. This approach is particularly appropriate when the interfering electromagnetic sources have a harmonic variation. However, for transient electromagnetic sources such as lightning strikes where EM protection is important, a frequency domain analysis cannot provide an all-around and versatile assessment of the ability of the shielding structure. Consequently, in some recent publications new parameters have been defined and used to evaluate the level of shielding structures in the time domain [13]. Since many electric and electronic devices are susceptible to the maximum level reached by the electromagnetic fields and their induced effects caused by time varying magnetic or electric flux, the shielding parameters can be defined in a way to show the reduction of the mentioned effects. According to [13], the relevant shielding parameters are the *electric peak value reduction shielding effectiveness* ($\mathrm{SE_{E-PR}}$) and the *magnetic peak value reduction shielding effectiveness* ($\mathrm{SE_{H-PR}}$) defined as

$$\mathbf{SE_{E-PR}} = \mathbf{20log}\left(\frac{\left|\boldsymbol{E}^{Max}_{absence}(\boldsymbol{t},\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})\right|}{\left|\boldsymbol{E}^{Max}_{presence}(\boldsymbol{t},\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})\right|}\right) \tag{4}$$

$$\mathbf{SE_{H-DR}} = \mathbf{20\,log}\left(\frac{\left|\boldsymbol{H}^{Max}_{absence}(\boldsymbol{t},\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})\right|}{\left|\boldsymbol{H}^{Max}_{presence}(\boldsymbol{t},\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})\right|}\right) \tag{5}$$

where $\boldsymbol{E}^{Max}_{absence}$ and $\boldsymbol{E}^{Max}_{presence}$ denote the maximum level of the electric field at each observation point, with and without the shielding over the duration of the transient event, respectively, while $\boldsymbol{H}^{Max}_{absence}$ and $\boldsymbol{H}^{Max}_{presence}$ represent the magnetic field in absence and presence of the enclosure. It is worth mentioning that $\mathrm{SE_{E-PR}}$ ($\mathrm{SE_{H-DR}}$) shows the peak reduction of the electric (magnetic) field, which can be helpful in designing structures employed to protect systems and devices sensitive to a specific level of EM field. The network under study is analyzed in the time domain.

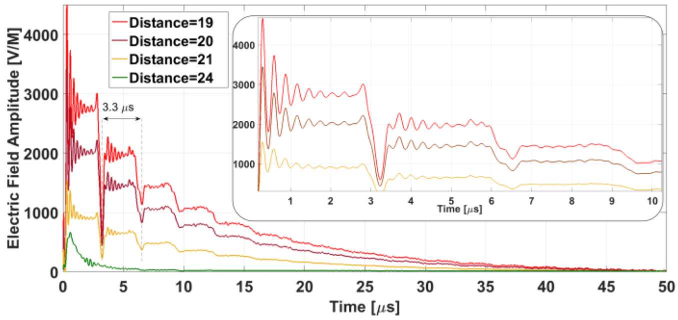


Fig. 7. Time trend of the electric field (Scenario 1).

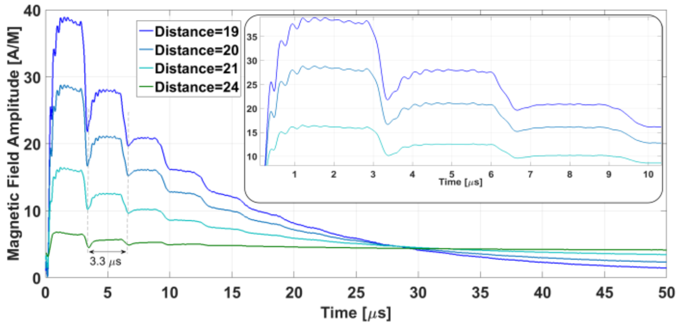


Fig. 8. Time trend of the magnetic field (Scenario 1).

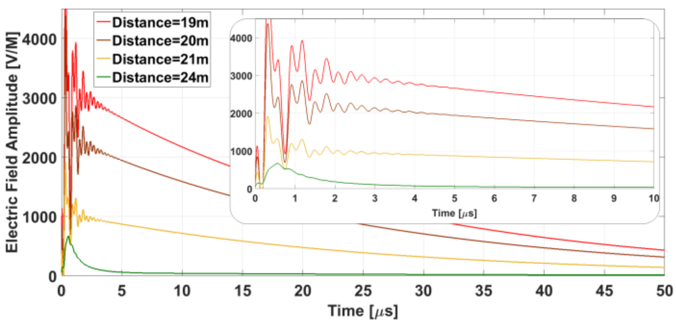


Fig. 9. Time trend of the electric field (Scenario 2).

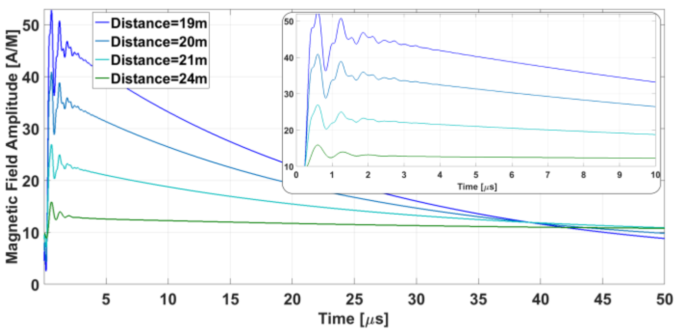


Fig. 10. Time trend of the magnetic field (Scenario 2).

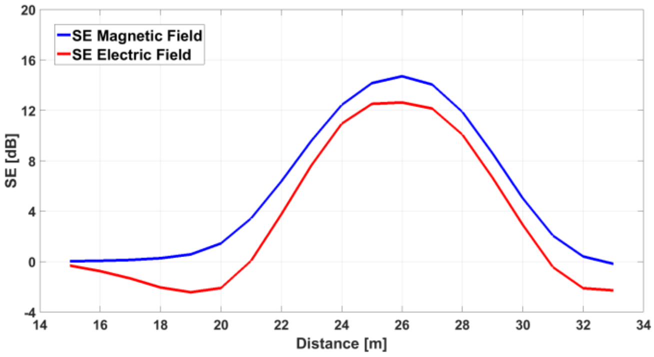


Fig. 11. Electric SE and Magnetic SE for Scenario 1.

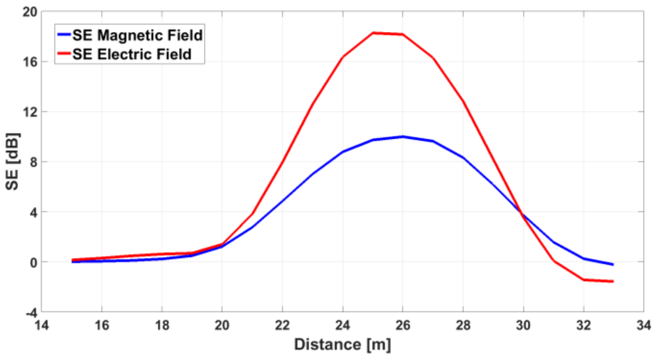


Fig. 12. Electric SE and Magnetic SE for Scenario 2.

The results for the electric and magnetic fields at different distances from the EM source (the tower) for both scenarios are shown in Fig. 7 to Fig. 10. For Scenario 1, the fast oscillations are due to the multiple reflections of the lightning current along the tower, while the abrupt changes that occur every 3.3 microseconds are related to the lightning surge propagation on the shield wires and their induced effects over the phase wires.

The electric and magnetic peak value reduction shielding effectiveness for all points on the observation profile are shown in Fig. 11 and Fig. 12 for the first and second scenarios, respectively. The maximum level of the electric and magnetic shielding for both scenarios occurs in the middle of the enclosure at a distance of 26 m from the power line network. It is worth mentioning that the horizontal axes of Fig. 11 and Fig. 12 (varying from 14 m to 34 m) shows the distance of each observation point located on the observation line profile from the central phase of the transmission line, which is considered at x = 0 as shown in Fig. 1-b. Moreover, as is seen in these two figures, some negative values are observed for the electric and magnetic shielding effectiveness. These negative values (or EM field amplification) occur at position of apertures (windows) where the total amplitude of the field has been intensified due to the reflection of the waves from the surface of the metallic walls.

VI. Conclusion

The shielding performance of a metallic enclosure with apertures located in the vicinity of a transmission line tower hit by lightning is investigated in both frequency domain and time domain using the CDEGS software package. Two scenarios are analyzed: a case where entire power network including the tower, the grounding structure, the shield wires and the phase conductors are considered when examining the level of interference, and a case where only the tower with no shield wires or phase conductors is considered as the source of interference in the model. The simulation results show that the electric and magnetic shielding effectiveness in the frequency domain for the first scenario have some oscillations caused by multiple reflection between the towers and the mutual coupling between the shield wires and phase conductors. Moreover, the effects of the shield wires and phase conductors are more apparent in the time domain analysis since the transient electric and magnetic fields in the first scenario have more oscillations compared to those in the second scenario.

Acknowledgment

The authors wish to thank Safe Engineering Services & Technologies Ltd. for the support and facilities provided during this research work.

References

[1] S. Celozzi, R. Araneo, and G. Lovat, *Electromagnetic Shielding*. Hoboken, NJ, USA: IEEE, 2008.

[2] V. A. Rakov and F. Rachidi, "Overview of recent progress in lightning research and lightning protection," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 3, pp. 428–442, August 2009.

[3] V. A. Rakov, M. A. Uman, M. I. Fernandez, C. T. Mata, K. J. Rambo, M. V. Stapleton and R. R. Sutil, "Direct lightning strikes to the lightning protective system of a residential building: triggered-lightning experiments," *IEEE Trans. Power Del.*, vol. 17, no. 1, pp. 575–586, 2002.

[4] J. Takami; and S. Okabe, "Characteristics of direct lightning strokes to phase conductors of UHV transmission lines," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 537–546, 2007.

[5] F. P. Dawalibi, W. Xiong and J. Ma, "Transient performance of substation structures and associated grounding systems," *IEEE Trans. Ind. Appl.*, , vol. 31, no. 3, pp.520-527, 1995.

[6] F. P. Dawalibi and W. Xiong "Transient performance of substation grounding systems subjected to lightning and similar surge currents," *IEEE Trans. Power Del.*, vol. 9, no. 3, pp. 1412-1420, 1994.

[7] F. Grange, S. Journet, S. Fortin and F. P. Dawalibi, "Analysis of grounding grids influence on lightning generated magnetic field," *International Symposium on Electromagnetic Compatibility (EMC EUROPE)*, pp. 828-832, 2013.

[8] R. Araneo, S. Celozzi, A. Tatematsu and F. Rachidi, "Time-Domain analysis of building shielding against lightning electromagnetic fields," *IEEE Trnas. Electromagn. Compat.*, vol. 57, no. 3, pp. 397-404, June 2015.

[9] "CDEGS 15.1.4080", Safe Engineering Services & Technologies ltd. Laval, Québec Canada, 2015 [Online]. Available: www.sestech.com.

[10] W. C. Gibson, "The method of moments in electromagnetics", CRC press, 2014.

[11] J. F. Lee, R. Lee, and R. J. Burkholder, "Loop star basis functions and a robust preconditioner for EFIE scattering problems,". *IEEE Trans. Antennas Propag.*, vol. 51, no. 8, pp.1855-1863, August 2003.

[12] *Standard Method for Measuring the Effectiveness of Electromagnetic Sheilding Enclosure*, IEEE Standard 299, Feb. 2007.

[13] S. Celozzi and R. Araneo, "Alternative definitions for the time-domain sheilding effectivemess of enclosures," *IEEE Trnas. Electromagn. Compat.*, vol. 56, no. 2, pp. 482-485, April 2014.