Transient Voltages on Lightning Protection System with Stratified Soils and Failure Conditions

José L. A. D'Annibale * **Walter L. M. de Azevedo** *
Anderson R. J. de Araújo * **José Pissolato Filho** *

* *School of Electrical and Computer Engineering, University of Campinas, Campinas, São Paulo, Brazil*
(e-mails: annibale_jose@yahoo.com.br, w157573@dac.unicamp.br, ajusto@dsce.fee.unicamp.br, pisso@dsce.fee.unicamp.br)

Abstract: Lightning Protection System (LPS) must provide a low-impedance path through its grounding system to lightning currents hitting the top of buildings. This grounding system is composed by combination of vertical and horizontal electrodes and a precise computation of the its grounding impedance must consider stratified layers of ground. Additionally, due to corrosion and electromagnetic forces, the electrode may present failures given by disconnections on welded parts. These factors affect the transient voltages along the grounding grid. In this paper, transient currents and voltages are investigated for a real LPS, subjected to a lightning strike, whose grounding system is buried in a homogeneous and stratified soil. In each soil model option, the system is analysed under a normal and failure condition. In this study, a lumped approach for the vertical and horizontal electrodes are obtained by the Vector Fitting technique and by the electromagnetic radiation theory, respectively. Results show that transient currents and voltages are affected by a failure condition in the grounding electrodes, being these variation more pronounced in high resistive homogeneous soil which may have an impact on the safety of people surrounding the LPS area.

Resumo: O Sistema de Proteção contra Descargas Atmosféricas (SPDA) deve fornecer um caminho de baixa impedância através de seu sistema de aterramento para as correntes de raios que atingirem o topo dos edifícios. Este sistema de aterramento é composto pela combinação de eletrodos verticais e horizontais e um cálculo preciso da impedância de aterramento deve considerar o solo formado por camadas estratificadas. Além disso, devido à corrosão e forças eletromagnéticas, o eletrodo pode apresentar falhas causadas por desconexões em peças soldadas. Esses fatores afetam as tensões transitórias ao longo da malha de aterramento. Neste trabalho, correntes e tensões transitórias são investigadas para um SPDA real, sujeito a um raio, cujo sistema de aterramento é enterrado em um solo homogêneo e estratificado. Em cada modelo de solo, o sistema é analisado em condições normais e de falha. Neste estudo, uma abordagem por parâmetros concentrados para os eletrodos verticais e horizontais é obtida pela técnica Vector Fitting e pela teoria da radiação eletromagnética, respectivamente. Os resultados mostram que correntes e tensões transitórias são afetadas pela condição de falha no aterramento, sendo essas variações mais pronunciadas em solos homogêneos de alta resistência, que podem comprometer a segurança das pessoas ao redor do SPDA.

Keywords: electromagnetic transients; lightning; grounding electrodes; stratified soils.

Palavras-chaves: transitórios eletromagnéticos; descargas atmosféricas; malha de aterramento; solos estratificados.

1. INTRODUCTION

Lightning Protection System (LPS) is essential to provide safety during thunderstorms where lightning strikes may hit the top of buildings and facilities. The LPS is composed by three main parts: lightning rods connected to a upper grid, a down-conductor system installed vertically to earth, and a termination system (grounding system) composed of interconnected vertical and horizontal electrodes. When lightning strikes on the LPS, lightning currents are carried via down-conductor system into the grounding electrodes where they should properly dissipated these impulsive surges into soil. As a consequence, electric potential rises in the injection point where dangerous voltages are generated in the vicinity of these electrodes which may affect people's safety due to step and touch voltages and damage equipment connected to the grounding systems.

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In this context, grounding system modeling plays a fundamental role to accurately compute the electric potential rise occurred on electrodes in a given soil. Many approaches have been proposed to represent electrodes and to compute its grounding impedance based on:(i) lumped or distributed parameters or (ii) Maxwell's equations using full-wave electromagnetic solvers applying numerical methods, such as: Method of Moments (MoM), Finite Element Method (FEM), Finite-Difference Time-Domain (FDTD) Salarieh et al. (2020).

Many aspects must to be considered in the grounding modelling, such as: inhomogeneity of the soils (stratified layers of ground), frequency-dependence on soil parameters and ionisation effect Yang et al. (2013). Additionally, ruptures on the conductors of the LPS may occur by corrosion Ghavamian et al. (2015) caused by environmental conditions, such as temperature, moisture and salinity of the ground. Mechanical efforts due to high currents flowing through conductors may also impact on the LPS integrity.

In this paper, the transient currents and voltages are investigated for a real LPS subjected to lightning strike whose grounding system is buried in a homogeneous and a stratified soil, considering a whole and failure condition in the grounding electrodes. Traditional transmission line models represent the upper grid and down-conductors of the LPS. The lumped approach is used to model the grounding electrodes buried in the soil under the whole and failure condition of the conductors. The lumped circuit of vertical and horizontal electrodes are obtained by the Vector Fitting technique and by the electromagnetic radiation theory, respectively. As an advantage of the lumped approach, vertical electrodes buried in stratified soil and ruptures in grounding electrodes can be easily represented. Results show that transient voltages decrease when a stratified soil is taken into account, due to its lower equivalent resistivity. When a failure occurs in the grounding electrodes, the transient voltages increase significantly which may affect the safety of people and damage equipment nearby the LPS structure.

2. MODELING OF THE LPS

A generic LPS for a building is shown in Fig.1. The modelling of each part of the LPS is presented as follows:

2.1 Upper grid modelling

The upper grid of the LPS, also called air termination, is composed by metallic rods placed on the structure in order to provide protection from a lightning strike. If a lightning hits the structure, it will tend to hit these metallic rods and must be conducted directly to grounding system (earth termination) through the down-conductors. These upper grid conductors are made of either copper or aluminium; the wires are arranged horizontally and vertically under a given separation between them, covering the top of the building and then connected to the down-conductor system.

Considering that the horizontal wires in the upper grid can be modelled as aerial single-phase transmission lines, several approach can be employed such as: (i) 2-port representation (admittance or impedance matrices) based on the Telegrapher's equations in frequency domain Gomez (2016) or (ii) classical transmission line models such as J.Marti or Bergeron available in EMTP-software. An accurate assessment of the series impedance of the horizontal wire requires that the frequency dependence, due to the Skin effect, on the parameters of the conductor must be considered. Furthermore, the impedance of the horizontal cable is also affected by return ground currents through a soil of finite resistivity.

2.2 Down conductors modelling

Several approaches have been proposed to model the vertical which can be used as down conductors in LPS, transmission towers or grounding electrodes in power systems Gomez (2015). These vertical conductors can be characterized by a *surge impedance* where several formulae have been proposed since 1930s. The first formula to compute the surge impedance was proposed by Jordan (Eq(1)) in 1934. Employing the electromagnetic field theory, several authors have found simplified equations to compute the surge impedance of a vertical cylinder, seen as a simple representation of a transmission tower. Based on the assumptions that the ground is a perfect conductor plane, the vertical conductor is kept perpendicular to the ground plane and the conductor is lossless, many formulae may also be used A. R. J. Araujo (2017). The most known formulae are: Wagner and Hilleman (Eq.(2)), Sargent and Darveniza ((Eq.(3)), Hara et al. (Eq.(4)) and the one proposed by Cigre (Eq.(5)) and they are shown as follows:

$$Z_j = 60\left[ln\left(\frac{h}{r}\right) - 1\right]; \quad (1)$$

$$Z_{Hi} = 60\left[ln\left(2\sqrt{2}\frac{h}{r}\right)\right]; \quad (2)$$

$$Z_{Sa} = 60\left[ln\left(2\sqrt{2}\frac{h}{r}\right) - 1\right]; \quad (3)$$

$$Z_{Ha} = 60\left[ln\left(2\sqrt{2}\frac{h}{r}\right) - 2\right]; \quad (4)$$

$$Z_{Cigre} = 60ln\left[\cot\left(0.5\tan^{-1}\left(\frac{r}{h}\right)\right)\right] \quad (5)$$

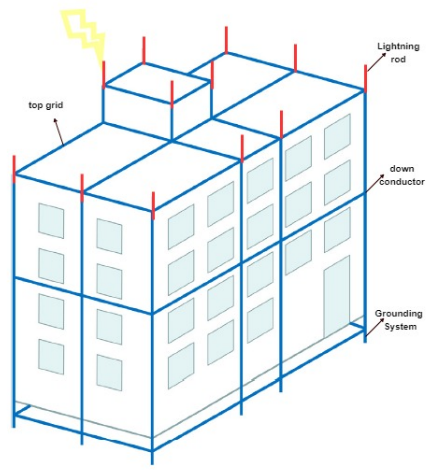

Fig. 1. Generic LPS, adapted of (Gomez,2016).

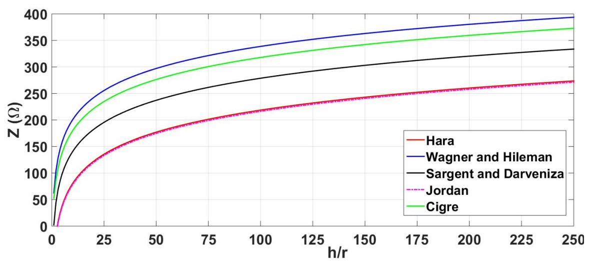

Fig. 2. Surge impedance of a vertical cylinder computed by several formulae.

where h and r are the height and radius of the vertical conductor. The surge impedance of a vertical conductor, calculated by the formulae proposed, as a function of the ratio h/r is depicted in Fig. 2.

It can be seen that the all curves present the same behaviour, although the amplitude is different for each formula. Gomez (2015) has calculated the surge impedance using the Finite Element Method (FEM) and compared to various curves; in this analysis the Hara's formula presented the lowest error rate. Thus the Hara's approach will be adopted in this paper to model the down conductors as a short transmission line in ATP-software, as further detailed.

2.3 Grounding system modeling-Vertical electrodes

A vertical rod of length L and radius r buried in a two-layer soil can be characterized by its electrical parameters given by resistivity ρ_i, relative permittivity ε_{ri} and relative permeability μ_i in each layer of soil, respectively, as depicted in Fig. 3a. The vertical electrode can be replaced by the same conductor of length L buried in a ground of equivalent soil resistivity ρ_{eq}, relative permittivity ε_r and relative permeability μ_r as illustrated in Fig.3b.

The adopted equivalent ε_r is the same in each soil layer and relative permeability $\mu_r \approx \mu_0$. The equivalent resistivity can be calculated by adapting the Blattner's formula, given by Caetano et al. (2018):

$$\frac{\rho_{eq}}{\rho_1} = \frac{L}{h + \frac{\rho_1}{\rho_2}(L-h)}(1+B); \tag{6a}$$

$$B = [ln(4L/r) - 1]^{-1} \sum_{n=1}^{\infty} k^n ln\left[\frac{2nh+L}{(2n-2)h+L}\right]; \tag{6b}$$

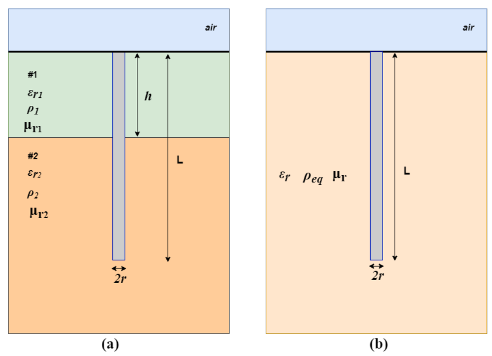

Fig. 3. Vertical rod buried in: [(a) a two-layer soil and (b) homogeneous soil of equivalent resistivity ρ_{eq}].

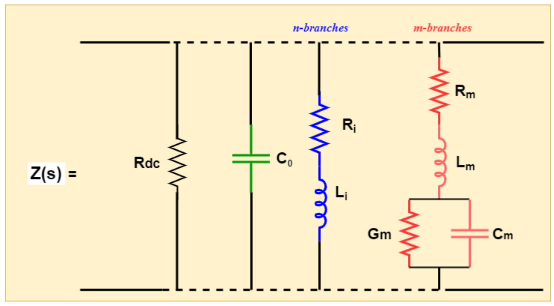

Fig. 4. Equivalent circuit for the vertical electrode fitted by VF.

$$k = \frac{1-\rho_1/\rho_2}{1+\rho_1/\rho_2} \tag{6c}$$

Once the grounding impedances $Z(s)$ are computed, the rational function approximation technique called Vector Fitting (VF) is used to fit the frequency-dependent curve into an equivalent electric circuit. The grounding admittance $Y(s)$ $(Y(s) = Z^{-1}(s))$ (computed by a numerical Method of Moments (MoM) as explained in item 3.1) can be written as a sum of the exponential functions as given by Gustavsen e Semlyen (1999):

$$Y_{eq}(s) \simeq \sum_{j=1}^{N_p}\left(\frac{z_j}{s+p_j}\right) + C_0 s + 1/R_{dc}; \tag{7a}$$

$$N_p = n + 2m \tag{7b}$$

where z_j can be the real or complex residues, and p_j can be the real or complex conjugate poles. The C_0 and R_{dc} are real constants, s is the complex angular frequency and ω is the angular frequency ($s = j\omega$). The N_p is the total number of poles and n and m are the number of RL and RLC//G branches of the equivalent circuit fitted by VF, as shown in Fig.4. Once the equivalent circuit of the vertical electrode is obtained directly in time domain, it can be incorporated in the grounding grid circuit and the transient voltages computed by any EMTP-programs.

2.4 Horizontal electrodes in a stratified soil approach

Horizontal electrodes can be represented based on lumped circuit approach to compute the grounding impedance of these conductors Yang et al. (2013). Considering that the horizontal electrode is a thin uniform cylinder of radius a, length of l_h and buried depth of d, as shown in Fig.5a.

Where μ_0, ε_0 and ρ_a are the vacuum permeability, permittivity and resistivity, respectively. The μ_r, ε_r and ρ_s are the relative permeability, relative permittivity and resistivity of soil. The horizontal conductor of length I_h can be divided into N segments of equal length, called elementary length, given by:

$$l_e = l_h/N. \tag{8}$$

Each segment can be represented by a π-circuit section whose electrical parameters are: a resistance R_h and a inductance L_h, in series, and a conductance G_h and a capacitance C_h, in shunt, as shown in Fig.5b. These electrical parameters are calculated as follows Sunde (1949)

$$L_h = \frac{\mu_0 l_e}{2\pi} ln\left(\frac{2l_e}{\sqrt{2ad}} - 1\right); \quad (9a)$$

$$C_h = \frac{\pi\varepsilon_0\varepsilon_r l_e}{ln\left(\frac{2l_e}{\sqrt{2ad}} - 1\right)}; \quad (9b)$$

$$G_h = \frac{C_h}{\rho_s\varepsilon_0\varepsilon_r}; \quad (9c)$$

$$R_h = \frac{\rho_c}{\pi a^2} \quad (9d)$$

where ρ_c is the conductor resistivity.

The proper size of each segment of the electrode can be calculated based on the electromagnetic radiation theory Yang et al. (2013) by which the conductor is approximated to a thin-wire. Using the electromagnetic theory, the wavelength (λ) of a wave propagating through a lossy medium is given by Yang et al. (2013):

$$\lambda = \frac{2\pi}{\beta}; \quad (10a)$$

$$\beta = \omega\sqrt{\frac{\mu_m\varepsilon_m}{2}\left[\sqrt{1+\left(\frac{\sigma_m}{\omega\varepsilon_m}\right)^2}+1\right]} \quad (10b)$$

where β is the phase-constant of a wave in a medium. The $\omega= 2\pi f$ is the angular frequency and f is the maximum frequency of the injected current wave. The variables μ_m, ε_m and σ_m are the relative permeability, relative permittivity and conductivity of the medium (soil), respectively.

Based on the electromagnetic radiation theory, in order to properly represent the grounding electrode the size of each segment conductor, called elementary length l_e must be smaller than the critic length (l_{crit}) given as follows Yang et al. (2013):

$$l_{crit} = \lambda/10; \quad (11a)$$

$$2a/10 \ll l_e \ll l_{crit} \quad (11b)$$

When this condition is satisfied, the each segment of the grounding electrode can be interpreted as a current-carrying conductor and equal potential Yang et al. (2013). Then, the electrode can be properly represented by a large number N of lumped circuits in cascade.

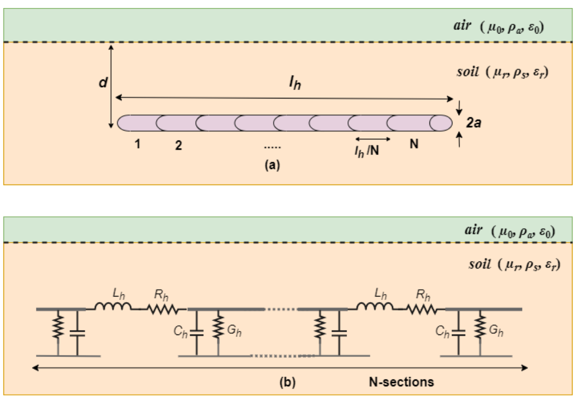

Fig. 5. Horizontal electrode buried in a given soil: [(a) represented by N-segments and (b) Lumped π-circuit approach].

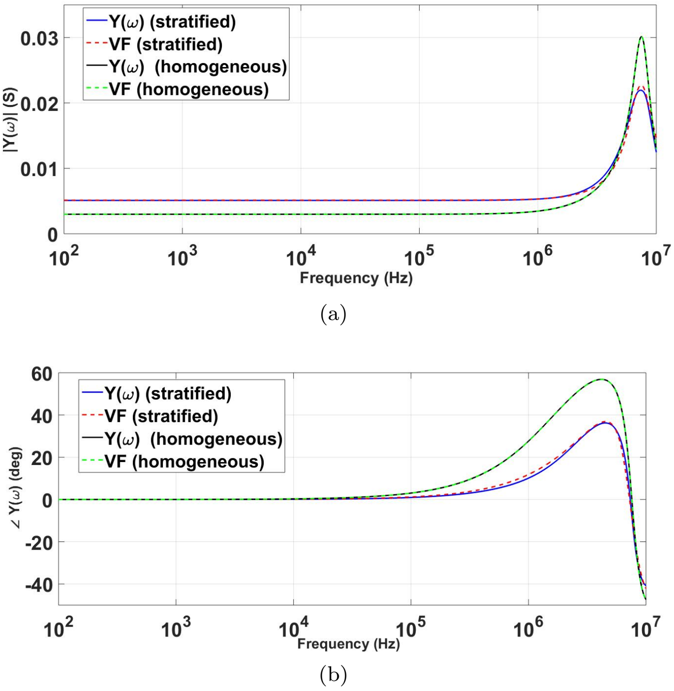

Fig. 6. Grounding admittances of the 3-m vertical electrode buried in homogeneous and two-layer soils and adjusted by the VF technique: [(a) Magnitude and (b)Phase];

3. NUMERICAL RESULTS

The results are divided into two sections. First, validations on the vertical and horizontal lumped approach and the LPS in ATP software are described. Then, a real LPS on a building is studied where a stratified soil and the integrity of the grounding electrodes are considered. In this study, the frequency-dependence on the electrical soil parameters, soil ionization and mutual coupling effects are not considered.

3.1 Validation de the LPS

The grounding admittances of the vertical electrodes buried in the homogeneous and two-layer soils are computed in the frequency domain by a numerical Method of Moments (MoM) via full-wave electromagnetic solver FEKO . The vertical conductor of length L = 3 m and radius r = 15.87 mm is considered. The soil parameters are: homogeneous soil of ρ =1,000 Ωm and the two-layered soil where ρ_1 =1,000 Ωm with a 1 m-thick layer, and ρ_2=500 Ωm. The relative permittivity ε_r = 10 is adopted and the equivalent resistivity ρ_{eq} is computed by Eq.(6). The computed grounding admittances by MoM and fitted curves by the Vector Fitting techniques are shown in Fig.6.

It can be seen at low frequencies the grounding impedances are purely resistive, however they vary from inductive to capacitive behaviour at high frequencies. The Vector Fitting curves (dashed lines) have presented an excellent agreement, where lumped circuits are obtained for each grounding admittance and inserted in the LPS circuit. A horizontal electrode of length 31.5-m, radius a = 15.87 mm, buried at d = 0.70 m in two types of soil: (i) in a homogeneous soil of ρ_s = ,000 Ωm e and (ii) 2-layer soil of ρ_1 = 1,000 Ωm (upper layer of 1 m of thickness) and

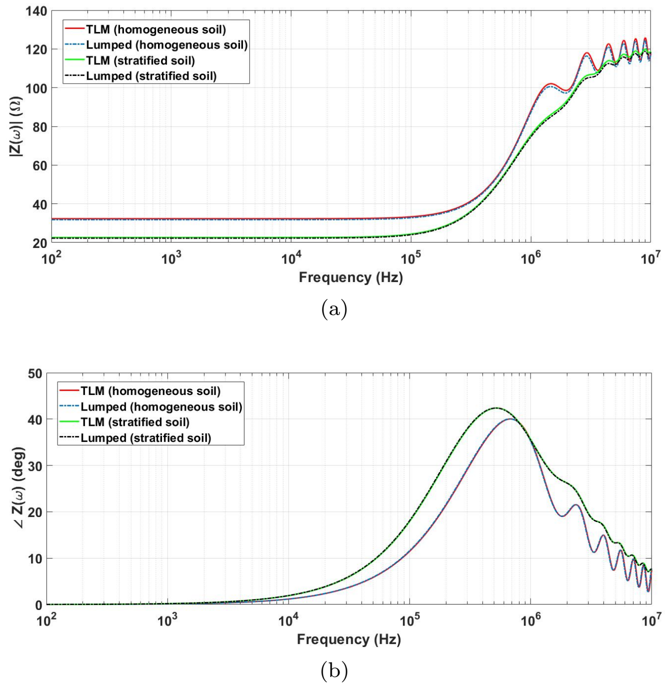

Fig. 7. Comparison of the horizontal electrode impedances obtained with the lumped parameter model and with transmission line model:[(a) Magnitude and (b) Phase].

ρ_2=500 Ωm. The relative permittivity $\varepsilon_r = 10$ is considered. Adopting that the maximum frequency of 10 MHz for the injected current, the critic length is calculated by the condition in (11). From (11)b, the l_{crit} is approximately 1 m, for both cases. The horizontal electrode is represented by N = 100 π-circuits in cascade and the elementary length l_e is 0.315 m, which satisfies the condition (11)b. A comparison of the grounding impedances obtained between the lumped approach and the Transmission Line Model (TLM) is illustrated in Fig.7. It can be seen that a good agreement in comparison with the TLM as depicted in Fig.7 for N = 100.

Finally, in order to validate the adopted models for upper grid and down-conductor, a simple LPS from Gomez (2015) is reproduced, in which the upper grid is represented by frequency-dependent transmission line model (J.Marti in the ATP representation of this work) and the down-conductor is represented as a simple transmission line. The LPS topology is seen at Fig.5 in Gomez (2015), in which a soil resistivity of 1,000 Ωm is considered. The surge impedance is computed by the Hara's equation where the height h = 12 m and radius r = 1 mm. The conductor is made of copper and the propagation velocity is equal to light speed. The grounding system is represented by a lumped resistance of 2 Ω in each branch. A transient current is injected at the upper corner of the structure and its waveform given by (12):

$$i(t) = \sum_{i=1}^{n} t^{\delta_i} A_i e^{-\alpha_i t}. \qquad (12)$$

The corresponding parameters to generate Eq.(12) are given in Table 1.

Table 1. Parameters of the lightning current injected in the circuit.

i	$\mathbf{A}_i(A/\mu s^2)$	δ_i	α_i (1/μs)
1	100,500	2	0.99
2	390	2	0.063
3	2,100	2	0.18
4	14,500	2	0.4

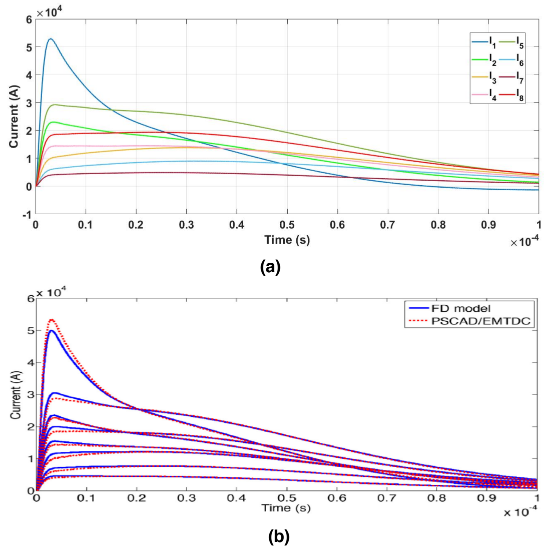

Fig. 8. Comparison between the currents: (a) Obtained with proposed representation in ATP/EMTP; (b) calculated by Gomez (2016)

The LPS topology is implemented in the ATP-software and the transient currents at the several nodes of the structure obtained in the ATP software and a comparison with the results obtained from PSCAD in Gomez (2016) is shown in Fig.8. It can be seen that the transient currents are in a good agreement in comparison with PSCAD results. Once the upper and down conductors are properly modelled, the grounding system will be modelled by the lumped approach seen in the Section 2.3 and 2.4. The real LPS is presented in the next section.

3.2 Transient Voltages on LPS

A real LPS depicted in Fig.9 is simulated in ATP-softaware where the transient currents and voltages at the points A', A, B, C and D are calculated in homogeneous and stratified soils. Simulations are performed under the whole integrity of the grounding electrodes, normal condition where all the parts of the LPS are properly connected , and in the failure condition, where a rupture or disconnection in specific points of the grounding electrodes are made. The upper grid is formed only by horizontal wires and modelled by the transmission line J. Marti model, where the frequency dependence on the wire parameters are taken into account. The down-conductor system is modelled by the distributed transmission line model (1-phase LINEZT). The coupling effect between the horizontal and vertical wires is neglected in this study. The geometric parameters of the upper grid and the down-conductor are shown in Table 2 and the grounding parameters are shown in Table 3. The electrical soil parameters for these simulations are:

- homogeneous soil of resistivity ρ =1,000 Ωm;

- two-layer soil where the first layer of ground has the resistivity of ρ_1 =1,000 Ωm and thickness of 1 m and a second layer of resistivity ρ_2 = 500 Ωm.

The relative permittivity $\varepsilon_r = 10$ is adopted for all cases. The vertical electrodes buried in the homogeneous and stratified soil are modelled by the lumped approach obtained with Vector Fitting as detailed in the previous section where the admittances is depicted in Fig.6. Each 31.5-m horizontal electrode segment is modeled by electromagnetic theory where 100-π circuits in cascade is employed to represent the conductor,as depicted previously. In the case of the 2-layer soil, the equivalent impedance is computed by the Endrenyi's abacus described in Caetano et al. (2018).

The same lightning current in Eq.(12) with a impedance channel of 400 Ω is employed to compute the transient currents and voltages at the LPS structure in Fig.9. The current shape used in the LPS model is close related to the first negative impulse as defined in the IEC 62305-1 (Annex B); its current rise is in the order of 1 s. The LPS model used in this work is based on a real system and one of its project premises is the Lightning Protection Level One (LPL-I), the most rigorous criteria, which is needed in this case as a result of risk analysis (IEC 62305-2). Besides that, as indicated in item A.1 (IEC 62305-1 Annex A), downward flashes (negative) occur in flat territory and to lower structures, which is the corresponding scenario of the referenced real LPS, also explaining the choice of a first negative impulse for the injected current pattern.

The table A.1 (IEC 62305-1 Annex A) expresses the probability of occurrence of lightning peak current values exceeding a determined value; thus the peak magnitude of 100 KA is adopted as per this table and item A.3.3 (IEC 62305-1 Annex A), considering the first negative impulse condition and, as per table B.1, the LPL-I condition. It's important to notice the amplitude density of the lightning current for the first negative stroke, as expressed in figure B.7 (IEC 62305-1 Annex B), which indicates not significant amplitudes above 1 MHz. This fact contributes to error reduction whenever the lumped element representation is adopted and an approximation is provided of those frequency dependent soil parameters.

The imposed failure condition is made by extracting the whole horizontal $\overline{AF}$, vertical rod at F and a disconnection of an end in $\overline{FE}$ (all marked as red segments and X in Fig.9). Transient currents, flowing through the down vertical ($I_{A'A}$) and horizontal (I_{AB}) electrodes , are calculated for homogeneous soil under normal and failure condition as shown in Fig.10. The same transient currents are also calculated for stratified soil under normal and failure conditions as shown in Fig.11 and a comparison for the current peaks are presented in Table 4. It can be seen that the when the rupture occurs, the current $I_{A'A}$ decreases as the equivalent impedance seen in A' increases and the current I_{AB} will increase due the lost of a horizontal conductor $\overline{AF}$ to flow.

The transient voltages are computed at the points A', A, B, C and D of the structure for the homogeneous soil for the normal and failure conditions are depicted Fig.12. The transient voltages for the stratified soil under the same conditions are shown in Fig.13. In order to show the voltages variation (Var) between the two conditions, the voltage peaks are organized in the Tables 5 and 6 for the homogeneous and stratified soil, respectively.

Table 2. Geometric parameters of the upper grid and down-conductors.

Upper grid		Down-conductor	
radius (mm)	3.34	radius (mm)	3.34
D_1(m)	30	height (m)	8.80
D_2(m)	40	resistivity(Ωm)	1,72e-8
		velocity(m/s)	3e8

Table 3. Parameters of the vertical and horizontal electrodes.

Vertical electrode		Horizontal electrode	
radius (mm)	15,87	radius (mm)	15,87
length (m)	3	length (m)	31.5
		depth (m)	0.70

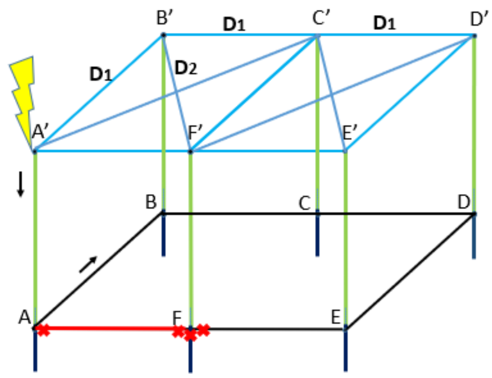

Fig. 9. Real LPS employed at the simulations.

It can be seen that, independently of soil resistivity, the highest voltage peaks are obtained at the point A (injection point of the lightning current) and the lowest peaks occur at the points D, which has presented the highest delay in the transient responses. The injected current at homogeneous soil produces higher voltage peaks than the stratified soil whose resistivity is lower than the homogeneous case.

The relative variation (%), in comparison to the normal condition, are obtained for the homogeneous and stratified soil. There is an significant increase in the voltage peaks at all points on the grounding system (A, B, C and D) under failure condition. It is seen that the greater variation is obtained at the points A and B. This is explained by the fact that the current I_{AB} has a pronounced increase in the failure condition in the homogeneous or stratified soil. Additionally, a soil of higher resistivity will present higher voltage peaks during the transient state. Thus, when the failure condition is studied, these results clearly show how safety of people surrounding these points on soil may be affected concerning the step potential rise. Equipment inside the building can also be damaged, as they are connected to these earth electrodes through the grounding system. As alternatives to mitigate these problems, larger electrodes must be considered to reduce these rise potential as well as a proper or reinforced welding in the grounding grid connections must be performed.

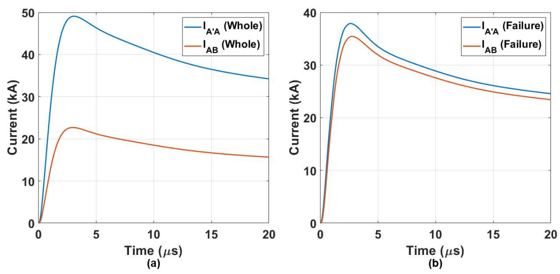

Fig. 10. Grounding currents in homogeneous soil for (a)whole grid (b)grid with failure.

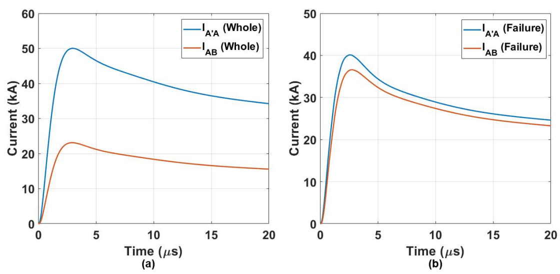

Fig. 11. Grounding currents in stratified soil for (a)whole grid (b)grid with failure.

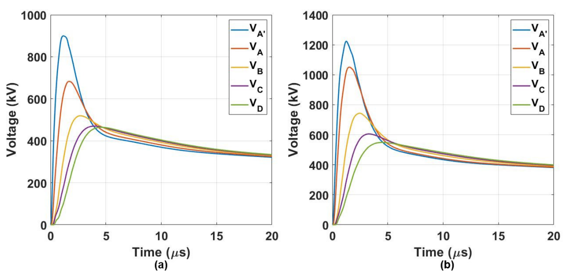

Fig. 12. Transient Voltages for the homogeneous soil:(a) whole grounding system; (b) grounding system with a rupture.

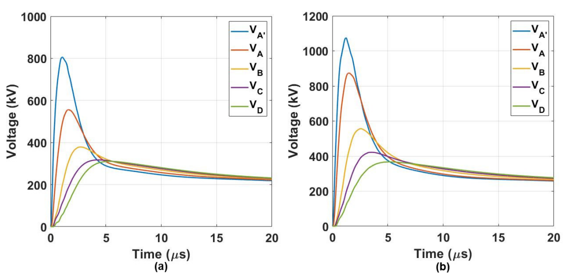

Fig. 13. Transient Voltages for the stratified soil: (a) whole grounding system; (b) grounding system with a rupture

Table 4. Current peaks in vertical and horizontal electrodes.

	Homogeneous Soil		Stratified Soil	
Currents	Whole	Rupture	Whole	Rupture
$I_{A'A}$(kA)	49.1	37.9	50.0	40.1
I_{AB}(kA)	22.7	35.4	23.1	36.6

Table 5. Voltage peaks (kV) and relative variation in the transient voltages for the homogeneous soil.

Homogeneous Soil			
Points	Whole	Rupture	Var.
A’	900	1.225	36.13%
A	683	1.051	53.89%
B	519	744	43.31%
C	470	606	28.97%
D	464	549	18.34%

Table 6. Voltage peaks (kV) and relative variation in the transient voltages for the stratified soil.

Stratified Soil			
Points	Whole	Rupture	Var.
A’	806	1.074	33.33%
A	556	874	57.06%
B	379	557	46.94%
C	317	421	32.79%
D	311	367	18.16%

4. CONCLUSION

This paper has presented an alternative approach to represent Lightning Protection System whose grounding system is buried in a homogeneous and in a stratified soil. The upper and down-conductors are modelled by the transmission line J. Marti model and distributed transmission line model, respectively. The grounding system composed by the vertical and horizontal conductors are represented by equivalent circuits obtained from the Vector Fitting and from electromagnetic radiation approach, respectively. The grounding impedances of the horizontal and vertical electrodes as well as the transient currents computed by the lumped approach have presented an excellent agreement with the results in the literature using ATP-software.

Considering a real LPS structure on homogeneous and stratified soil, the transient currents in horizontal electrode $\overline{AB}$ have presented a significant variation when a failure condition occur on grounding system. This variation is higher for the homogeneous soil due to its higher resistivity. As a consequence, the transient voltages present a pronounced increase, specially at points A and B in the failure condition due to higher current flowing the the horizontal conductor $\overline{AB}$. Higher peaks are produced when the soil of higher resistivity are considered. In case of a not properly maintained or designed grounding systems for LPS, a potential rise may affect the safety of people on the areas around the building and even damage equipment connected to this grid.

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