Benefits of the ground PEEC modelling approach – Example of a residential building struck by lightning

Edith Clavel, James Roudet, A. K. Hayashi Feuerharmel, B. de Luca, Zaki Gouichiche, P. Joyeux

Benefits of the ground PEEC modelling approach – Example of a residential building struck by lightning

E. Clavel, J. Roudet, A. K. Hayashi Feuerharmel, B. de Luca, Z. Gouichiche and P. Joyeux

***Abstract*— This article aims to prove the effectiveness of the PEEC method adapted to the modelling of meshless earth whose formulations have been explained in our first theoretical article [1]. This publication is the second part of [1]. Its robustness is emphasized on the simulation of a complex system. The chosen example is to calculate the response of a residential building struck by a lightning wave including models for all components of the distribution network. This method would allow a precise and rapid sizing of the earth protections of buildings. Today this is achieved using empirical approach or meshing methods which can be heavy and costly in terms of time solving and memory storage. An integral method based on an analytical resolution of the Poisson equation in the case of current injection has made it possible to obtain excellent results in terms of precision with a great simulation speed [1] compared to conventional methods such as finite elements. A sensitivity analysis can be undertaken through the variation of physical parameters of the earth systems in order to better design them. This method is obviously suitable for taking into account other EMC disturbances such as power electronics.**

***Index Terms*—Earth modelling, Grounding systems, Lightning conductor modelling, PEEC approach, Power system protection, Earth measurements.**

I. Introduction

Today, new buildings integrate more and more electrical or electronic devices, both to accommodate data handling systems and improve their energy efficiency. These new uses make them easily disturbed in the case of electromagnetic disturbances whose origins can be various. The sizing of grounding devices whose major aim is to provide good quality ground references requires to develop wider band models. They have to take into account not only the disturbances such as lightning, whose equivalent frequency can reach 400 kHz, but also the conducted disturbances emitted by the many power electronics converters which are necessary to control the new actuators that manage the many energy flows. Power electronics equipment can generate common mode and differential mode perturbations up to 1GHz. Today, sensitive buildings such as hospitals are victims of such a phenomenon.

The aim of this article is to show that the PEEC approach adapted to modelling without earth mesh is the most suitable for simulating a complex system integrating heterogeneous components (cabling, filters, protection devices, loads, transformers,...) facing different kinds of perturbation sources. In [1], the theoretical bases and formulations for establishing an equivalent electrical circuit of buried conductors were developed. All the geometric configurations of buried conductors that were not previously available in the literature have been developed analytically.

In section II, the principles of modelling method are recalled [1]. The developed approach is based on the evaluation of an electrical equivalent circuit of grounding conductors associated to an electrical model of all the equipment of the building.

Section III is dedicated to the implementation of this method to model a complex system. Current and potential everywhere in the building can be evaluated focusing on the injection of a lightning current. Several configurations are investigated in order to evaluate the efficiency of protection devices and conclude on their sizing.

II. Grounding modelling

The aim of this part is to present the modelling process to determine the potential and current everywhere in the system. The studied domain is constituted of two media in presence of conductors. The injected current in the conductors and the media characteristics are known. Since the studied application deals with buildings, soil and air will be considered as the media of our system.

For numerical applications, except when comparisons are made with other papers and for which values are specified, the following values are used in the next evaluations:

- Medium 1: soil: $\sigma_1 = 0.018$ Sm^{-1} and $\varepsilon_1 = 80\ \varepsilon_0$
- Medium 2: air: $\sigma_2 = 0$ Sm^{-1} and $\varepsilon_2 = \varepsilon_0$

Some authors have proposed a frequency dependent expression for the soil characteristics (100 Hz - 4Mhz). This dependence is all the more important as the resistivity of the soil is high [2-3]. Using [2] at a frequency of 400 kHz, the value of 45 is calculated for the relative permittivity. In order to deal with the worst case (when soil is very wet) that is why the value of 80 has been adopted which is the value for water.

Since we are seeking to develop a system modeling approach for establishing design rules, it is legitimate at first not to take them into account, knowing that the proposed method will naturally allow this variation to be later introduced.

A. Modelling principles

First of all, considering the equivalent frequency of lightning (around 350kHz) and the mean distances in residential houses, propagation effect may be neglected (wave length around 900m).

This work was supported in part by Hager company.

E. Clavel, J. Roudet and Z. Gouichiche belong to Univ. Grenoble Alpes, CNRS, Grenoble INP, G2ELAB, 38000 Grenoble, France (e-mail: edith.clavel@g2elab.grenoble-inp.fr).

A. Kazuti Hayashi Feuerharmel and B. de Luca are with the federal University of Santa Catarina of Brazil (e-mail: beatriz.de-luca@grenoble-inp.fr)

P. Joyeux is with Hager Company, Hager Electro, 67215 Obernai, France (e-mail: joyeuxp@hager.fr).

Moreover, it is easier to study physical phenomena and analyse the sensitivity of different models while neglecting propagation phenomena. These may be introduced later and will not modify principles leading to design rules for grounding systems protection.

In order to evaluate the potential everywhere, an electrical equivalent circuit of the conductors in the two media taking into account the interface between them is established. It is constituted of parallel resistances and capacitances and will naturally allow to take into account the frequency dependence of impedances.

The method is based on Laplace's and Poisson's equations. Their solving is widely detailed in [1]. To that extent, a complex conductivity $\underline{\sigma}$ can be defined with the physical characteristics of each medium (conductivity (σ) and permittivity (ε)) (1).

$$\underline{\sigma} = \sigma + j\omega\varepsilon \quad (1)$$

The major assumption to establish the expression of potential is a uniform current density through the conductor. If this is not valid, a meshing of the length of conductor allows to take into account the amount of current that is progressively dispersed in the medium along the conductor.

For this first step, the conductor is considered as ideal that is to say with no series resistance and inductance.

In [1], we have shown how to take into account, in a second step, the inductive and resistive characteristics of buried conductors.

1) Case of one element of a conductor

The general case of one element of a vertical conductor buried in medium 1 at distance h from the interface, and fed by current I_0 at one of its end, is presented on Fig. 1.

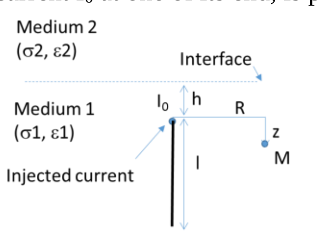

Fig. 1. Geometrical data of one conductor vertically buried in medium 1.

When point M is in medium 1, its potential, $\underline{V}1$, is given by (2), where one can recognize a similarity with the PEEC formulations [4].

The expression of $\underline{V}1$ is constituted of two terms. The first term is linked to the conductor as if it was in a single medium characterized by its complex conductivity $\underline{\sigma_1}$. The second term represents the interface contribution via an equivalent conductivity $\underline{\sigma'_1}$ that considers both media (3).

$$\underline{V}1(\mathrm{R},\mathrm{z}) = \frac{1}{4\pi\underline{\sigma_1}}\frac{I(0)}{\mathrm{l}}\ln\left(\frac{\mathrm{z-h}+\sqrt{(\mathrm{z-h})^2+\mathrm{R}^2}}{\mathrm{z-l-h}+\sqrt{(\mathrm{z-l-h})^2+\mathrm{R}^2}}\right) + \frac{1}{4\pi\underline{\sigma'_1}}\frac{\mathrm{I}(0)}{\mathrm{l}}\ln\left(\frac{\mathrm{z+l+h}+\sqrt{(\mathrm{z+l+h})^2+\mathrm{R}^2}}{\mathrm{z+h}+\sqrt{(\mathrm{z+h})^2+\mathrm{R}^2}}\right) \quad (2)$$

$$\underline{\sigma'_1} = \frac{\underline{\sigma_1}+\underline{\sigma_2}}{\underline{\sigma_1}-\underline{\sigma_2}}\underline{\sigma_1} \quad (3)$$

If point M is located in medium 2, its potential, $\underline{V2}$, is given by (4).

A similar expression of potential can be established for the case of a horizontal conductor.

$$\underline{V2}(R,z) = \frac{1}{4\pi}\frac{2}{\underline{\sigma_1}+\underline{\sigma_2}}\frac{I(0)}{l}\ln\left(\frac{z+l+h+\sqrt{(z+l+h)^2+R^2}}{z+h+\sqrt{(z+h)^2+R^2}}\right) \quad (4)$$

When point M is located on the element of the conductor, R should be taken as equal to the radius of the conductor. From these two expressions, (2) or (4), an impedance $\underline{Z}$ can be deduced. It characterizes the impedance of the conductor to the distant earth (the ground). From the expression of this impedance, an equivalent electrical circuit which is constituted of a resistance in parallel with a capacitance can be defined.

2) Case of two elements of conductors

Since real configurations include several conductors, couplings between them should also be evaluated. The most basic configuration is of two conductors; the expression of potential $\underline{V12}$ between them is function of the medium in which the conductors are. As done before, an impedance can be deduced, representing the mutual impedance between the two conductors $\underline{Zm}$.

Two conductors in the same medium: Let us take the case of two parallel conductors in the same medium as shown on Fig. 2. The expression of $\underline{V12}$ is established by integrating (2) along the second conductor and is given by (5).

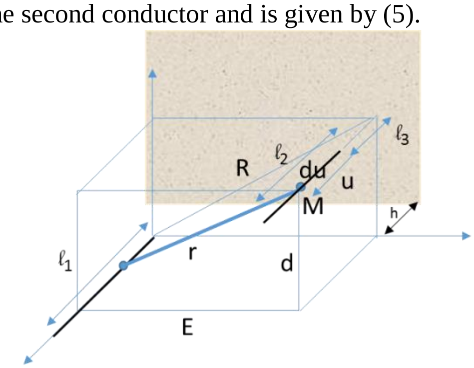

Fig. 2. Case of two parallel elements.

$$\underline{V}12(R) = \frac{1}{4\pi\underline{\sigma_1}}\frac{I(0)}{l_1 l_2}\left[z ln\left(z+\sqrt{R^2+z^2}\right) - \sqrt{R^2+z^2}\right]_{l2+l3-l1,l3}^{l3-l1,l3+l2} + \frac{1}{4\pi\underline{\sigma'_1}}\frac{I(0)}{l_1 l_2}\left[z ln\left(z+\sqrt{R^2+z^2}\right) - \sqrt{R^2+z^2}\right]_{l3+2h+l1,l3+2h+l2}^{l2+l3+2h+l1,l3+2h} \quad (5)$$

With: $[F(Z)]_{Z2,Z4}^{Z1,Z3} = F(Z1) - F(Z2) + F(Z3) - F(Z4)$

Two conductors, each of them in a separate medium: Considering buildings in general, conductors are present inside the earth for grounding systems but also in the air as for the cables. In that case, the expression of potential $\underline{V12}$ between these two kinds of conductors can be established integrating (4) along the second conductor in medium 2.

For example, the studied case of two perpendicular conductors is presented on Fig. 3 and the potential between the two conductors is given by (6).

$$\underline{V}12 = \frac{1}{4\pi}\frac{2}{\underline{\sigma_1}+\underline{\sigma_2}}\frac{I(0)}{l1l2}\left[\left[x\ ln\left(z+\sqrt{x^2+d^2+z^2}\right) + z\ ln\left(x+\sqrt{x^2+d^2+z^2}\right) + d\ Arctg\left(\frac{xz}{d\sqrt{x^2+d^2+z^2}}\right)\right]_{z+h}^{z+l1+h}\right]_{R}^{R+l2} \quad (6)$$

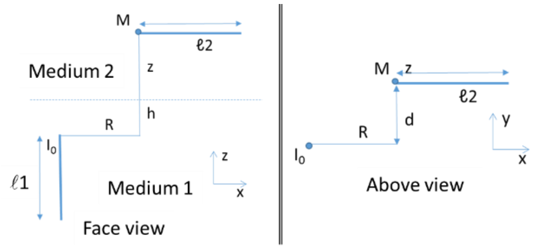

Fig. 3. Case of two perpendicular conductors each of them in a separate medium.

<u>Notes:</u> In the same way, other geometrical configurations can be inferred. For example, the potential of two elements of horizontal, parallel or perpendicular conductors can be expressed.

<u>Equivalent circuit of two conductors:</u> In that case, the expression of three potentials can be established (7):

- The potential of each conductor to the ground using (2) or (4), according to the medium in which it is located. The impedances <u>Z1</u> and <u>Z2</u> are then evaluated.
- The potential V12 between the two conductors which depends on the studied configuration and allows to define the coupling (<u>Zm</u>) between the two conductors.

An impedance matrix <u>Z</u> can be defined with these three impedances (7).

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} \underline{Z1} & \underline{Zm} \\ \underline{Zm} & \underline{Z2} \end{pmatrix} \begin{pmatrix} \underline{I1} \\ \underline{I2} \end{pmatrix} = \underline{Z} \begin{pmatrix} \underline{I1} \\ \underline{I2} \end{pmatrix} \quad (7)$$

An electrical equivalent circuit is associated to <u>Z</u> matrix (Fig. 4) whose values are evaluated using (8). It allows to associate equivalent impedances (to the ground and between conductors) which are constituted of a resistance in parallel with a capacitance.

$$\underline{Z}^{-1} = \begin{bmatrix} \underline{Y1} + \underline{Y12} & -\underline{Y12} \\ -\underline{Y12} & \underline{Y2} + \underline{Y12} \end{bmatrix} = \begin{bmatrix} \frac{1}{\underline{Z11}} + \frac{1}{\underline{Z12}} & -\frac{1}{\underline{Z12}} \\ -\frac{1}{\underline{Z12}} & \frac{1}{\underline{Z22}} + \frac{1}{\underline{Z12}} \end{bmatrix} \quad (8)$$

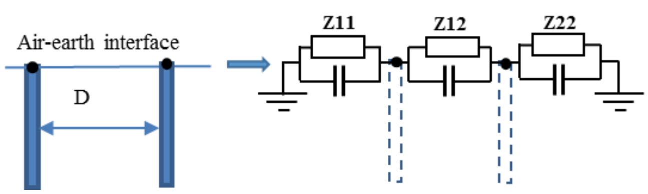

Fig. 4. Equivalent circuit of two conductors inside the earth.

B. Application to elements of grounding systems in buildings

In this part, an analysis according to the value of geometrical parameters is detailed using the previous formulations. Except for the last example, we focus on the evaluation of resistances and capacitances of buried conductors.

1) Analysis on conductors

Let us take the simple configuration of one vertical conductor in the soil. Fig. 5 underlines its geometrical parameters and its equivalent electrical circuit evaluated using (2),

Starting from this configuration, the effects of geometrical variations are observed. Fig. 6 shows that if the radius is doubled, the equivalent resistance only decreases by 10%. And, on the other hand, the variations of the conductor's length show that the equivalent resistance of the conductor to the ground decreases by 45% if the length is doubled.

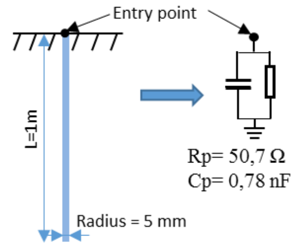

Fig. 5. Standard case of one conductor with an air-earth interface.

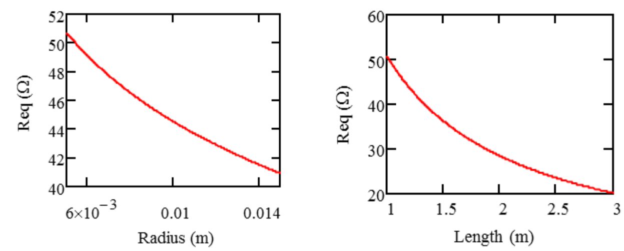

Fig. 6. Variation of the equivalent resistance to the ground with the radius (left) and the length (right) of the conductor (real part of impedance).

In Fig. 7 the resistance of the vertical conductor of Fig. 5 is compared to the same horizontal conductor while its depth is varying. Both conductors have the same dimensions. For the same length, it is better to use a vertical conductor than a slightly buried horizontal one.

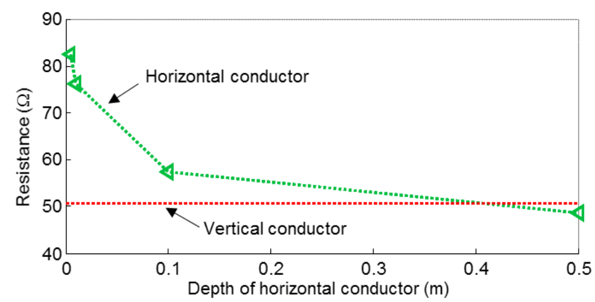

Fig. 7. Variation of the resistance of a horizontal conductor according its depth – comparison with a vertical conductor.

Fig. 8 shows the evolution of the mutual resistance between two vertical parallel conductors (real part of impedance) with the same length. We can observe that if conductors are far enough, this parameter is non-dependent on the length of conductors.

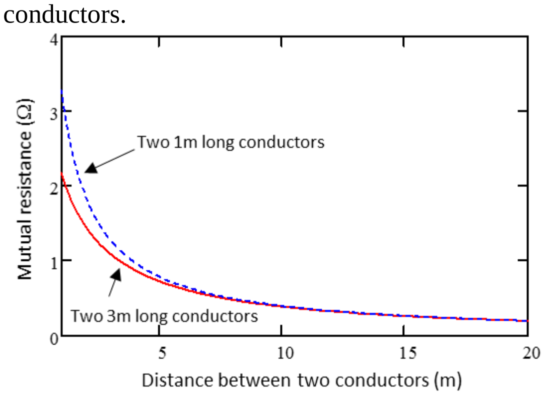

Fig. 8. Variation of the mutual resistance between two conductors of same length according to the distance D between them (real part of impedance).

The equivalent impedance, Zeq, between two conductors (Fig. 4) is given by (9).

$$Zeq = \frac{(Z11+Z22)Z12}{Z11+Z22+Z12} \quad (9)$$

On Fig. 9, the real part of this equivalent impedance is drawn according to the distance between the conductors. If conductors are far enough, the equivalent impedance is only due to the impedance of each conductor to the ground, the mutual between them is negligible.

The GC parallel equivalent circuit of conductor in the earth can be completed by the series inductive one using PEEC method as shown on Fig. 10 in order to take into account parasitic characteristics of conductor. On Fig. 10 a T model is adopted but in fact, according the studied situation a Π or a Γ model can be applied.

As it has been explained in [1], if conductor is long enough or in order to evaluate the current density coming out the conductor, a meshing is adopted and leads to the equivalent circuit presented Fig. 10 right.

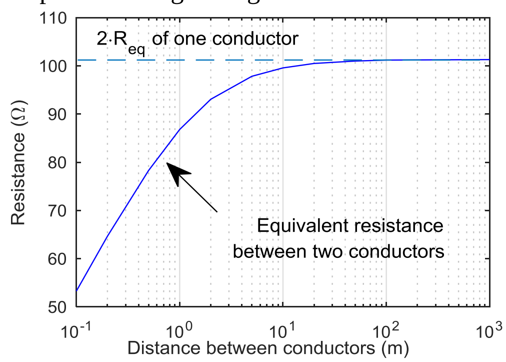

Fig. 9. Variation of the equivalent resistance between the two conductors according to the distance between them.

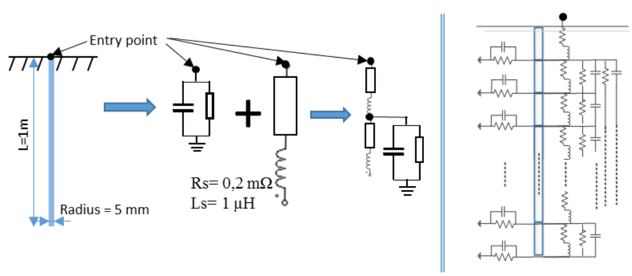

Fig. 10. Complete electrical equivalent circuit of a conductor in the soil (left) – using a meshing (right)

2) Analysis on a grid

The grid is a very widespread component of grounding systems.

Important works on the behaviour of grids struck by lightning in the soil have been published in particular by Visacro and al. [5]. However, in this paper, the proposed approach radically differs since a generic electrical model is sought. It is a PEEC-like approach. The grid can be seen as a set of connected straight conductors. For each of them, a rL and GC electrical equivalent circuit can be evaluated respectively based on the PEEC method and the one proposed in this paper.

To continue to validate our GC modelling approach, and since it is difficult to make experiments, we have decided to compare it with some results found in literature from different authors. The series resistive and inductive characteristics are not taken into account in this part except for the last example.

The first one concerns the evaluation of the equivalent conductance (G) of a buried grid in the earth (Fig. 11). Results are compared with literature [6].

Data and results are listed in Table I. We can observe a good concordance between our evaluation and the reference.

To complete this case study, our approach makes it possible to evaluate the current density of this grid. It has been plotted on Fig. 10 for a 1A current which is injected at the centre of the grid and a 500Ωm soil.

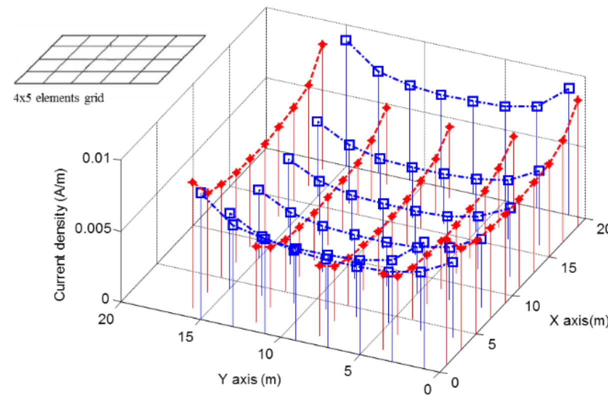

Fig. 11. Current density coming out of a grid towards the soil

TABLE I

Data and results of test case Fig. 10 [6]

Radius (mm)	Length (m) of elements	Number of elements	σ1 (S/m)	Depth (m)	R(Ω) modelled in [6]	R(Ω) our approach
5	4	4x5	0.01	10	2.6	2.57
			0.002		13	12.86

In [7], the measured resistance of another example of grid is available to compare to our approach. Table II gives data of this case and allows to conclude on the relevance of our approach.

TABLE II

Data and results of test case of [7]

Radius (mm)	Length (m) of elements	Number of elements	σ1 (S/m)	Depth (m)	R(Ω) measured in [7]	R(Ω) our approach
10	10	5x5	0.01	0.5	0.523	0.5022

The last example concerns the frequency dependence of the impedance of a grid. In [8], authors evaluate three impedances of a grid (Fig. 12) taking into account all parasitic effects, series resistance and inductance and parallel resistance and capacitance:

- Z_{11} impedance of point 1 to the ground,
- Z_{22} impedance of point 2 to the ground,
- Z_{12} coupling impedance between points 1 and 2.

On Fig. 12, the values given by our approach are plotted (dotted lines) on the curves of [8] (straight lines). A good agreement can be observed between these two simulations. For high frequencies the inductive nature of conductors is predominant on the capacitive behaviour as it can be observed with the impedance increase with the frequency for Z_{11} and Z_{22}.

This allows to valid the complete modelling process, resistive, inductive, capacitive with couplings we propose.

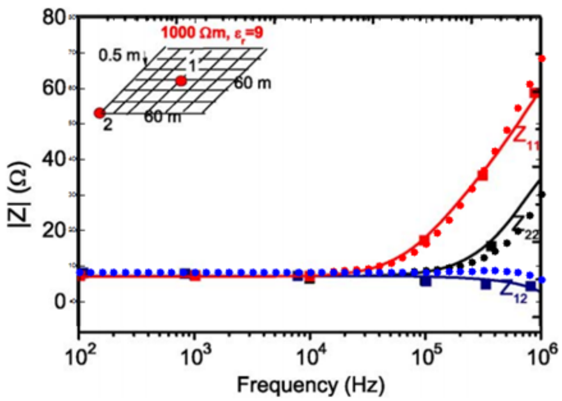

Fig. 12. Impedance: [8] straight lines – our approach dotted lines

3) Conclusions

Thanks to several comparisons with literature, the accuracy of the proposed modelling method is demonstrated. The following section will focus on the modelling of a complete building.

III. Application to a Complex System

A. The studied system

For complex systems, a transient analysis is required by designers in order to evaluate the relevance of protection devices. Some examples can be found in literature but either their complexity is far from a realistic configuration [9-10] or they are far from the residential case we propose [11-12].

Let us take the example of a generic residential housing.

The lightning current can be dissipated by auxiliary grids located under the lightning conductor but also by the main grid located under the house whose role is to maintain the protective conductor as equipotential as possible. Depending on the grounding connection, the neutral at the transformer output is also connected to earth by an electrode. The protection of persons is ensured by a Residual Current Device (RCD) and we will show that the lightning current can cause the opening of this component, affecting the current continuity while there is no danger of electrification for persons.

The described modelling method has been applied on the realistic configuration presented in Fig. 13. It is constituted by:

- A lightning conductor;
- Grounding grids (two of them are directly connected to the lightning conductor);
- A filter and a RCD representing the entry point of the building;
- A R-L series representing the housing load;
- An equipotential protection cable;
- A grounding electrode connected to the transformer (black arrow on Fig. 14);
- A transformer and a part of an electrical network to complete the system.

This configuration (Fig. 13) is considered as the reference case, noted (reference) on the following figures. Fig. 14 represents the electrical system which is modelled including all elements.

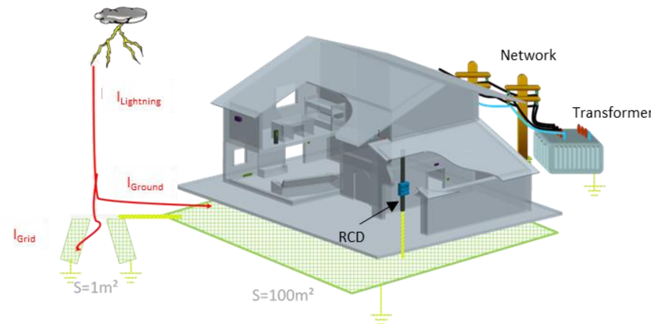

Fig. 13. Complex system

B. Different configurations under study

The effectiveness of various simple and inexpensive cabling solutions used by installers to minimize the nuisance tripping of the RCD is evaluated, as explained in the previous section.

To answer this issue, the whole system has to be described since potentials can appear between the different components and the distant earth. In this dynamic study, the power source of the network will be replaced by a short circuit which requires to include serial impedances simulating the different power supply cables (Fig. 14).

Thanks to the generality of the proposed modelling approach, different configurations can be investigated. They consist in evaluating the influence of additional cables or components on the common mode current and potential values at some points of the system (Fig. 15):

- Configuration (a): a long non insulated cable is added between the grids to simulate the increase of the impedance. Its inductance is evaluated to around 80µH.
- Configuration (b): an inductance (100 µH) is introduced to separate the grids for the high frequency range and represents a bar filter.

C. Modelling

Each element of this system has been modelled. For the transformer, works of Kéradec and al. [13] have been applied. In Table IV the characteristics of type of conductors are listed as well as the adopted model. Each element of this system has been separately modelled. Then all equivalent circuits have been integrated into a unique equivalent circuit which has been simulated using SPICE.

D. Results

A lightning signal has been injected; the potential of several points which are marked on Fig. 14 has been evaluated, as well as the common mode current (Icm).

On Fig. 16, the potential at point (2) is observed for the three configurations. It can be noted that this potential is all the higher than this part of the system is electrically separated from the rest of the circuit by an impedance.

Note that the added cable in the configuration (a) not only adds impedance but also participates in the evacuation of the current towards the earth.

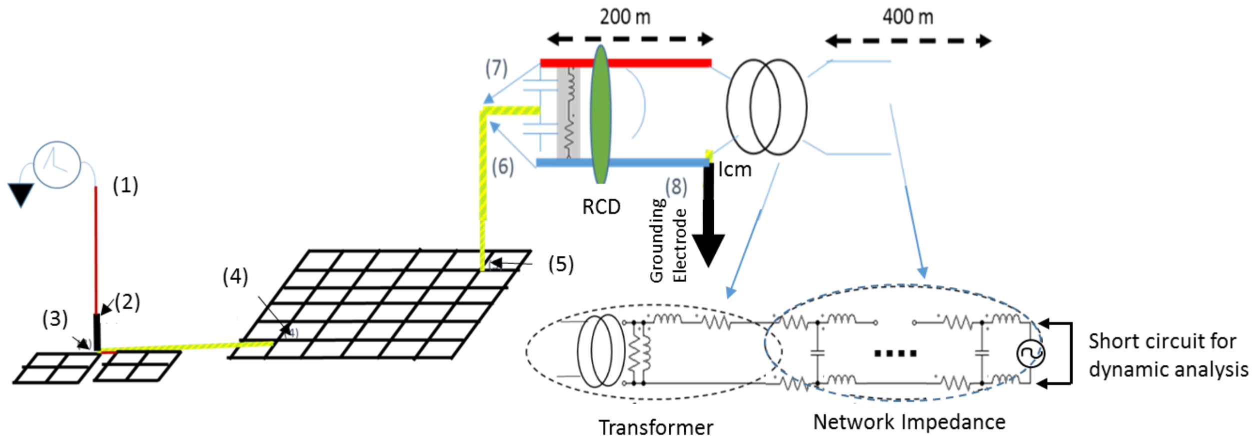

Fig. 14. Reference configuration

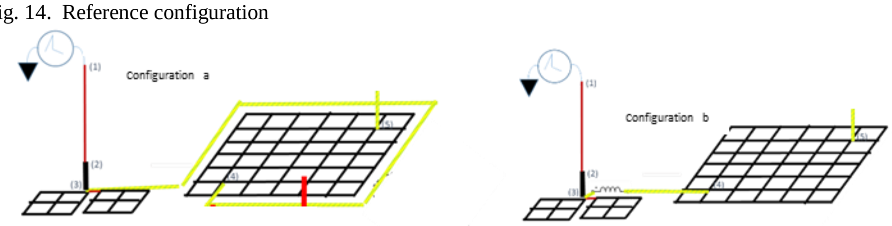

Fig. 15. Two modifications of grounding systems connections from the reference configuration

TABLE IV

Characteristics of each element of the studied system

Element	Sizes	Model
Copper conductors (straight conductor, grid, …)		
Lightning injection	1.2/50 µs ~ 8/20 µs	
Lightning conductor	Length = 10m Section= 6mm²	R-L
Cable between lightning conductor and small grids	Length = 0.5m Radius = 5mm	vertical conductor in the earth (rLCG) 5 subdivisions
2 grids	1m², 0.5m deep 2x2 elements	Grid in the earth (rLCG) 2 subdivisions per element
Cable between lightning conductor and building grid	Length = 3m Section = 6mm² 0.5m deep	Horizontal conductor in the earth (rLCG) 10 segments
Building grid	100m², 0.5 m deep 6x6 elements	Grid in the earth (rLCG) 2 subdivisions per element
Equipotential Protection Cable	Length = 1.5m Radius = 1.4mm	R-L
Cable between building and transformer	Insulated conductors Length = 200 m	Distributed (rLCG) model Discretization: 10 cells
Cable between transformer and network	conductors Length = 400 m	Distributed (rLCG) model Discretization: 10 cells
Conductor in the earth connected to transformer	Length = 1 m Radius = 5 mm	Vertical conductor in the earth (rLCG) 10 subdivisions
Common mode filter		Capacitances Cy 2x 10nF

On Fig. 17, the potential of the building grid is observed for the three configurations. To that extent, two points have been defined (4) and (5). However, it appears that the grid can be considered as equipotential, which is very important to ensure a good grounding of the building. Since an impedance has been added between the grids for the configurations (a) and (b), the elevation of the potential is reduced compared to the reference.

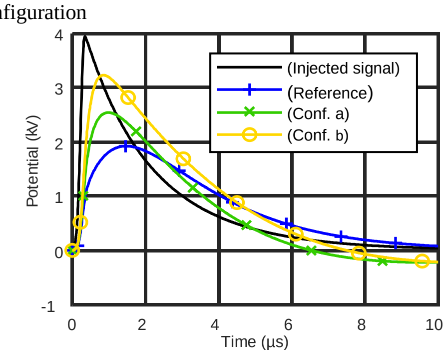

Fig. 16. Potential at point (2) for the three configurations

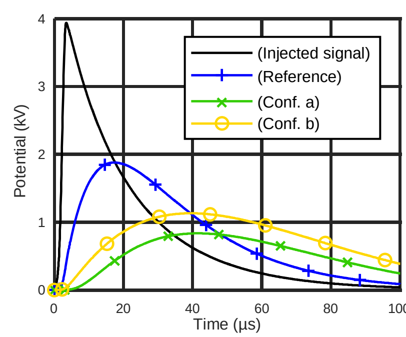

Fig. 17. Potential at point (4) for the three configurations

It can be observed that since the added cable in the configuration (a) turns away a part of injected current in the earth, the potential in this case is lower than in configuration (b) even if the impedance is lower.

On Fig. 18, the potential at point (6) is observed for the three configurations. This signal is important to verify the voltage on the Cy capacitors of the filter. Once again, the level is lower if an impedance is added between the grids and the same conclusion as for the previous curves can be given.

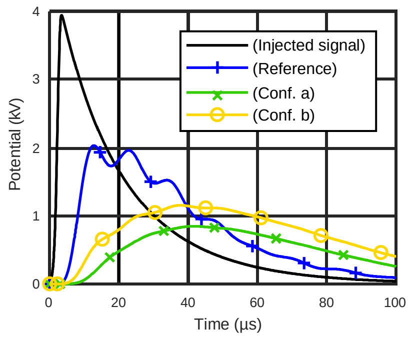

Fig. 18. Potential at point (6) for the three configurations

On Fig. 19 and Fig. 20, currents flowing at points (3) and (4) (Fig. 14) have been drawn. These curves allow to confirm the benefit of the added cable in the configuration (a) which has been previously described. Note that the current for configuration (a) which is higher at point (3) than for the configuration (b) becomes lower at point (4). The cable is longer than for the reference configuration, that is why the current in that configuration is higher.

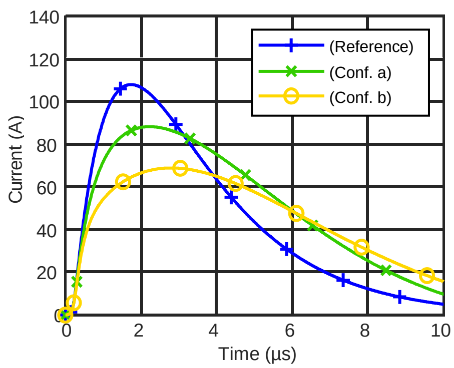

Fig. 19. Current flowing away from node (3) for the three configurations

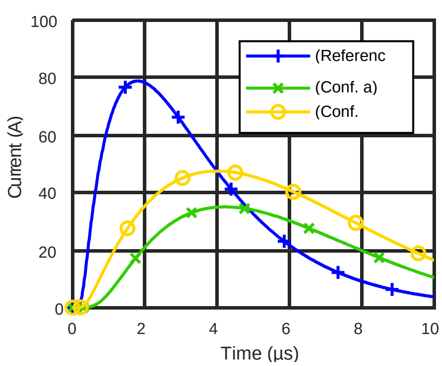

Fig. 20. Current flowing towards node (4) for the three configurations

On Fig. 21, the common mode current at the RCD is observed for the three configurations. A RCD must open for a common mode current of 15mA-50Hz in residential installation. Theoretically, the lightning current through the RCD previously calculated in the different configurations has a high frequency spectral content which should not trigger it. But in the reality, the lightning wave form is a sequence of pulses every 20 to 30ms with an average of 5 pulses (repetition frequency between 30 and 50Hz) [14] (Fig. 22). This kind of configuration could be modelled using our approach to verify if the current level can reach a value high enough to induce the RCD to open. In addition, in practice, even if test set-up verify the standard, they do not always give same result. This last point is extremely critical in both simulation and experimentation.

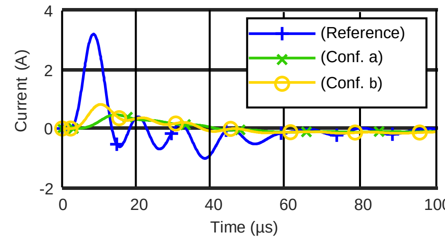

Fig. 21. Common mode current for the three configurations

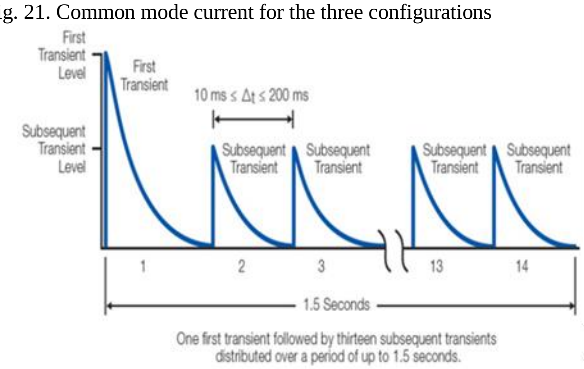

Fig. 22. An example of a real lightning strike

These curves show that configurations (a) and (b) are two alternatives which allow to protect the RCD since it must not open in case of a lightning shock on the building insofar as there is no risk for persons.

From Fig. 21, it is more interesting to extend the cable between the two grid systems than to add bar filters which will be more expensive and less efficient in order to reduce the common mode current in the RCD.

IV. Conclusions

In this paper, we have shown how to apply the soil modelling process allowing to use various electrical models for different kinds of components. It has been detailed on the example of a residential building struck by lightning. However, this is not limited to this specific application. Other sources of disturbance, as power electronics, can be addressed by ensuring that all models are sufficiently wide bandwidth. Several formulations have been established to represent as faithfully as possible the common geometrical configurations of buildings. The main advantage of such an approach is to have an electrical equivalent circuit for grounding systems which is compatible with models of other electrical components of the buildings (cables, transformers, filters, loads, RCD [15]…). All of them can then easily be integrated into circuit softwares to simulate a complete system and evaluate currents and potentials and compare configurations.

This method can be applied particularly for the design stage of specific sensitive buildings system layouts to justify and conclude on the efficiency of protection devices. And to achieve this design process, optimization algorithms are regularly requested. The use of analytical formulas is particularly interesting for optimization processes based on the most efficient gradient methods because derivative functions can be analytically expressed.

V. References

[1] E. Clavel, J. Roudet, J-M. Guichon, Z. Gouichiche, P. Joyeux, A. Derbey, “A nonmeshing approach for modeling grounding”, IEEE Trans on EMC, vol. 60, Issue: 3, June 2018, pp. 795-802.

[2] F. H. Silveira, S. Visacro, R. Alipio, A. De Conti, “Lightning-Induced Voltages Over Lossy Ground: The Effect of Frequency Dependence of Electrical Parameters of Soil”, IEEE Transactions on Electromagnetic Compatibility, Year: 2014, Volume: 56, Issue: 5, Pages: 1129 - 1136

[3] R. Alipio, S. Visacro, “Impulse Efficiency of Grounding Electrodes: Effect of Frequency-Dependent Soil Parameters”, IEEE Transactions on Power Delivery, Year: 2014, Volume: 29, Issue: 2, Pages: 716 - 723

[4] A. E. Ruehli, “Inductance calculation in a complex integrated circuit environment,” IBM Journal of Research and Development, vol. 16, no. 5, 1972.

[5] S. Visacro, R. Alipio, C. Pereira, M. Guimarães, M. A. O. Schroeder, “Lightning Response of Grounding Grids: Simulated and Experimental Results”, IEEE Transactions on Electromagnetic Compatibility, Year: 2015, Volume: 57, Issue: 1, Pages: 121 - 127

[6] M. N. Guimarães, L. Araujo, R. V Castro, L. F. D. Santos, M. H. M. Vale, and S. Visacro, “Impulse Response of Grounding Grids : Experimental versus Simulated Results,” *Proceedings on 31st Int. Conference on Light. Prot. (ICLP)*, Vienna, 2012, pp. 1-4., pp. 6–9, 2012.

[7] F. P. Dawalibi, “Modern Computational Methods for the Design and analysis of power system Grounding,” Potentials, pp. 122–126, 1998.

[8] S. Wang, J. He, B. Zhang, R. Zeng, and S. Member, “Time-Domain Simulation of Small Thin-Wire Structures Above and Buried in Lossy Ground Using Generalized Modified Mesh Current Method,” IEEE Trans. Power Deliv., vol. 26, no. 1, pp. 369–377, 2011.

[9] A. P. Meliopoulos and M. G. Moharam, “Transient Analysis of Grounding Systems,” IEEE Trans. Power Appar. Syst., vol. PAS-102, no. 2, pp. 389–399, 1983.

[10] M. Heimbach and L. D. Grcev, M. Heimbach, and L. D. Grcev, “Grounding System Analysis in Transients Programs Applying Electromagnetic Field Approach,” *IEEE Trans. Power Deliv.*, vol. 12, no. 1, pp. 4–5, 1997.

[11] H. Chen and Y. Du, "Lightning Grounding Grid Model Considering Both the Frequency-Dependent Behavior and Ionization Phenomenon." IEEE Trans on EMC, vol. 61 no. 1, FEB. 2019, pp.157-165

[12] H. Chen, Y. Du and M. Chen, "Lightning Transient Analysis of Radio Base Stations." IEEE Trans on PWRD, vol 33, no. 5, Oct. 2018, pp.2187–2197.

[13] X. Margueron, J.-P. Keradec, "Design of equivalent circuits and characterization strategy for n-input coupled inductors", IEEE Transactions on Industry Applications, Institute of Electrical and Electronics Engineers, 2007, 43 (1), pp. 14-22

[14] http://sites.ieee.org/northern-canada-pesias/files/2015/10/IEEE-Fall-2015-Overvoltages-and-the-Distribution-System.pdf

[15] Xiang Luo, Y. Du, X. H. Wang, and M. L. Chen, “Tripping characteristics of residual current devices under nonsinusoidal currents,” IEEE Trans. on IAS, vol. 47, no. 3, May/June 2011, pp. 1515-1521.

VI. Biographies

E. Clavel received the Engineer and Ph.D. degrees in electrical engineering from the Institut Polytechnique de Grenoble, Grenoble, France, in 1993 and 1996, respectively.

She is an Assistant Professor at Grenoble-Alpes University (France). She has been a permanent researcher with the Grenoble Electrical Engineering Laboratory since 1996, in the field of power electronics.

Her main activities concern the modelling and design of any kind of connections of power structures, massive bars, bus bars, printed circuit boards, etc. Her research team develops a tool (InCa3D) which models and optimizes connections in order to improve the performances of power structures, including electromagnetic compatibility, mechanical and thermal aspects.

J. Roudet was born in 1962. He received the Electrical Engineering Dipl. in 1986 and, the Ph.D.degree in 1990.

He is a Professor at Grenoble-Alpes University (France), and he currently holds the director position of G2ELab (Grenoble Electrical Engineering Lab).

His major field of interest is the modelling of parasitic elements of power converter and systems, to improve layout and power design. He is a source of creation of numerical tools to take into account EMC effects for designing power converters and systems. He had also led the power electronics team during several years.

Z. Gouichiche was born in 1987. He received the Engineer and Ph.D. degrees in electrical engineering from the National Polytechnic School of Algiers (ENP), Algeria in 2010, and from Grenoble University in 2017 respectively. He has been a member of the Grenoble Electrical Engineering Laboratory (G2ELab), working on grounding systems modelling for building applications. He has also worked on the analysis of electric transient behaviour in lithium batteries in LAAS-CNRS, Toulouse.

P. Joyeux received the Engineer and Ph.D. degrees in electrical engineering from the Institut Polytechnique de Grenoble, Grenoble, France, in 1996 and 2000, respectively. He has started at Hager as an expert on residual current device since 2001. Then from 2009 he has worked on the short-circuit performance (arc breaking). He currently works in the Technical Advanced Engineering Service for electrical protection.

B. De Luca received the Engineer’s degree in electrical engineering from the Institut Polytechnique de Grenoble, France, and from the Universidade Federal de Santa Catarina, Brazil, in 2018 and 2019, respectively, as a result of a double degree program. Her main activities concern the electrical risk caused by complex signals.

A. K. Hayashi Feuerharmel received the Engineer’s degree in electrical engineering from the Institut Polytechnique de Grenoble, France, and from the Universidade Federal de Santa Catarina, Brazil, in 2018 and 2019, respectively, as a result of a double degree program. His main activities concern the EMC modeling and design of smart buildings.