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Simulation of a Lightning Protection System Considering the Different Protection Levels

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***Abstract*—The present paper has as main approach a performance study of a Lightning Protection System (LPS) as a function of the different conditions of the protection levels predicted on the IEC 62305, in effect today. Also based on a bibliographic research, a study of the implementation of an LPS in a real building was carried out. From the data of this installation, the modelling and simulations were performed in ATPDraw™ for the various risk classification conditions. The results of the simulations confirm that the higher the level of the protection, the lower are the currents in the down conductors systems and the lower are the voltages between the down conductors and the grounded points inside the installations.**

Key-words: Lightning flash; grounding system; equipotential bonding; protection; overvoltages.

I. Introduction

The great dimensions and tropical climate make Brazil a leader country on the world ranking of lightning flash incidence (~77,8 millions/year) [1]. This elevated incidence index results on a high number of deaths, mainly in the South and Midwest, as though as great losses to the society. Thus, the studies related to the protection of human life and reduction of the physical and material losses are becoming more important over time.

Another issue that brings out the theme is the update of the NBR 5419 "Protection against Lightning", in 2015. The current standard is based on the international standard IEC 62305-1, 62305-2, 62305-3 and 62305-4, where the main change was the division of the NBR into four distinct parts, as the IEC standards, becoming more detailed and then assuring better protection conditions [2].

Thus, this paper has as objective to present a methodology of analysis of the protection subsystems of an LPS in the protection levels I, II, III and IV predicted at the standard, proving its effectiveness. For this, a bibliographic research was carried out to find data as: ground flash density, topology of the air-termination systems, down conductors, earth-terminations and lightning equipotential bonding. An LPS were implemented in a real building, where the segments of vertical and horizontal cables, grounding grid and rods were modelled as transmission lines, allowing the use of the ATPDraw™ as main tool for the simulations, with the aim to analyze several protection conditions.

II. LPS Topologies

The LPS is formed by internal and external subsystems. The external part is composed by the air-termination subsystem, down conductors and earth-termination. These subsystems are projected to intercept the lightning strokes on the building, including the side strokes, and to conduce the lightning current from the impact point to the earth, spreading it into the ground without causing any damage or sparkling [3]. Each subsystem has its characteristics and can be projected according to the type of structure to be protected.

A. Air-termiantion subsystem

Rods and masts, suspended conductors and conductors in a grid can form the air-termination subsystems. The components should be positioned in the protruding corners, exposed tips and at the edges of the structure due to the physical property known as tip power [3; 4].

The most acceptable methods to determine de installation point of the air-termination subsystem are the protection angle method (Franklin method), electrogeometric method (rolling sphere) and the grid method (Faraday cage). The electrogeometric and grid methods are adequate for all cases, while the protection angle method is recommended for simple format buildings, being subjected to height limits for the captors. In many cases, the tree methods can be combined [3].

According to the Franklin method, one or more combined rods can be installed, with the protection of the structure made by a suspended conductor between them or not. The protection angle α of this method, as exposed on Fig. 1, is defined according to the height and the recommended protection level for the building. This angle is related to the protection region, which is the zone protected by the captor. When a stroke hit this zone, it will be attracted by the air-termination subsystem, protecting the build. The minimum heights of the rods are determined in a way to protect the whole volume of the building [3; 5].

In many applications, the Franklin method is not sufficient to project an effective protection system and thus, is combined with the grid method. Conductors are added in a grid topology into this subsystem and, in very long structures, the system is also complemented by 30~50 cm lightning rods spaced in 1~2 m. Some researches indicate that, in buildings with heights superiors than 60 m, side strokes can happen, especially in the tips, making necessary the use of the grids as a side capture subsystem, as shown on Fig. 1, with its dimensions defined in accordance to the protection level [2; 5].

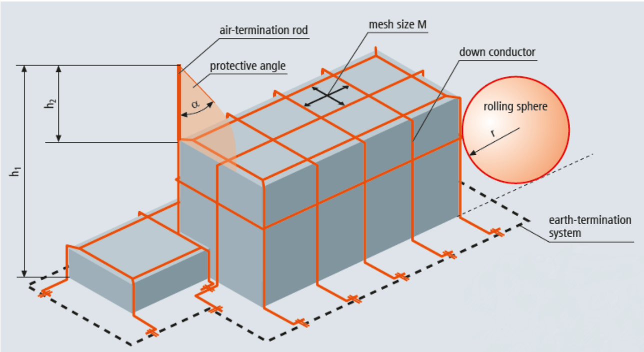

Fig. 1 – Air-termination, down conductors and earth-termination subsystems [6, adopted].

The basic protection principle proposed by Michael Faraday, known as Faraday cage or grid method, is to use capture conductors disposed in a ring topology, forming grids or cages. This kind of protection is ruled by the Lenz law, which establish that any conductor system connected in a lace reacts to the variations of magnetic fields due to the circulation of induced currents in its lace, which creates an inductive magnetic field [5].

Formed by several conductors' grids, with its dimensions expressed in NBR 5419-3, the Faraday cage works preventing the entrance of the lightning current inside the building. Faraday showed that when the currents are uniformly distributed, the magnetic field inside the cage is null and when they are not uniform, the magnetic field inside the edification is very small. When the lightning flash hit the building, it does not dissipate itself uniformly and then generates internal inductions due to the variation of magnetic field inside the cage. The protection provided by this method is efficient because the small grids create opposite magnetic fields, conducting the lightning current to the corner of the grid and obligating it to flow to the earth by the down conductors [3;5]. The mechanism of this phenomenon is explained in Fig. 2.

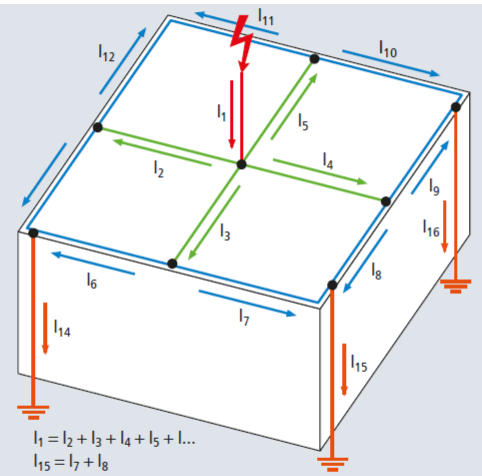

Fig. 2 - Current in the air-terminations and down conductors [6].

The electromagnetic method, also known as rolling sphere, is the most used nowadays to determine the protection zone of the LPSs. As in the Franklin method, the striking distance of the lightning flash is defined by the protection level required. The rolling sphere, with a radius equal or superior to the striking distance, as defined by NBR 5419-3, goes through the whole outside part of the building in a way to estipulate the zone where the capitation rods should be installed. It is defined that no point of the structure can get in touch with the fictitious sphere that rolls through the top and the side parts in all directions, the sphere only can touch the air-termination subsystem [3;5]. Figs. 3 and 4 show an edification being submitted to a rolling sphere in all directions.

B. Down conductors subsystems

The main objective of the down conductors is to reduce the probabilities of damage on the building due to the lightning current. The down conductors should be arranged in a way to provide several parallel paths to the electrical current and also with the shorter length as possible, turning equipotential all the conductive parts of the building, as shown on Fig. 2 [3].

The down conductors should be interconnected to the earth-termination subsystem and installed, preferably, in each outgoing chant of the building, beyond the other conductors imposed by the security distances defined through the protection level expressed at NBR 5419-3 [3].

C. Earth-termination subsystem

The function of the earth-termination subsystem is to drain the lightning currents to the ground, causing the least possible disturbance. Interconnected electrodes buried vertically and/or horizontally, compose the system. The vertical electrodes are the metallic ground rods, or also called natural electrodes, and the undergrounded structures of the building with guaranteed electrical continuity. The grounding grid forms the horizontal electrodes, which is a ring of underground conductor material that interconnects the whole system [3;7].

Preferably, the grounding infrastructure should be integrated, incorporating the LPS, the electricity and signal systems (telecommunications, cable TV, data, et. al) [3].

III. Calculation of the Transmission Lines Parameters

The subsystems described in the previous sections are represented by straight cable segments, modelled in this work as transmission lines. The transmission lines are represented by the parameters R (conductor resistance), L (internal and external inductance of the conductor), C (external capacitance) and G (conductance) that represents the dielectric losses [8].

An LPS is formed by the interconnection of the cables horizontally, vertically or still orthogonally disposed (generic disposition). Considering this straight cables as transmission lines, it is possible to calculate the parameters of each vertical or horizontal element.

The capacitance of a horizontal cable C_h is defined by Eq. (1), that considers a line with infinite length modelled as a cylinder of radius a, in a height h from the ground and over a perfectly conductive surface. The constant ε [F/m] represents the dielectric permittivity of the surroundings [9].

$$C_h = \frac{2\pi\varepsilon z}{\ln\left(\frac{2h}{a}\right)} \quad [F] \tag{1}$$

The magnetic flux along a line with the same geometry than that used on the capacitance calculus is invariable, as it is considered an infinite length. Thus, to determine the inductance on a horizontal cable L_h of a line, it is used the Eq. (2) [9].

$$L_h = \frac{\mu z}{2\pi} ln\left(\frac{2h}{a}\right) \quad [H] \tag{2}$$

To calculate the capacitances and inductances of vertical cables C_v and L_v, it is considered a cable with a cylindrical form, with length *z*, diameter *d* in *s* meters height from the ground. Thus, [9] proposes the Eqs. (3) and (4) for the capacitance and inductance of vertical cables, respectively.

$$C_v = \frac{2\pi\varepsilon z}{\ln\left(\frac{2z}{d}\sqrt{\frac{4s+z}{4s+3z}}\right)} \quad [F] \tag{3}$$

$$L_v = \frac{\mu z}{2\pi}\ln\left(\frac{2z}{d}\sqrt{\frac{4s+z}{4s+3z}}\right) \quad [H] \tag{4}$$

The resistance *R* of the vertical and horizontal straight cables segments can be ignored in some situations, as its magnitude is regularly from the order of mΩ. For a cable with circular cross-section, radius *a* and homogenous conductivity σ [S/m], the resistance is given by Eq. (5) [10].

$$R = \frac{z}{\sigma 2\pi a\delta} \quad [\Omega] \tag{5}$$

Where:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad [\Omega/m] \tag{6}$$

The resistance R_{rod} of a grounding rod with length *z* and diameter *d* is given by Eq. (7), while the capacitance C_{rod} that appears in parallel with R_{rod} is represented by Eq. (8), where $\varepsilon_s = 10\varepsilon_0$ is the soil dielectric permittivity and ρ_s is the soil resistivity. The rod inductance L_{rod} is represented by Eq. (9), where μ [H/m] is the soil magnetic permeability constant [11].

$$R_{rod} = \frac{\rho_s}{2\pi z}\left(ln\frac{8z}{d} - 1\right) \quad [\Omega] \tag{7}$$

$$C_{rod} = \frac{2\pi\varepsilon_s z}{\left(ln\frac{8z}{d} - 1\right)} \quad [F] \tag{8}$$

$$L_{rod} = \frac{\mu z}{2\pi}\left(ln\frac{8z}{d} - 1\right) \quad [H] \tag{9}$$

The grounding grid of the LPS is formed by rods and cables disposed in a horizontal way. Each cable is undergrounded in a depth *h*, with diameter *d* and length *z*, where ρ_e is the electrode resistivity and S_e is its the cross-section. In this way, the resistance, capacitance, inductance and conductance are given by the Eqs. (10), (11), (12) and (13), respectively [11].

$$R_{grid} = \frac{\rho_e}{S_e} z \quad [\Omega] \tag{10}$$

$$C_{grid} = \frac{\pi\varepsilon_s z}{\left(ln\frac{2z}{\sqrt{dh}} - 1\right)} \quad [F] \tag{11}$$

$$L_{grid} = \frac{\mu z}{2\pi}\left(ln\frac{2z}{\sqrt{dh}} - 1\right) \quad [H] \tag{12}$$

$$G_{grid} = \frac{\pi z}{\rho_s\left(ln\frac{2z}{\sqrt{dh}} - 1\right)} \quad [S] \tag{13}$$

IV. SIMULATED BUILDING

The simulations where carried out considering the LPS of a residential and commercial building, about 60 m height and with 232 m of perimeter, distributed in 17 floors, where 13 of them are apartments, 2 are for the stores and the other 2 are garages.

From the risk management calculations, found at NBR 5419-2, it was agreed that, for the complete protection of the building, the parameters of the risk class III are sufficient on preventing eventual damages and losses caused by lightning flashes. Figs. 3, 4 and 5 represent the front, side and superior views. On the superior view, it is shown the projected grounding grid of the building LPS in accordance with the classification of risk III.

It exists four risk classes with divergent project parameters where, beyond the values of the protection angles and radius of the rolling sphere, the typical distances between the down conductors and the ring conductors are specified. For the classes I and II, it is used the distance of 10 m, for the class III, 15 m, and class IV, 20 m. The standard considers the maximum tolerance of 20% of the established values [3].

For the simulations, detailed on the subsequent section, it was considered the patterns of the four risk classifications, with the objective of assess the performances of each one of the four topologies.

I. MODELLING

As the modelled LPS is composed by many straight conductors segments, with divergent characteristics and equation, the Microsoft – Excel® was used as a tool to obtain the capacitances, inductances, resistances and conductance, due to its practicality and flexibility on building mathematical functions. By the transitory nature of the problem-situation, it was used the software ATPDraw™, as it allows the simulation of time intervals smaller than one microsecond (μs).

As already seen, the simulated LPS is composed by horizontal and vertical conductor segments, that can be better visualized in the project perspective of the protection level III in Fig. 6. The dotted lines represent the horizontal and vertical segments and the continuous lines, the grounding grid. The grounding rods are represented by the grounding symbol.

For the straight horizontal and vertical segments, it was considered the π model of transmission lines, and for the cable's segments of the grids and grounding rods, it was used the equivalent circuits presented in Fig. 7 [11]. All the parameters were defined according to the formulations expressed in Section III-B. In the software ATPDraw™, the module of the conductance G is represented by its inverse value, in this case, a resistance R that is the grounding resistance for low frequencies.

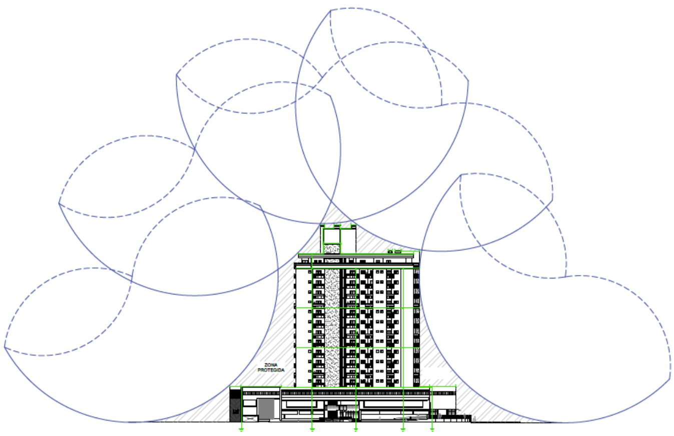

Fig. 3 - Front view of the class III LPS project.

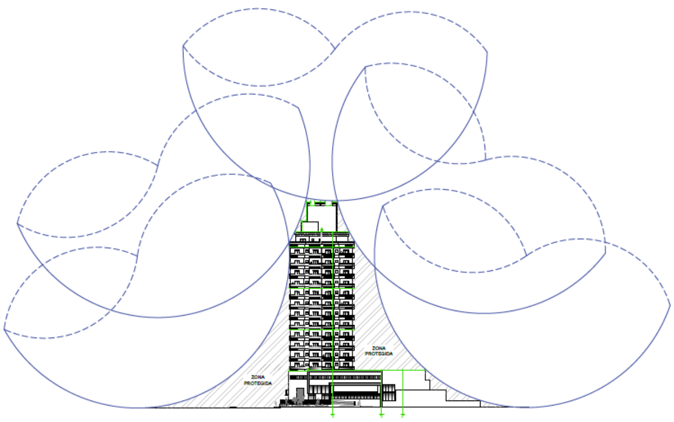

Fig. 4 - Side view of class III LPS project.

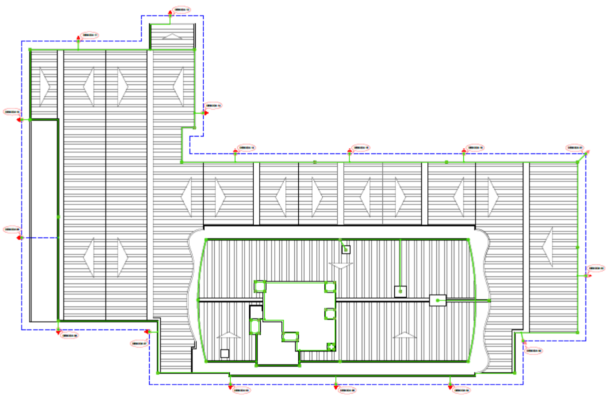

Fig. 5 - Superior view of the class III LPS project.

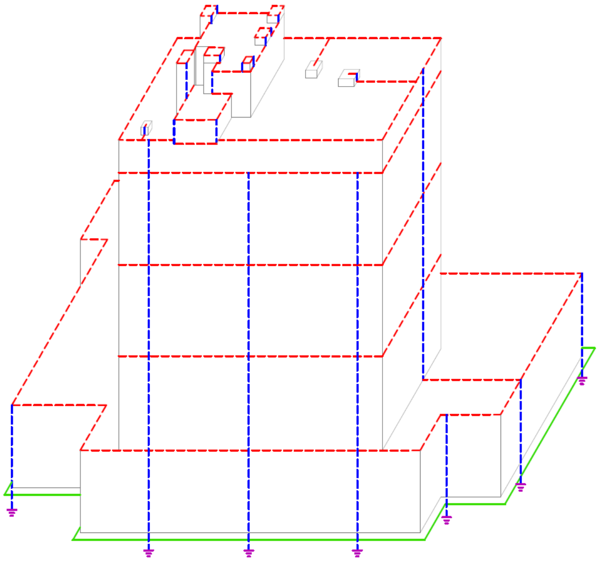

Fig. 6 - Simulated class III LPS in perspective.

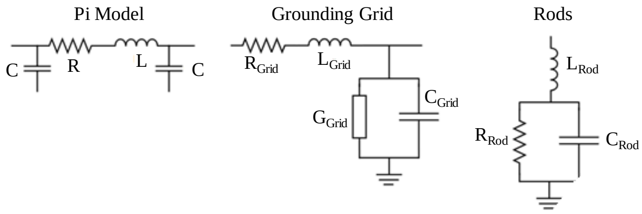

Fig. 7 - Model of the straight cables' segments [11, adapted].

For the grounding of the building energy entrance, composed by five rods installed each 3 m, it was used the same model exposed on Fig. 6.

In this work, it was considered that the cables are in a perfectly conductor soil and immersed in air, whose dielectric permittivity is $\varepsilon_0 = 8.854.10^{-12}$ F/m and the magnetic permeability is $\mu_0 = 4\pi.10^{-7}$ H/m. The soil and grounding electrodes resistivities were considered as 500 Ω.m and $1.773.10^{-8}$ Ω.m, respectively, being the resistivity of the electrode the inverse of the cooper conductivity. As the horizontal and vertical resistances vary with the frequency, it was simulated, with basis on the established parameters in NBR 5419-4, a lightning flash with 25 kHz of frequency. The cables of the capture and down conductor subsystems have 35 mm² of cross-section, while the grounding conductors have 50 mm² [12].

It was also represented, in a simplified way, the transformer of the energy entrance, the equipotential bonding bar, loads and the cables of the phases R, S, T, the neutral and ground. The cables and loads were divided in stretches between the equipotential bonding conductor rings of the LPS, which are represented by RL circuits in the simulations. The electrical quantities of the cables were obtained through the equations exposed in the Section III for vertical cables, while the loads, in parallel with the cables stretches, are the real loads of the building. For the cables, it was considered the cross-sections of 3x120 mm² for the phases and the neutral and of 50 mm² for the ground cables, as the specifications found on the energy entrance project of the building.

II. Simulations

After the elaboration of the projects and the calculation of the electrical quantities of the cables segments for the four protection classifications, it were developed tree circuits in ATPDraw™ that represent the LPS as a group of transmission lines. Fig. 8 exposes one of the simulated circuits.

In the left side is exposed the LPS circuit of the building with the lines and components in red representing the horizontal cables, in blue the vertical cables, in green the grounding cables and in purple, the grounding rods. The circuit in the right side represents the electrical installations of the building.

III. Analysis and Discussion of the Results

The obtained and analyzed results in the following sections refer to the several models and conditions simulated, where the main results of the calculations are the currents in the down conductors and in the laces of the equipotential bonding rings. It is also presented the induced voltages between points of the equipotential bonding rings and the grounding conductors installed inside the building.

A. Currents in the down conductors

Through the simulations, it was determined the currents in each descent of the LPS determined according to the risk classes. Table I shows the average value of these currents, since they vary according to their positioning in relation to the system point hit by the lightning flash.

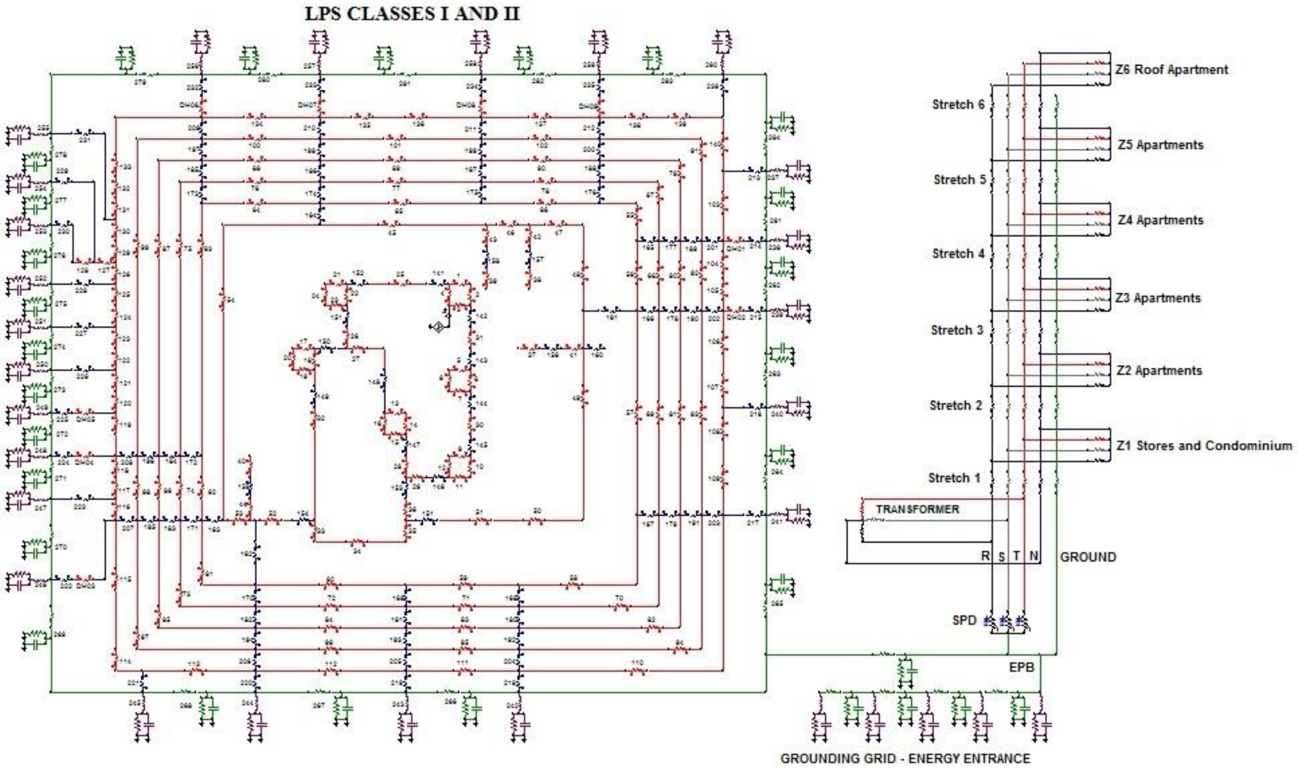

Fig. 8 - Simulated circuit for the protection classes I and II.

It can be seen that the circuits of the protection classes I and II have 24 down conductors and six equipotential bonding rings. The protection class III and IV have, respectively, 16 and 12 down conductors and five and four rings.

To reproduce the lightning current waveform, the Heidler function is used in the simulations. This analytical function allows the adjust of its parameters in an independent way, that is, modifying the wave front will not affect significantly the wave tail and vice versa [4; 13]. In the simulations, it was used the Heidler source of ATPDraw™ with a current peak of 100 kA, 3.64 µs of front time and 0.269 ms as 37% time (0.37Ip). The point of incidence of the lightning flash is in about 60 m height, being one of the highest points of the capture subsystem.

The sum of the currents is superior than the peak of the lightning current (I = 100 kA), being 26% to 30% higher. It is supposed that this result can be explained due to the kind of measurement used, as it measured only the maximum current peaks in each point.

TABLE I. Average Current in the down Conductos [kA]

Protetction Levels	Current (Average kA)	Difference (%)
I and II	5.28	100
III	8.08	152.87
IV	10.89	206.10

During the simulations, it was verified that the current values vary in accordance with the point hit by the lightning and the cables of the down conductor subsystem. Given these divergences, it was also noticed the dissimilarity between the waveforms found at each simulated point.

Fig. 9 shows the waveform for one of the protection levels at the closest and at the most distant point of the lightning incidence point.

The distances between the down conductors are determined in accordance with the risk classification and in the three situations, the shortest cable distance between the impact point of the lightning flash and the ground system is in average 78 m, the furthest being 120 m.

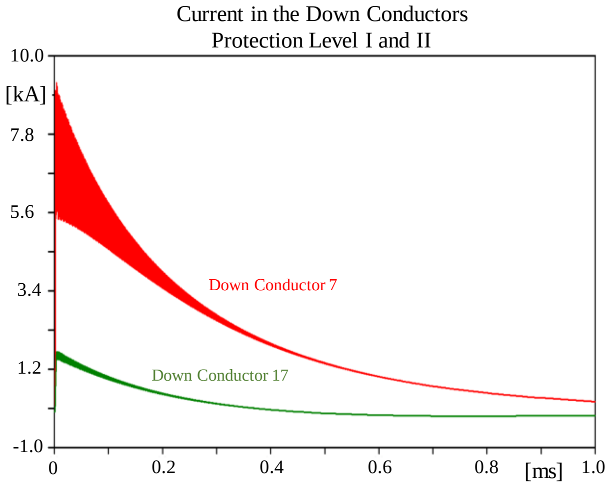

Fig. 9 - Down conductors 7 and 17 for the protection levels I and II. In red: closest point of the impact of the lightning flash; In green: most distant point of the impact of the lightning flash.

It is observed through the graphics of Fig. 9 the difference between the waveforms found in the down conductors and the applied lightning current waveform. This difference happens due to the reflections, where all the points of the wave front behave as punctual sources for secondary waves. This event can be observed on Fig. 10, where it is shown a smaller time period for the down conductors of the protection level IV.

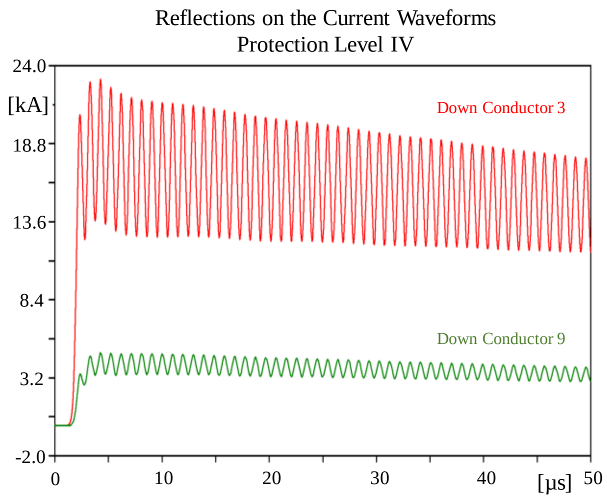

Fig. 10 - Reflections on the current waveforms.

B. *Currents in the laces*

The LPS is subdivided in down conductors and equipotential bonding ring. The junction of these elements form laces, as it can be observed in the example of Fig. 11, composed by 3 laces between the equipotential bonding rings.

It was only verified the currents of a lace in each equipotential bonding ring, whose average value are shown on Table II. The current that passes in the laces produce magnetic fields and, therefore, can generate significant induced voltages in the internal installations of the building. It can be seen that, as higher the protection level adopted (I and II), smaller are the currents in the laces.

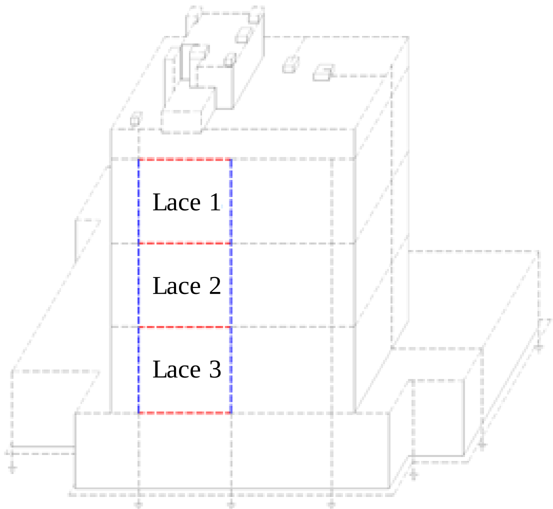

Fig. 11 - Down conductors 7 and 17 for the protection levels I and II.

TABLE II. AVERAGE CURRENTS IN THE LACES

Average Currents (kA)			
Lace	**Levels I and II**	**Level III**	**Level IV**
1	5.80	8.18	12.60
2	6.01	7.60	15.50
3	6.35	6.59	-
4	6.26	-	-

C. *Overvoltages between the equipotential bonding rings and the ground wire*

Besides the external subsystems and internal equipotential bonding aforementioned, the LPS has an internal subsystem called as electrical insulation from the external LPS. This system corresponds to the isolation between the external subsystem and the metallic structural parts, metallic installations and internal systems. This isolation can be obtained by adopting a distance *d* between the grounded parts of the installation and the external LPS points, superior to a security distance *s*. This security distance is calculated by an equation presented at NBR 5419-3. The equation considers coefficients that depend on the protection level, current of the lightning flash in the down conductors, insulation material and the length between the installation points and the closest equipotential bonding [3; 6]. Fig. 12 represents the security distance mentioned.

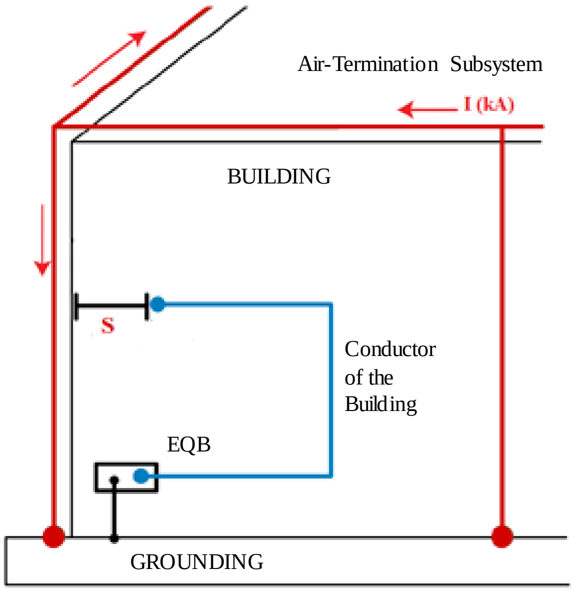

Fig. 12 - Security distance of the internal LPS [6, adapted].

Through the simulations, the voltages between the grounded points of the internal installations and the points of the down conductors of the LPS were obtained. The measurements were made between the equipotential bonding rings and the grounding cables in the interior of the building, simulating the loads and cables in the stretches in between the rings, as presented on Fig. 8 of the circuits.

Table III indicates the voltages values in each protection level in accordance with the equipotential bonding ring and its height. It can be seen that the overvoltages increase with the protection level and the distance to the grounding system. The graphic of Fig. 13 proves this effect and indicates that, as smaller the protection level, more steep and linear is the voltage curves.

The NBR 5419-3 presents simplified methods for the calculation of the security distances *s* through the protection coefficients (amount of down conductors), type of the insulation material and lightning current. For the case of the simulated building, the security distance were smaller than 1 m.

IV. Conclusions

Through the developed studies in this paper, it was verified the complexity on developing models and simulations of LPS systems, as the simulated building is high and is full of details on its shape. The modelled circuit is composed by more than 200 straight cable segments. The simulations in ATPDraw™ presented similar results as those found in the literature [8].

The current values obtained in the different down conductors, in the tree protection levels, have significate differences. The average current values for the levels III and IV were superior to 52.87% and 106.1%, respectively, when compared to the values obtained for the levels I and II. These divergences happen as a function of the total amount of down conductors and equipotential bonding rings, that is, they are more numerous on the levels I and II, confirm the established at NBR 5419.

TABLE III. Voltages between the Equipotential Bonding Rings and Grounded Cables

Equipotencial Bonding Rings	Levels I and II	
	Height (m)	Voltage Grounded Wire (V)
1	10.94	356
2	19.65	693
3	28.75	961
4	37.9	1136
5	47.47	1194
6	51.83	1877
Equipotencial Bonding Rings	**Level III**	
	Height (m)	**Voltage Grounded Wire (V)**
1	10.94	554
2	23.09	1074
3	35.31	1566
4	47.62	1804
5	51.83	2417
6	-	-
Equipotencial Bonding Rings	**Level IV**	
	Height (m)	**Voltage Grounded Wire (V)**
1	10.94	890
2	29.47	2132
3	47.47	3219
4	51.83	3577
5	-	-
6	-	-

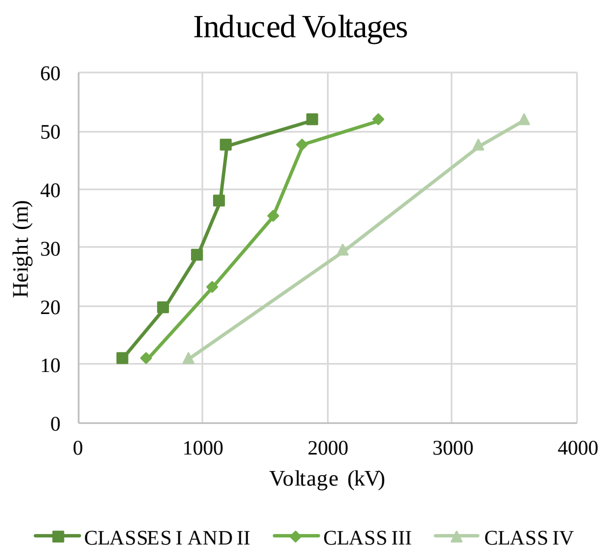

Fig. 13 - Induced voltages vs height of the equipotential bonding ring.

It was also estimated the currents that circulate on the laces composed by the down conductors and equipotential bonding rings. As the currents flow through the down conductors, it was verified the differences between the risks classifications. The levels I and II are the ones that presented the smaller current average values. The currents obtained for the protection level III are between 5 and 40% higher than on the level I and II, and in the case of the level IV, the addition is about 117 and 147%.

In relation to the overvoltages between the equipotential bonding rings and the grounded cables inside the building, it was also verified significant differences between the voltage values. As higher the protection level, smaller are the calculated overvoltages, as shown on the graphic of Fig. 13.

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