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Calculation of Lightning Effects in the Frequency Domain with a Program based on Hybrid Methods

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SUMMARY

The calculation of touch and step voltages as well as the separation distance in Grounding System (in the following GS) or Lightning Protection System (in the following LPS) is required by several standards, e.g. EN 50522 – 2010 or IEEE-Std. 80-2013 and IEC 62305 series.

The methodology for the calculation of touch and step voltages at power frequency is well established and permissible values are well known. The current to earth calculation, the soil parameters evaluation and the GS design can be addressed by common tools. The GS can be considered as equipotential if its size is much lower than the wavelength of the electromagnetic field in the earth. If the GS cannot be considered equipotential, self and mutual impedance of and between conductors has to be taken into account.

At higher frequency the phenomena are more complex and standards seek to provide a workable approach for most cases. However, standards do not allow a carefully evaluation of lightning effects on a building or on a substation in the phase of planning. According to the IEC 61305 series, these evaluations affect the external LPS as well as the GS and involve lightning impulse currents having a frequency range from 25 kHz up to 1 MHz. The calculations are not trivial and on the other hand, in some case lack the permissible values. As known, international standards do not give permissible touch and step voltages in this frequency range.

New computational tools could help bridge some gaps. The proposed calculation model is based on an hybrid method and takes into account transmission line, circuit and electromagnetic theory combined into a single calculation model. The complete layout of LPS, GS included, can be simulated. The calculation model provides the lightning current distribution and then all the derived values such as touch and step voltages, electric and magnetic fields and consequently dangerous areas and separation distances. The performance

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of the used program is verified in comparison with time domain solutions using a network analysis program.

This paper sets out to define the requirements for the calculation of touch and step voltages and the separation distance for the frequency range of lightning currents. The frequencies for lightning impulse currents were derived from time into frequency domain. The first positive short stroke is represented by a 25 kHz sine wave with same peak value as the standardised values in IEC 62305-1. For the first and subsequent negative short strokes the equivalent frequencies are respectively 250 kHz and 1 MHz.

KEYWORDS

Lightning Strikes, Lightning Protection Systems, Grounding Systems, Touch and Step Voltages, Separation Distance, Computer Modelling, Hybrid Method, PEEC.

1 - INTRODUCTION

The large improvement of power computing performances is contributing to the diffusion of calculation programs for electromagnetic simulations taking into account realistic condition and in particular the earth effects.
These programs have many engineering applications, as for instance:
- Grounding Systems
- Cathodic Protection
- Electromagnetic Fields
- Electromagnetic Interferences
- Fault Currents Distribution
- Lighting Systems

Each application has specific needs as for example concerns a different frequency range.
As known, with increasing frequency the possible approximations are less and less and the calculation model is becoming increasingly complex. For instance, when frequency increases, mutual coupling, soil parameters frequency dependence and propagation delay cannot be neglected.
One of the most promising and effective calculation model in the frequency range between DC to a few MHz is the “Partial Element Equivalent Circuit (PEEC)” method that in the following for historical reasons or for tradition in the grounding community we prefer to call “hybrid method”.
Calculation models for electromagnetic simulations including the earth effects may be based on following different approaches: 1) Electromagnetic field theory; 2) Transmission line theory; 3) Hybrid methods, 4) Circuit theory. This classification is not rigorous as indicated in [11], but is generally adopted in the literature. For a comprehensive overview on these kind of computational methods refer to [11].
Hybrid methods consider transmission line, circuit and electromagnetic field theory combined into a single model, and are often preferred in the frequency range of interest. Hybrid methods are very useful for engineering purposes because they are accurate and flexible, and can allow an easy way to include additional external parameters such as electromotive forces, currents, and impedances [14].
In the following paper the calculation were performed by XGSA_FD® a module of the software package XGSLab®. This program is based on an hybrid method and on the main assumptions listed in Tab. 1.1.

Resistive Coupling	Yes
Capacitive Coupling	Yes
Self-Impedance	Yes
Inductive Coupling	Yes
Soil Parameters	ρ, $\varepsilon = f(\omega)$
Propagation Law	$e^{-\Upsilon r/r}$

Tab 1.1. Aspects taken into account in the used program.

2 – HYBRID METHOD

In the following, a short description of the hybrid method implemented in the used program is provided.
The implemented method can solve system of conductors arranged in an arbitrary way in the 3D space and including sources (conductors with current and voltages known), and victims (conductors with current and voltages unknown). The system of conductors is partitioned into small finite elements (current and charge cells), and then, the electromagnetic field and transmission line theories are used to calculate the circuit parameters, whereas circuit theory is employed to describe the relations among parameters such as voltages and currents and the metallic connections among elements. All conductors of the system have to be thin enough in order to be simulated with a suitable number of thin and straight elements.

The implemented method derives directly from the Maxwell equations. Using the scalar and vector potentials, Maxwell equations [3] can be written as in the following (Helmholtz equations):

$$\begin{cases} \Delta\dot{\mathbf{A}} - \dot{\gamma}^2\dot{\mathbf{A}} = -\mu\dot{\mathbf{J}} \\ \Delta\dot{V} - \dot{\gamma}^2\dot{V} = -\dfrac{\dot{q}}{\dot{\varepsilon}} \end{cases} \qquad (2.1)$$

where $\dot{\gamma} = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)}$ represents the propagation coefficient of the medium and $\dot{q}$ and $\dot{J}$ represent charge and current density distribution on the sources respectively.
Solution of (2.1) for sources with linear current and charge density distribution are given by the following equations:

$$\begin{cases} \dot{\mathbf{A}} = \dfrac{\mu}{4\pi}\displaystyle\int_L \dot{I}\,\frac{e^{-\dot{\gamma}r}}{r}dl \\ \dot{V} = \dfrac{1}{4\pi\dot{\varepsilon}}\displaystyle\int_L \dot{q}\,\frac{e^{-\dot{\gamma}r}}{r}dl \end{cases} \qquad (2.2)$$

Maxwell equations give the following well known relation between electric field and scalar and vector potentials:

$$\dot{\mathbf{E}} = -grad\dot{V} - j\omega\dot{\mathbf{A}} \qquad (2.3)$$

Taking into account that the electric field and vector potential on the surface of a conductor are parallel to the conductor axis [7], only the magnitude of vectors in (2.3) need to be considered and (2.3) written along the conductor axis gives:

$$\dot{E} = -\frac{\partial\dot{V}}{\partial l} - j\omega\dot{A} \qquad (2.4)$$

On the other hand, the tangential electric field on the surface of a conductor, taking into account their self impedance, gives:

$$\dot{E} = \dot{z}\dot{I} \qquad (2.5)$$

Combining (2.4) and (2.5), the following fundamental differential equation is obtained:

$$\dot{z}\dot{I} + j\omega\dot{A} + \frac{\partial\dot{V}}{\partial l} = 0 \qquad (2.6)$$

Equation (2.6) is derived directly from the Maxwell equations and is then valid in all conditions (also non stationary). In practical cases, (2.6) can be solved only in a numerical way. The system of conductors is then partitioned into a suitable number of short elements. Each element is oriented between its start point (in) and its end point (out). Integrating (2.6) between the ends of an element, replacing the vector and scalar potential with (2.2) and rearranging, the following linear equation is obtained:

$$\dot{Z}_i\dot{I}_i + \sum_{j\neq i}\dot{M}_{ij}\dot{I}_j + \sum\left(\dot{W}_{outij} - \dot{W}_{inij}\right)\dot{J}_j = 0 \qquad (2.7)$$

with:

$$\dot{M}_{ij} = \frac{j\omega\mu}{4\pi}\int_{in}^{out}\int_{in}^{out}\frac{e^{-\dot{\gamma}r}}{r}dl_i dl_j$$

$$\dot{W}_{outij} = \frac{\dot{\rho}}{4\pi l}\int_{in}^{out}\frac{e^{-\dot{\gamma}r}}{r}dl_j\bigg|_{out}$$

$$\dot{W}_{in\,ij} = \frac{\dot{\rho}}{4\pi l}\int_{in}^{out}\frac{e^{-\dot{\gamma}r}}{r}dl_j\bigg|_{in}$$

and where $\dot{Z}$ represents the self impedance of the element, $\dot{M}$ and $\dot{W}$ represent partial mutual coupling and partial potential coefficients between elements respectively, and $\dot{I}$ and $\dot{J}$ represent longitudinal and leakage currents respectively.

Writing a linear equation for each element, the Maxwell equation are then reduced to a linear system. For the calculation of the linear system coefficients and then of the self and partial mutual coupling and partial potential coefficients between elements, the formulas in [1], [6], [8], the shifting complex images method (SCIM) [10] and the modified images method (MIM) [9] has been used respectively. If these coefficients are calculated taking into account the propagation delay, the resulting model is a full-wave hybrid method.

Each element is represented with a simplified “T” equivalent circuit as shown in Fig. 2.1 and introduces the following unknowns:

- Input and Output currents I_{in} and I_{out}
- Leakage current J
- Potential V of the middle point

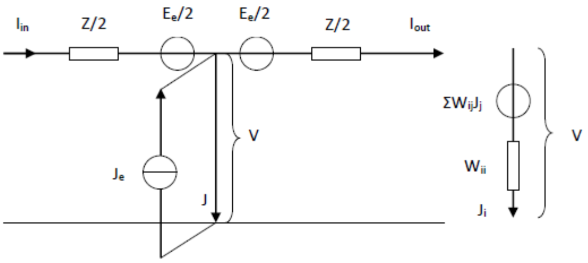

Fig. 2.1. Equivalent circuit of each element

The resulting linear systems can be written as follows:

$$\begin{cases}\{V\} = [W]\{J\}\\ \{E_z\} + \{E_e\} = -([Z] + [M])\{I\}\\ \{J\} = [A]\{I\} + \{J_e\}\end{cases} \tag{2.8}$$

where:

- $[W]$ = matrix of self and mutual partial potential coefficient
- $[Z]$ = matrix of self-impedances
- $[M]$ = matrix of partial mutual impedances
- $[A]$ = incidence matrix which expresses the elements connectivity
- $\{V\}$ = array of potentials
- $\{I\}$ = array of currents
- $\{J\}$ = array of leakage currents
- $\{E_z\}$ = array of voltage drops

- $\{E_e\}$ = array of forcing electromotive force
- $\{J_e\}$ = array of injected currents

The linear system (2.8), provides the distributions of currents, potentials and leakage currents along the victims taking into account the influence of eventually sources. From these main results, it is possible to calculate other important distributions as for instance:

- Earth surface potentials and then Touch and Step Voltages
- Electric Fields
- Magnetic Fields

The calculation model above described is suitable for the “frequency domain” but also in the “time domain” by using the direct and inverse Fourier transform. As known a time domain transient “s(t)” can be considered as a superposition of many single frequency signals as follows:

$$s(t) = \sum_{n=-\infty}^{\infty} \dot{S}_n e^{j2\pi nft} \qquad (2.9)$$

where:

- $\dot{S}_n$ = magnitude of the n^th^ harmonic
- f = base frequency

The “ $\dot{S}_n$ ” values can be calculated by using a direct Fourier transform. In practical cases the maximum harmonics number in (2.9) is limited to a value “N” depending on the frequency spectrum of the input transient. The above described frequency domain model can be used for each harmonic and at the end “N” different output in the frequency domain will be obtained. Then, the time domain output can be obtained by using the inverse Fourier transform.

This described process is quite easy to implement but, even limiting the harmonics to a reduced number of critical frequencies, the calculation may be time consuming and results in the time domain not so useful. In fact, in many cases, only the peak values of the time domain output is interesting and a good approximation of this value can be calculated in an easier way using the frequency domain approach and an equivalent single frequency input as explained below.

3 – LIGHTNING’S EQUIVALENT SINUSOIDAL WAVE FORM

Cloud to earth lightning are classified by [19] as follows:

- First positive short stroke
- First negative short stroke
- Subsequent negative short stroke
- Long stroke

First strokes current may have positive (in 10% of cases) or negative polarity, while subsequent stroke polarity is always negative. Polarity indicates the sign of the charges in the part of the cloud where the lightning starts. The negative and positive charges are in the bottom and upper part of the cloud respectively.

The standard lightning wave shape of short strokes may be defined with the following Heidler function (Fig. 3.1):

$$i = \frac{I}{k}\frac{(t/T_1)^n}{1+(t/T_1)^n} e^{-\frac{t}{T_2}} \qquad (3.1)$$

where:
- I = peak current
- k = parameter
- T_1 = front time
- T_2 = time to halve value
- n = current steepness factor

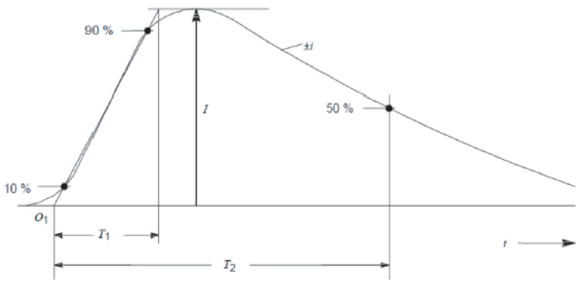

Fig. 3.1: Standard lightning wave shape represented with the Heidler function

The Heidler function is based on years of statistical analysis of lightning strokes. The current rise may be adjusted by the coefficients “n” and “T1” ([19] uses “n = 10”). The IEC 62305-1 and waveform parameters (front time to peak and time to half value) of the standard lightning are listed in Tab. 3.1:

Type of short stroke	IEC 62305-1 parameters						Impulse parameters		Equivalent frequency
	I Class I (kA)	I Class II (kA)	I Class III-IV (kA)	k	T1 (μs)	T2 (μs)	T1 (μs)	T2 (μs)	f (kHz)
First positive	200	150	100	0.93	19	485	10	350	25
First negative	100	75	50	0.986	1.82	285	1	200	250
Subsequent negative	50	37.5	25	0.993	0.454	143	0.25	100	1000

Tab 3.1. Standard lightning parameters and equivalent frequency for peak current representation in the frequency domain

As anticipated, by using the frequency domain approach and an equivalent single frequency input can allows to obtain similar results than with a time domain approach. The equivalence between impulse and sinusoidal wave forms means that, the maximum values of the two wave forms are the same for engineering perspective. As known, for the calculation of touch and step voltages, induced voltage, electrodynamic forces, dielectric effect (flashover/cracking) applications, it is sufficient to consider the peak value of the current [19].

Otherwise people usually believe, the lightning is a phenomenon at relatively low frequency. The equivalent frequency of a standard lightning with front time to peak value “T1” can be calculated as follows:

$$f_{eq} = \frac{1}{4T_1} \qquad (3.2)$$

The effective value of the sinusoidal wave form has to be calculated assuming that the maximum values of impulse and sinusoidal wave forms are the same. For instance, the equivalent sinusoidal wave form of a impulse 100 kA - 10/350 μs has an effective value 70.7 kA and a frequency 25 kHz (Fig. 3.2). The front steepness of the sine currents is around 12 % higher than the corresponding Heidler function.

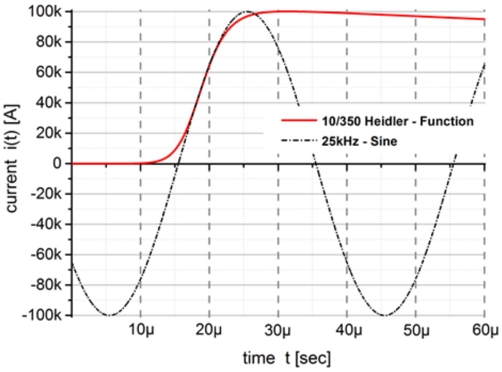

Fig. 3.2: Comparison between Heidler function and the equivalent sinusoidal wave form

The results of the calculation with the equivalent sinusoidal wave form have to be compared with limits related to the same frequency. For instance, the touch and step permissible effective value at 25 kHz can be respectively 2000/√2 = 1414 V and 25000/√2 = 17730 V ([13], [17]). Anyway there aren't enough study about the life hazard caused by lightning effects on the human body and as consequence in the international standard there aren't touch and step voltages as for the low frequency.

4 – CALCULATION OF LIGHTNING EFFECTS WITH HYBRID METHODS

Structures can be protected against lightning by a LPS according to [20]. The function of a LPS is to protect structures from fire or mechanical destruction, electrical equipment from overvoltage of electromagnetic fields and people from injury or even death.

A LPS can include the following components:

- Air termination system
- Down conductor system
- Earth termination system (here called GS)
- Equipotential bonding
- Electrical insulation of the external LPS (here called separation distance)

A lightning strike on the air termination system of a building, represents a typical case of study. In this case, lightning currents flow along the air termination system and the down conductor system until the GS and then is spread in the earth.

The currents cause electric and magnetic fields distributions. The magnetic fields can cause dangerous induced EMF and electric discharges between the external LPS and the structural metal parts. The currents spread in the earth can cause dangerous touch and step voltages.

4.1 –LPS Layout and Soil Parameters

As example, in the following the LPS of a building (GS included) is taken into account.

The external LPS size is 45 x 15 x height 10 m and is made with steel conductor with 10 mm diameter.

The GS includes rods 9 m length and is made with steel conductor with 20 mm diameter.

The main aim is to verify the distribution of the lightning currents, magnetic fields, earth surface potential and touch and step voltages. The equivalent sinusoidal wave form to standard lightning has been considered. The LPS layout and the injection point of the lightning current are shown in Fig. 4.1.

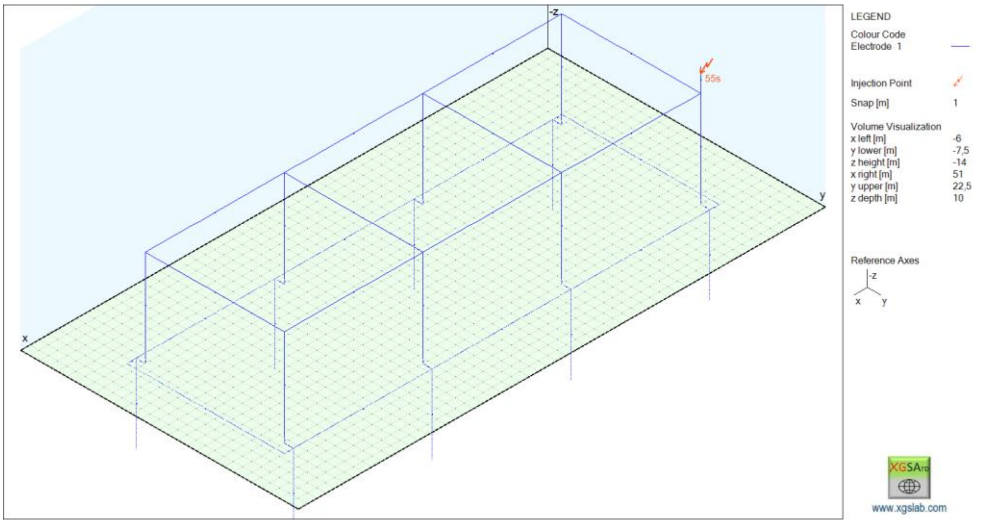

Fig. 4.1: LPS and GS layout and injection point of the lightning current

For the performed calculations below, the following soil parameters are assumed:

- Low frequency soil resistivity = 100 Ωm
- High frequency soil relative permittivity = 6
- Soil parameters dependence: Messier model [16]

4.2 – Lightning Current Distribution

The lightning current distribution taking into account an injected current RMS 35,5 kA - 1MHz (corresponding to the subsequent negative short stroke equivalent impulse Class I) is represented in Fig. 4.2. The lightning current tends to flow to earth across the down conductors closest to the injection point but in case of first negative and subsequent negative impulse the current distribution could be affected by travelling waves effects. Travelling waves effects usually appear starting from some hundred kHz depending on the size of the system of conductors and of the soil resistivity and anyway they add a complexity factor to the study of the LPS.

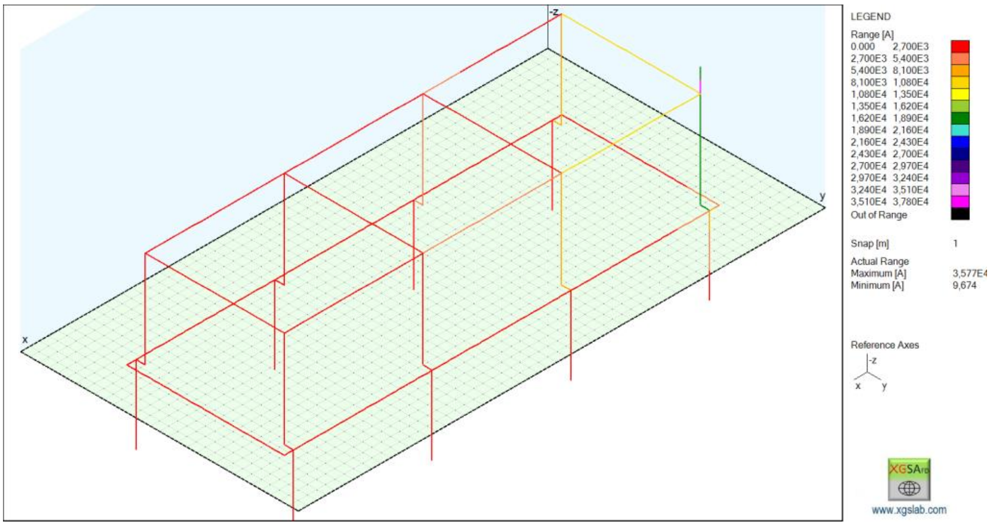

Fig. 4.2: Lightning current distribution

4.3 – Magnetic Field Distribution

The magnetic field distribution in horizontal areas lying on the earth surface are represented in the following figures and shown effectively also the current distribution on the down conductors and on the GS. As general rules magnetic field tends to reduce moving away from the down conductors and increasing the down conductors number.

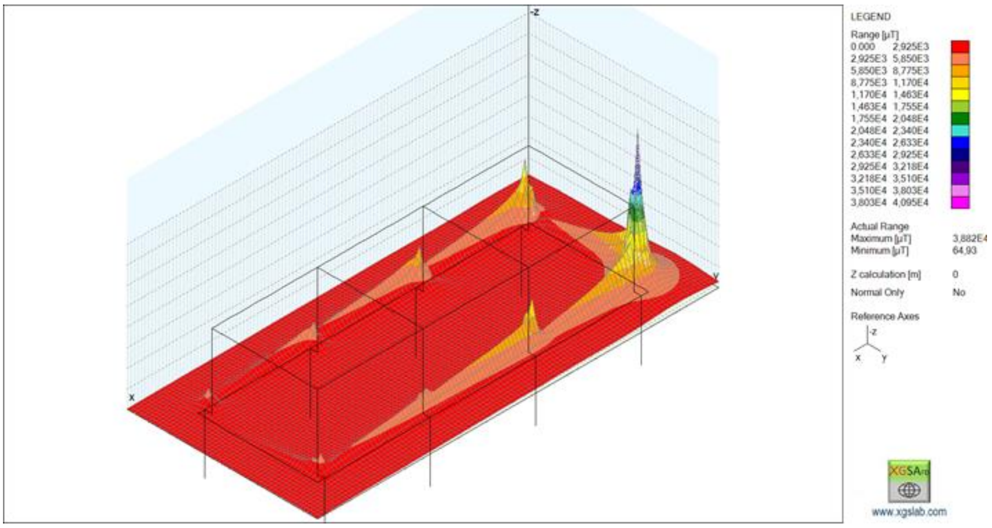

Fig. 4.3: Magnetic field distribution – 200 kA 10/350 µs = RMS 141.4 kA 25 kHz

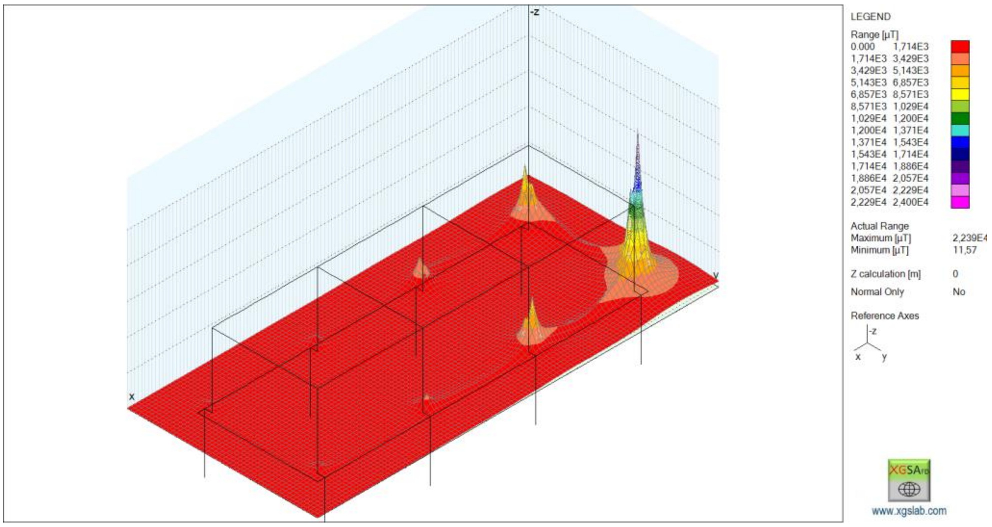

Fig. 4.4: Magnetic field distribution - 100 kA 1/200 µs = RMS 70.7 kA 250 kHz

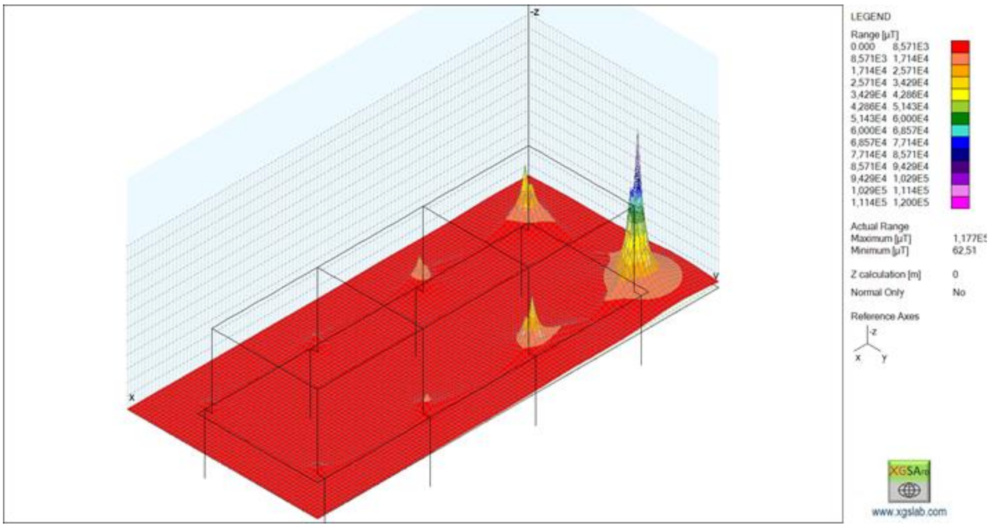

Fig. 4.5: Magnetic field distribution - 50 kA 0.25/100 µs = RMS 35.4 kA 1 MHz

4.4 – Magnetic Flux through a Surface

It is also possible to calculate the magnetic flux across the calculation area and then the induced EMF along its perimeter. Referring to the vertical area in Fig. 4.6, and to the subsequent negative short stroke Class I, a 120 kV peak value of EMF is evaluated. The calculated EMF represents with a good approximation the difference of potential between the upper ends of the fictitious vertical conductor that closes the loop. In this calculations, the maximum value of EMF is produced by subsequent negative short stroke.

In this regard, it is easy to verify that using the simplified formulas “EMF = M*di/dt” (taking account a single infinite long conductor and a uniform current) leads to strongly overestimate values (over 50%). In reality, current along the down conductor is not uniform and the contribution of the other conductors of the LPS (in this case in particular the horizontal conductors which radiate from the injection point the currents “I_A” and “I_B” as in the detail in the Fig. 4.6) cannot be neglected. However, the simplified formula is used by [20] in order to calculate separation distance that are therefore usually widely overestimated.

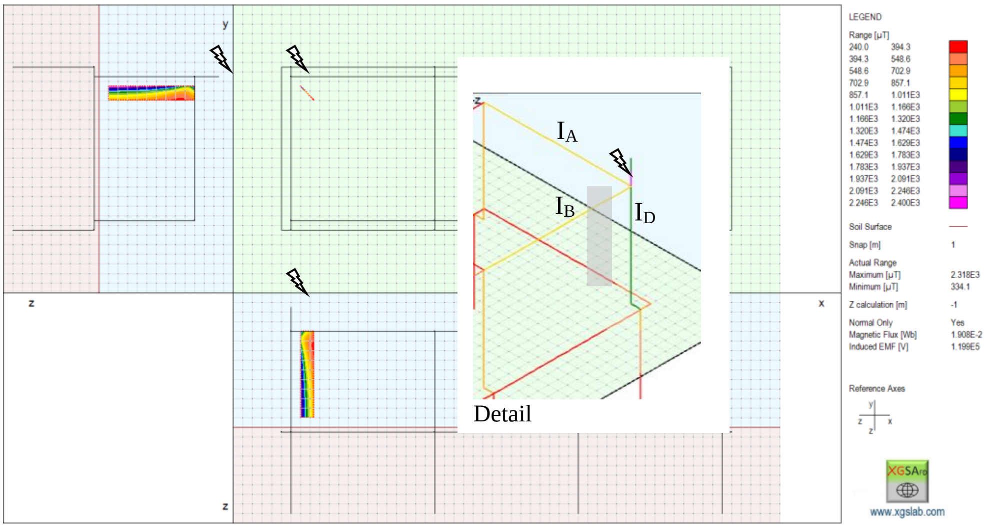

Fig. 4.6: Magnetic field distribution in a vertical area

4.5 – Calculation of the Separation Distance

The engineering of an external LPS requires the calculation of the separation distance “s”. According to [20], “s” is defined as the distance between two conductive parts at which no dangerous sparking can occur. Two procedures are possible to calculate the separation distance.

The first procedure involves the calculation of the induced voltage between two conductive parts and the application of the so-called time area law. The induced voltage in a defined loop or the voltage between two conductive parts (that includes also the non-equipotential GS) can be found as above described. With the application of the so-called voltage-time area law, the required value for the separation distance can be found as indicated in [20]. However the published parameters [5] are experimentally confirmed for impulse voltage 1,2/50 μs only but applied for the calculation in [20].

Anyway, the calculation of the separation distance in [20] is based on some wrong assumption. Only the subsequent short stroke current is taken into account and assumed as a linearly rising current. The induced voltage is then a rectangular wave shape with amplitude related to the current steepness.

Then, the maximum induced voltage occurs with a subsequent negative short stroke but the calculation of the separation distance involves also the breakdown voltage that depends on the front time of impulse and it is possible to verify that the worst case is represented by the first negative short stroke.

For a subsequent negative short stroke Class I the current steepness is 200 kA/μs and the breakdown voltage with a front time 0.25 μs is about 3000 kV/m (rod-rod air gap with a gap distance 1 m). For a first negative short stroke Class I the steepness is 100 kA/μs and in the same conditions, the breakdown voltage with a front time 1 μs is about 1200 kV/m. Then, the induced voltage with a subsequent negative short stroke is double than with a first negative short stroke but the corresponding breakdown voltage is more than double. In other words, the first negative short stroke is the critical one condition and requires about 25% more separation distance than a subsequent negative short stroke with the same Class.

In the present version of [20] this fact is not considered. It is also assumed that always a rod-rod configuration is given. In case of rod plane configuration the results are different.
The used program considers sine waves and the induced voltage would be a sine wave shape. The calculation of the breakdown voltage for a sine wave is a formidable task ([2], [5], [12]). Along with a future version of the used program that will allows the use time domain functions for the calculation of the induced voltage the voltage-time-curves for such impulses have to be numerically integrated.
Therefore the second procedure is recommended.

The second procedure involves the calculation according to [20]. The electrical insulation between the air-termination or the down-conductor and the structural metal parts, the metal installations and the internal systems can be achieved by providing a separation distance between the parts. The general equation for the calculation of "s" is based on the subsequent negative short stroke, a linearly rising current with steepness according to Tab 4.1 and an equipotential GS. The result is given by:

$$s = \frac{k_i k_c}{k_m} l \qquad (4.1)$$

where:
- s = separation distance (m)
- k_i depends on the selected Class of LPS (see Tab. 4.1)
- k_c depends on the lightning current flowing on the air-termination and the down conductor
- k_m depends on the electrical insulation material
- l = length, along the air-termination and the down-conductor from the point, where the separation distance is to be considered, to the nearest equipotential bonding point (m)

Class of the LPS	Subsequent negative short stroke 0,25/100 µs (1 MHz)			First negative short stroke 1/200 µs (250 kHz)		
	I (kA)	di/dt (kA/µs)	ki	I (kA)	di/dt (kA/µs)	ki
I	50	200	0.08	100	100	1
II	37.5	150	0.06	75	75	0.75
III-IV	25	100	0.04	50	50	0.5

Tab 4.1. Parameters for the calculation of the separation distance

The great advantage of the used program is the precise calculation of "k_c" with complex layout of the external LPS including the non equipotential GS. The partial lightning current in the considered down conductor "I_D" can be easily calculated, and "k_c" can be found using:

$$k_c = \frac{I_D}{I} \qquad (4.2)$$

where:
- I_D = partial lightning current in the down conductor (A)
- I = total injected lightning current in the LPS (A)

In a future version of the program it will be possible to use the time functions as per [19] and to determine the voltage. When the potential difference between two conductive parts is known, the required separation distance can be determined. This will allow to calculate the precise separation distance especially in large LPS with a non equipotential GS.

4.6 – Earth Surface Potential Distribution

The earth surface potential distribution inside and around the building are represented in the following figures. The GS is not equipotential and then the impedance to earth can be calculated only with reference to specific points. The maximum values of the impedance to earth are the following:

- $Z_E = 3.3\ \Omega$ at 25 kHz
- $Z_E = 17.5\ \Omega$ at 250 kHz
- $Z_E = 68\ \Omega$ at 1 MHz

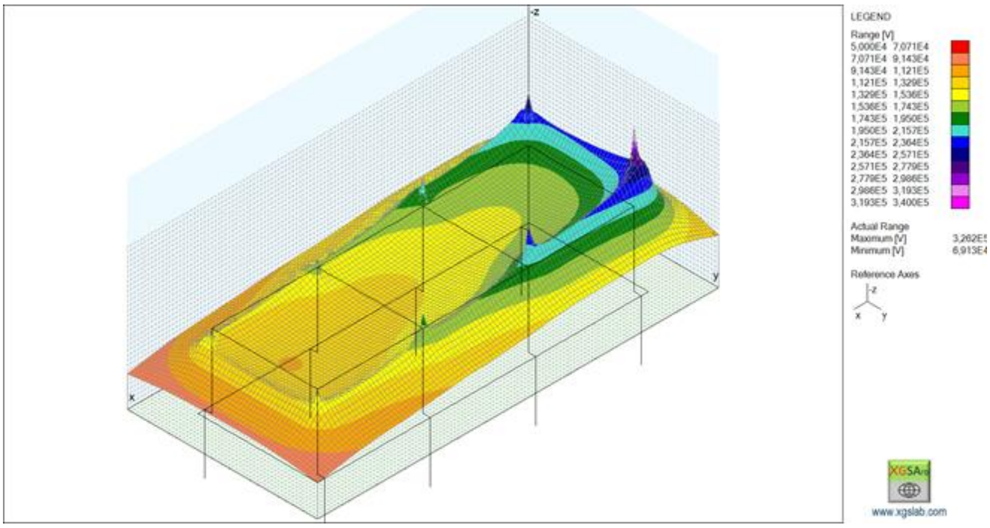

Fig. 4.7: Earth surface potential distribution - 200 kA 10/350 µs = RMS 141.4 kA 25 kHz

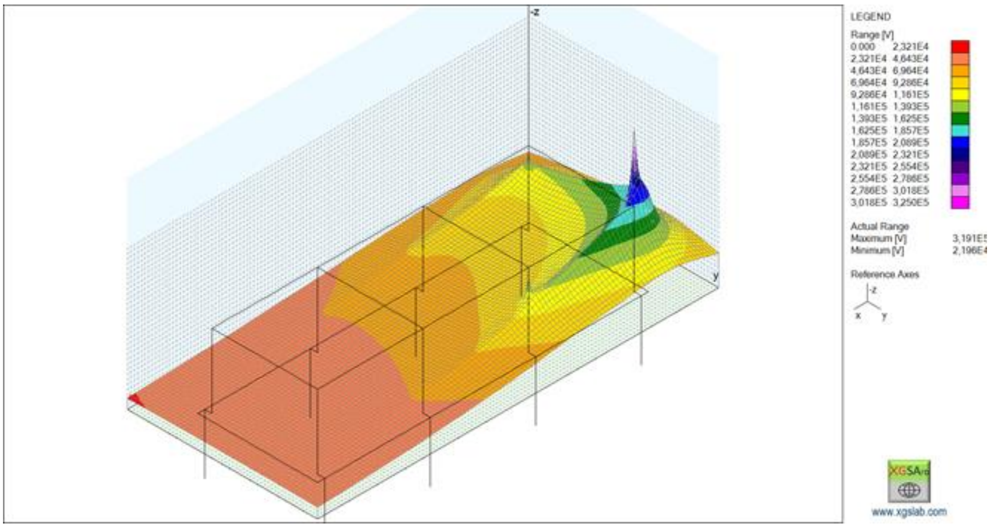

Fig. 4.8: Earth surface potential distribution - 100 kA 1/200 µs = RMS 70.7 kA 250 kHz

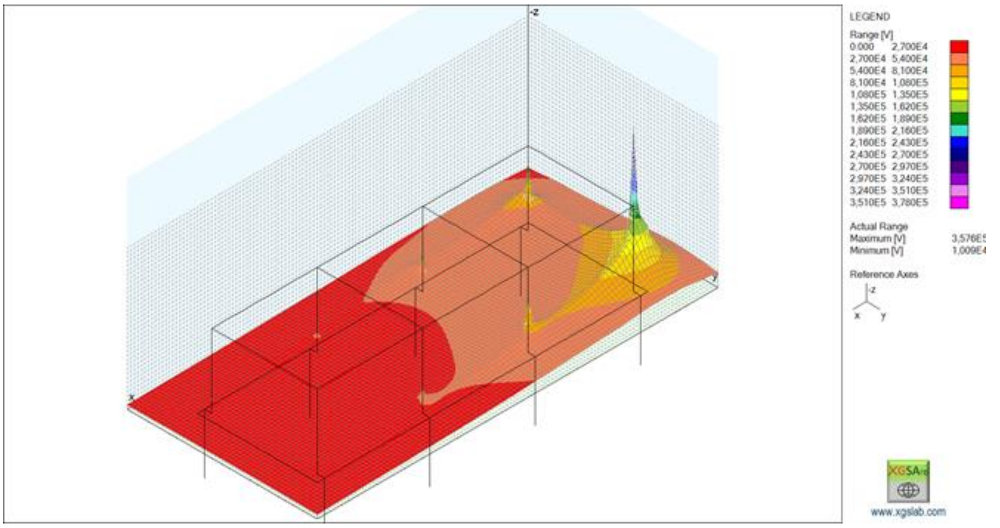

Fig. 4.9: Earth surface potential distribution - 50 kA 0.25/100 µs = RMS 35.4 kA 1 MHz

4.7 – Touch and Step Voltages Distribution

The safe and hazardous areas related to the touch and step voltages distribution above and around the GS are represented in the following figures compared to their high frequency permissible values. A review of existing literature leads to confident values of 2 and 25 kV peak for touch and step voltage respectively, both for the first positive short stroke 10/350 µs.

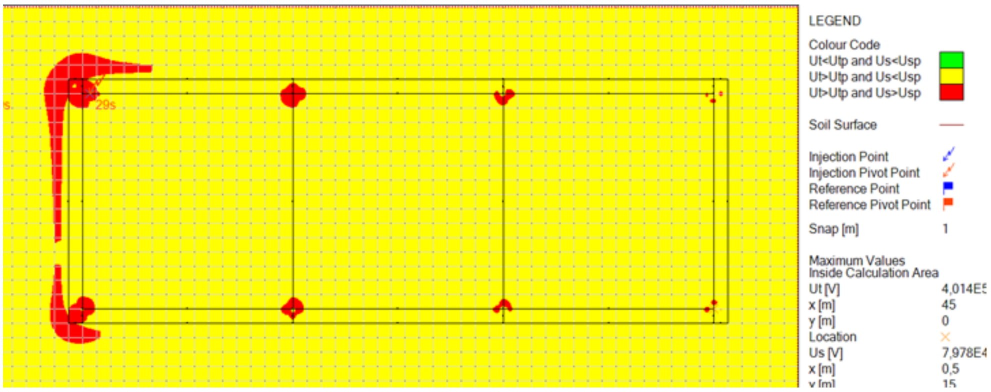

Fig. 4.10: Hazardous Areas related to Touch and Step voltages - 200 kA 10/350 µs = RMS 141.4 kA 25 kHz

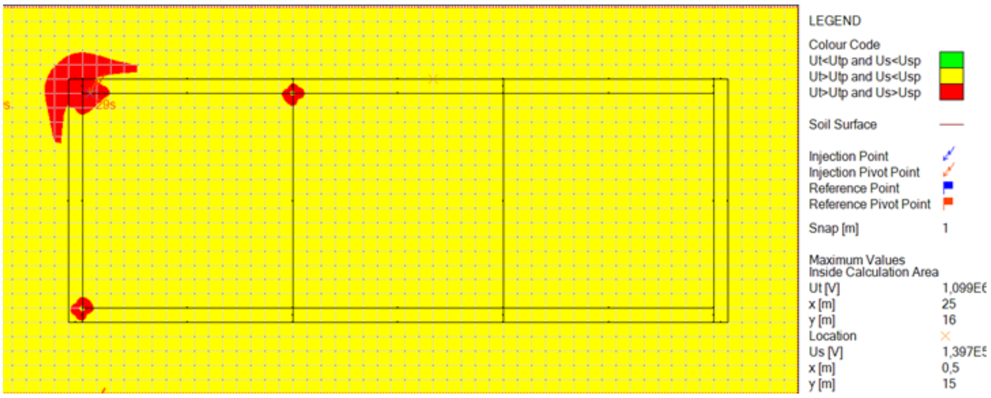

Fig. 4.11: Hazardous Areas related to Touch and Step voltages - 100 kA 1/200 µs = RMS 70.7 kA 250 kHz

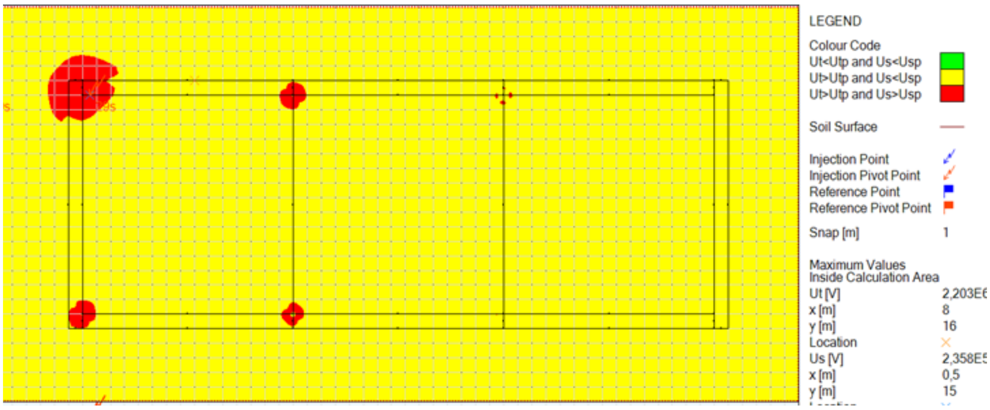

Fig. 4.12: Hazardous Areas related to Touch and Step voltages - 50 kA 0.25/100 µs = RMS 35.4 kA 1 MHz

The worst case is represented by the first positive short stroke.
Dangerous touch voltages can be usually avoided using o buried potential control loop outside the building, or a high resistivity soil covering layer, or insulated down conductors or preventing contact with the down conductors.
Dangerous step voltages can be usually avoided using improved earthing conductor configuration with potential grading or with a high resistivity soil covering layer. A danger can remains always at the edges of an earthing system.

5 – COMPARISON BETWEEN HYBRID METHOD AND NETWORK ANALISYS

In the following, it is proposed a comparison between results calculated with the transmission line theory and with the model based on hybrid method.
Using the transmission line theory, the vertical and horizontal conductors of the external LPS can be represented with their equivalent impedance while the GS can be represented using equivalent circuits for meshed grounding systems as published in [4]. The resulting network was studied in time and frequency domain using the commercial program Microcap [21]. In case of vertical rods the model can include the frequency dependent propagation speed in the earth.

The selected scenario is represented in Fig. 5.1 and includes a lightning stroke on a corner of the LPS of a building (45 x 15 x height 10 m). The GS is buried at 0.25 m depth. All conductors are solid, bare and steel made with 8 mm diameter. The same soil data of 4.1 were assumed.

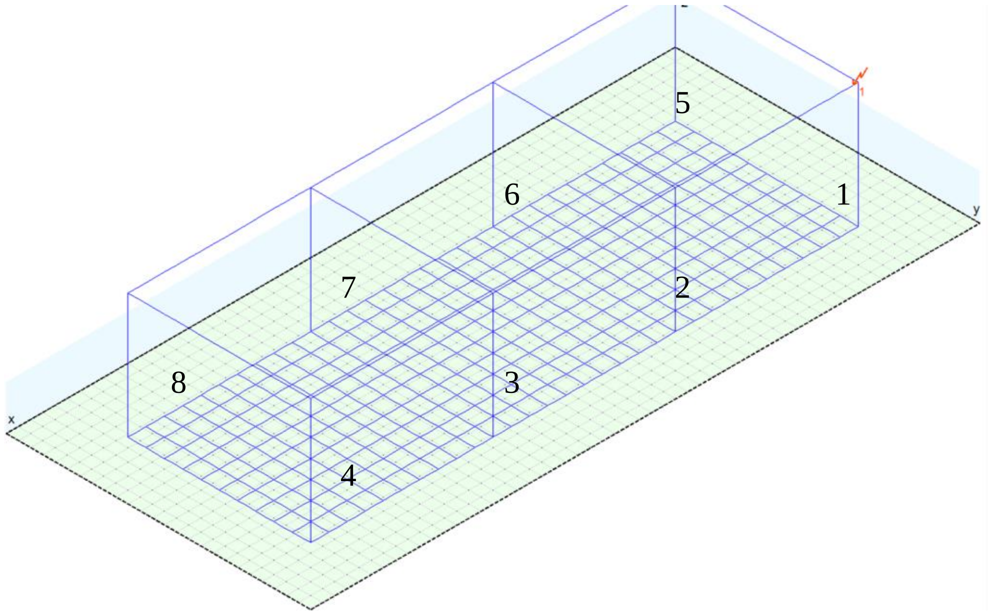

Fig. 5.1: LPS and GS layout

The three standard lightning and in all cases their equivalent sinusoidal wave forms are considered in the calculation. The following figures shown the percentage (with reference to the total injected current) of the current along the down conductors calculated in the literature [18] and with the used program based on hybrid method. The agreement between results are excellent in all cases.
At high frequency the longitudinal current calculated with the hybrid method change significantly along the down conductors. This phenomenon is evident at 1 MHz and visible also at 250 kHz. In the following figures an average current is considered.

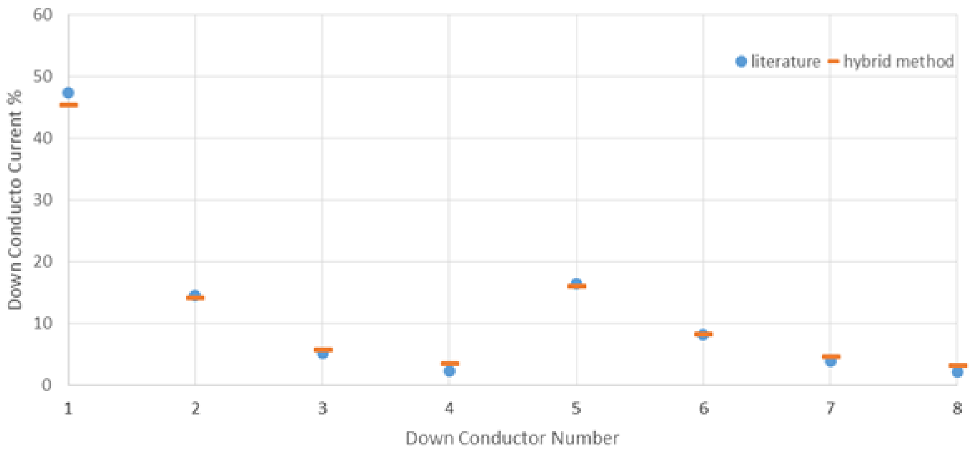

Fig. 5.2: Percentage of current along the down conductors - 25 kHz

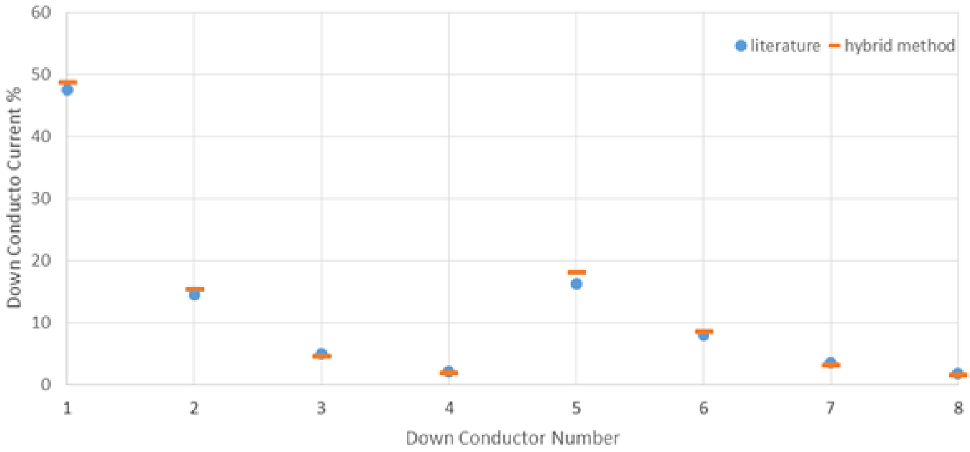

Fig. 5.3: Percentage of current along the down conductors - 250 kHz

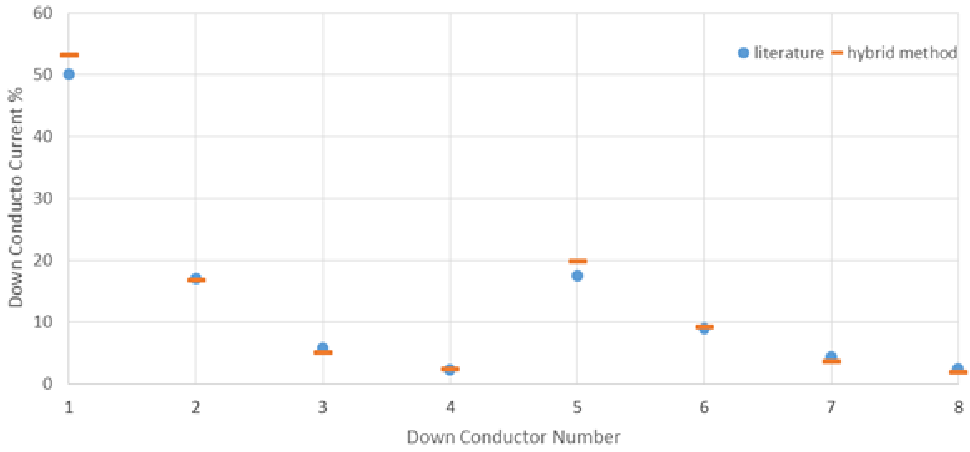

Fig. 5.4: Percentage of current along the down conductors - 1 MHz

Other comparison has been made by the authors considering a smaller building and frequency up to 10 MHz. The results highlight that the hybrid methods can be applied at least up to 5 MHz and they take into account also the effects of the travelling waves and the consequents resonance phenomena.

6 - CONCLUSION

The calculation of the lightning effects includes the evaluation of current distribution, electromagnetic fields, separation distances and touch and step voltages and represents a problem in many ways still open. The use of simplified formulas and tables is still the practice although poses serious limits. Also the reference standards in this area are based on simplified assumption (not always acceptable), and permissible values for instance for touch and step voltages are not provided.
In many cases, however, the LPS design requires more than the standard requirements compliance. More and precise information are required for instance when protection of strategical sites (large or high buildings, data or fuel or explosives storage …) or risk analysis including touch and step voltages are involved and this even when the LPS layout is complex and the GS is not equipotential.

The problem is not trivial. The calculation tool must allow a complete modelling of the LPS and its GS and must have a frequency range application covering the whole lightning spectrum (form DC to a few MHz). This implies that, the Sommerfeld integrals have to be carefully considered.
The commercial used program is based on an hybrid method and meets the main computing needs and is a valuable tool in this regard. The geometry of LPS and GS can be imported from CAD programs, data entry is quite easy and do not requires special skills, the CPU times are acceptable even in case of large buildings and the results can be displayed graphically in an effective way. The program allows to

determine all electrical parameters to design a LPS and a GS according to customer requirements or to fulfil the IEC requirements. The main results provided by the program have been validated by comparison with results available in literature.

The used program has been applied to study of the LPS of a simple building. The distributions of currents, magnetic fields, earth surface potential ant touch and step voltages have been represented and commented.

The lightning current tends to flow to the earth through the closest down conductors ant this is more evident when the frequency increases ant then with the subsequent negative short stroke. In some cases, travelling waves can make this distribution confused and not intuitive.
For the calculation of the separation distance the subsequent negative short stroke is required by [20] but the first negative short stroke represents the worst case.
The first positive short stroke is the most important impulse shape for touch and step voltages.

In any case, the right way to calculate the lightning effects seems the use of specialized programs. In order to obtain more realistic simulations, also time domain conditions and ionization phenomena should be taken into account.

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