Modeling of substation grounding for fast front overvoltage studies

X. Legrand, A. Xémard, P. Auriol, C.A. Nucci, C.Mouychard

Abstract—When performing insulation coordination studies, grounding electrodes of substations are frequently represented as as lumped resistances, in some cases even when extended grounding grids are dealt with. This paper presents an analysis of the approximations deriving from such a practice when studying fast transient phenomena, for several cases in term of grid geometry and soil electric resistivity. The influences of two models are compared for the grounding system: a very simple model that consists only of a resistor, and a model based on the more rigorous application of Maxwell's equations. The limits of applicability of these models are investigated and discussed by means of a comparative study. We conclude that depending on the type of engineering problem that one has to tackle, the adoption of one model instead of the other can lead to significant differences. For insulation coordination, lightning fast front overvoltages in the substation could be still computed in a first approximation using a simple resistor to model the grounding grid. Regarding EMC studies, the simplest model can lead to a certain underestimation of the potential rise of the grid, which means that, in general, the application of the Maxwell's equations-based model is recommended.

Keywords: Grounding, Substation insulation, Maxwell equations, Lightning.

I. INTRODUCTION

THE grounding system of a structure is the group of buried conductors whose goal is to provide an electrical connection to ground, for safety, functional grounding and/or fault protection [1]. For substations it is usually a large grid, with several terminals, whose overall dimensions can cover a surface of several thousands of square meters. As an example, we present in Fig. 1 a substation grid with two terminals (I_1 and I_2 are the currents flowing from the network to the grounding system in terminals 1 and 2, respectively, and U_1 and U_2 are the relevant voltage, referred to the remote grounding).

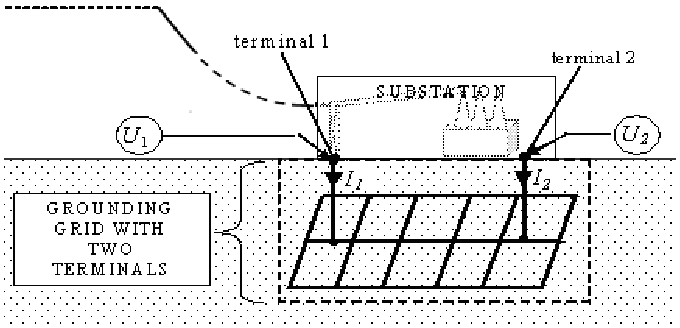

Fig. 1. Substation grounding with two terminals.

When carrying out insulation coordination studies, fast front overvoltages are usually computed considering grounding systems as simple resistors, even for large grids. However, due to the large extension of these systems and to the fundamental role that they play, one can wonder whether the use of more detailed models would be more appropriate to describe them.

One of the most detailed models for the grounding system is the so-called 'Electromagnetic model' [2]. It is based on the antenna theory and is renowned to be one of the most accurate ones for a frequency range up to 1MHz: we shall assume this model as the 'reference' one.

The structure of the paper is the following.

First of all, we will review the two approaches chosen (simple resistor and Electromagnetic Field model) to model the grounding system of a substation in EMTP-RV environment [3] in order to underline the relevant limits.

Then we will focus on overvoltages in a substation due to a lightning flash stroking a tower in the vicinity. We shall compare results obtained by using the two types of grounding models to estimate errors due to a low frequency representation of the grounding system of a substation. Several cases in term of the grid geometry and soil properties, using the standard CIGRE lightning current shape [4], will be analyzed.

Grounding potential rise and electrical stress on the transformer are computed to carry out a parametric study, leading us to conclude on the relevance of using one model or the other.

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II. DIFFERENT APPROACHES AND THEORICAL LIMITS

A. A models considered

1) Resistor model

The simplest model for grounding system is based on the following main assumptions [5]:

- The grounding conductors are perfect (zero resistivity).
- The frequency is low enough, comparing to the total length of the grounding system, to consider that all its parts have the same electric potential at any time (U_1=U_2 for the case of Fig. 1).

In simulation process, the whole grounding system can then be reduced to one terminal only connected to the reference potential by a simple resistor.

Many papers deal with the derivation of a value for the resistance to ground of a grounding grid at low frequency. The simplest are based on empirical formulas. Among others let us state Laurent and Nieman's, also called IEEE std 80 formula [1]:

$$R_{LF} = \frac{\rho}{4} \cdot \sqrt{\frac{\pi}{A}} + \frac{\rho}{L} \tag{1}$$

with:

- R_{LF}, low frequency resistance of the grid (in Ω);
- ρ, ground resistivity (in Ω.m);
- L, total length of the buried conduction (in m);
- A, area of the grid (in m^2).

2) Frequency dependent modeling

a) introduction

As a result of an extensive research, several models have been presented for grounding systems over a large frequency band, which are intended for applications in lightning protection. These models are often classified in 3 categories depending on authors' approach:

- Circuit theory [6];
- Transmission Line theory [7][8];
- Antenna theory (Electromagnetic Field Approach) [2][9].

b) the Electromagnetic model selected

In this paper, we choose as an alternative to the 'simple resistor model', the so-called Electromagnetic model proposed by Dawalibi and Grcev in [2]. It is based on the Antenna theory, with general application of Maxwell's equations, solved using moment's method [10]. We consider that it is one of the most accurate approaches, especially for high frequencies. It is based on several assumptions:

- Grounding system must be divisible into cylindrical conductors subject to thin wires approximation.
- Soil is homogenous and ionization is neglected.
- Electrical characteristics are linear, isotropic and frequency independent.

The first assumption is straightforwardly confirmed for the substation groundings presented in this paper.

In our case, the second assumption will lead us to consider that concrete of substation foundations has the same electrical properties than the ground. It is commonly accepted that it is a conservative compromise because concrete is strongly hygroscopic [11].

Finally, experimental and theoretical studies show that electrical properties of soil are not linear [12], but ignoring it often gives conservative results.

Except from the above-discussed assumptions, the only restriction for accuracy of the model used here comes from the application of the modified image theory, which limits the range of application to frequencies lower than few MHz.

c) The Electromagnetic model into EMTP

The electromagnetic model is included into EMTP following the approach presented in [13], which is briefly summarized here. The first step of this method is the calculation of the frequency response of the grounding system: impedances Z_{ij} (f_k) between terminals i and j, computed by means of the Electromagnetic model for several frequencies f_k on [0Hz; 1MHz]. The whole grounding system is then modeled into EMTP by means of a unique bloc describing the relationship between currents I_n flowing from the network to the terminal n and voltages of terminals V_n, with state space equations. In the case of two terminals (cf. Fig. 1), these equations are:

$$\begin{cases} \dot{X} = \mathrm{A} \cdot X + \mathrm{B} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \\ \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \mathrm{C} \cdot X + \mathrm{D} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \end{cases} \tag{2}$$

where X is the state vector, and matrixes A, B, C and D, which define the transient behavior of the grounding system, can be obtained from the discrete values of mutual impedances Z_{ij} computed with the Electromagnetic model.

B. Reflection on validity of the simplest grounding system model for lightning studies

1) Lightning phenomena

Lightning is classified as a 'fast transient phenomena'[14]. Experiments have lead CIGRE to define a shape model for lightning current. Here we will consider a current which grows to a maximum value I_{max}=100kA in t_f=6.3µs with a maximum steepness S_m=36.7kA/µs and decreases to reach its half value at T_h=77.5µs [4].

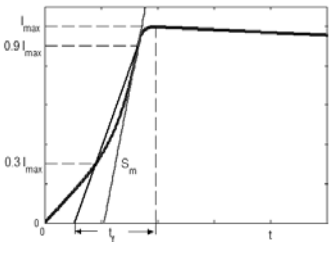

Fig. 2. Lightning current shape, CIGRE [4].

Classically, the frequency spectrum of the electrical variables considered for lightning studies extends from several Hertz to one MHz [15].

2) Theory limits of low frequency models

In the soil, the expression for the wavelength is: $\lambda = \frac{\lambda_0}{n}$, with λ_0 the wavelength in vacuum, and n the refractive index of the soil (if the soil relative permeability is 1):

$$n = \sqrt{\left|\underline{\varepsilon}_s\right|} = \sqrt{\left|\varepsilon_r - i\frac{1}{\rho \cdot 2\pi f \cdot \varepsilon_0}\right|} \qquad (2)$$

with f the frequency of the signal, $\underline{\varepsilon}_s$ the complex permittivity of the soil, ρ its resistivity and ε_0 the permeability of vacuum.

Then table 2 shows the wavelength of a 50Hz and a 1MHz wave in soil considering ε_s =5.

TABLE 2

WAVELENGHTS VS SOIL RESISTIVITY

ρ (Ω.m)	λ_{50Hz}	λ_{1MHz}
50	2.23 km	15.8 m
200	4.47 km	31.6 m

For fast transients, such as lightning-originated ones the frequency spectrum of the electrical variables extends from several Hz to several thousands of kHz. Then the wavelength is lower than the length of the underground conductors forming the grounding system. It follows that we may no longer consider that all parts of the grid have the same electric potential[1] [9][16] and that the 'resistor model' is, in principle, not theoretically adequate.

The error due to low frequency modeling of the grounding system will depend on soil properties, on the geometry of the grounding system and on the frequency of the signals of interest.

III. COMPUTATION OF POTENTIALS AND ERRORS DUE TO THE LOW FREQUENCY MODEL

A. CASES OF STUDY

1) Global configuration

We consider here a substation grounded with a grid of 10m separated conductors at 0.5m depth. All the grounding conductors have a section of 160mm². Each tower of the 225kV line is grounded by 4x3 loops [17]. Input voltage is 225kV. Fig.3 presents the configuration considered.

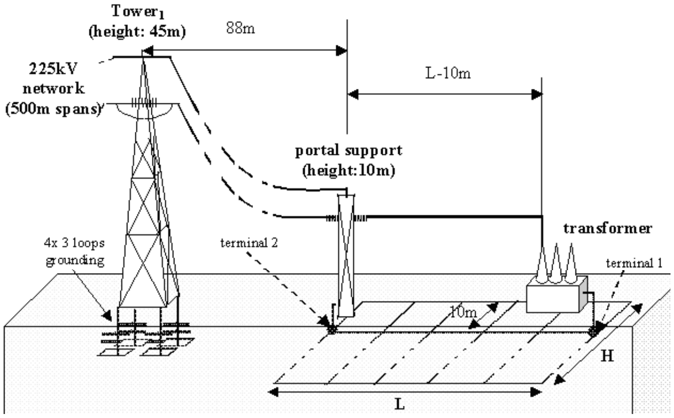

Fig. 3. Configuration studied.

2) Cases of interest

We will study the ground rise potential of terminals 1 (grounding of the transformer) and 2 (grounding of the portal support) and the electric stress on the transformer when Tower$_1$ is struck by lightning. As the error due to low frequency modeling of the grounding system depends on the soil properties and on the geometry of the grounding system, we will carry out a parametric study on ρ, H and L and consider a classical lightning current shape (as defined in B.1).

We choose four cases of study:

TABLE 2

CASES OF INTEREST

case	Soil ρ (Ω.m)	Geommetry L (m)	 H(m)
1	50	60	150
2	200	60	150
3	50	120	150
4	200	120	150

B. Modeling of the system

1) Global system

We consider here three spans; a long span (30km) is modeled at the left-end of the system to avoid reflection effects that would render less straightforward the discussion of the results .

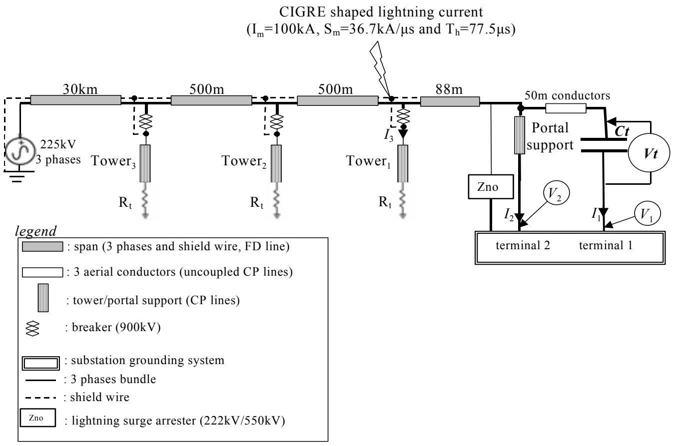

Fig. 4. Global system modeling.

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[1] By 'potential', we mean here 'scalar potential' because the electric vector potential is path dependent in high frequencies and is therefore not uniquely defined.

Towers/support are modeled by 45m/10m CP lines with a characteristic impedance Zc of 85Ω. Ideal flashover switches are used to represent insulations towers/phases (900kV). Lightning surge arresters with an effective assigned voltage of 222kV and a peak protection level of 550kV protect the portal support from lightning.

The transformer is modeled by 2.2nF capacitors between the phases and terminal 1. Grounding systems of towers are loops and are not large, as a consequence they can be considered as static resistors on the frequency band [0Hz;1MHz][16]. We take here R_t=10 Ω, which is the mean value on French transmission network:.

2) *Substation Grounding*

a) *Low Frequency modeling*

As presented in II.A.1, the simplest model will be reduced to a simple resistor R_{LF}:

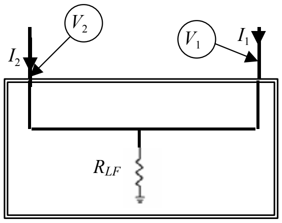

Fig. 5. Low Frequency Substation grid model into EMTP.

We compute with the empirical formula (1):

TABLE 4
LOW FREQUENCY GROUNDING GRID RESISTANCE

CASE	R_{LF}(Ω)
1	0.2613
2	1.0453
3	0.179
4	0.7161

b) *High Frequency modeling*

The Electromagnetic model is included into EMTP as a state space bloc relating currents in each terminal to voltages of all terminals, following the method presented in II.A.2.c)**.**

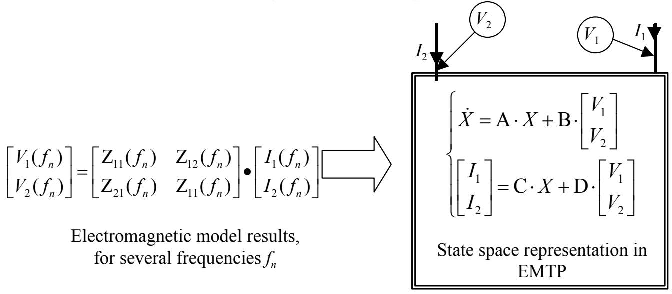

Fig. 6. Electromagnetic Field Substation grid model into EMTP.

Fig. 7 and Fig. 8 present the evolution of mutual and self impedances (Z_{11}, Z_{22}, Z_{12} and Z_{21}) on [100Hz,1MHz]. Note that due to the symmetry of the system, we have: $Z_{11}=Z_{22}$ and that the reciprocity principle involves: $Z_{21}=Z_{12}$.

Fig. 7 confirms the well known inductive behavior of large grounding grids: for high frequencies, the absolute values of Z_{11} and Z_{22} are higher than the low frequency ones [9][16].

Concerning the mutual coupling between terminals, Fig. 8 shows that it converges to zero for high frequencies, which means that high frequency transients on a terminal are not completely transmitted to the other one.

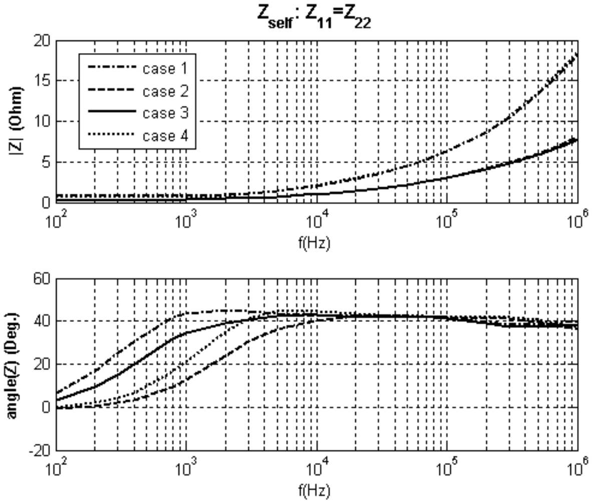

Fig. 7. Frequency response of Z_{self} terms.

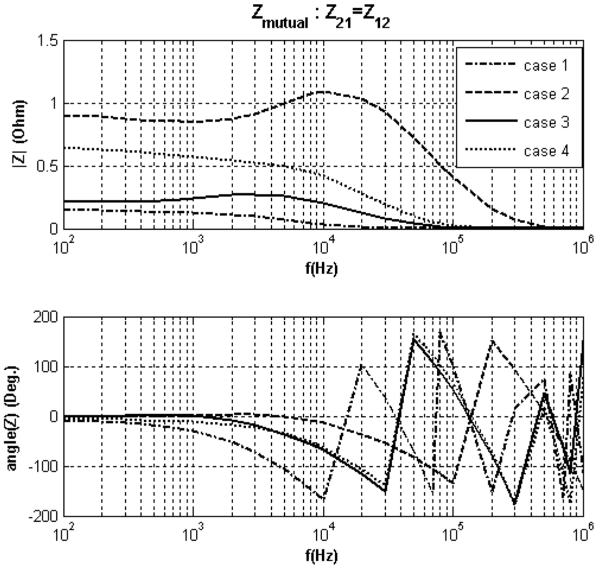

Fig. 8. Frequency response of Z_{mutual} terms.

C. *STRESS ON THE TRANSFORMER*

For the four cases of study, we have plotted voltage Vt, defined in Fig. 4, see Fig. 9 and Fig. 10. When $Tower_1$ is struck by lighting, a flashover occurs on phases 2 and 3, stressing the transformer (Vt_{ph1} and Vt_{ph2}).

We see that the computed maximum value of Vt_{ph1} and Vt_{ph2} does not depend strongly on the case and on the model of the grounding grid (maximum relative difference between peak values computed with BF and HF approaches, for phase 2, case 4: 14.8%.). This is mainly due to the fact that V_1 is much lower than the maximum potential of phases 2 and 3, as we will see in part *C*. Note that oscillations are due to coupling between the lines and capacity *Ct*.

In our case, the maximum admissible input voltage of the transformer should be greater than 10^6 V. This simplest model for the grounding system could have been reasonably adapted to carry out this insulation coordination study.

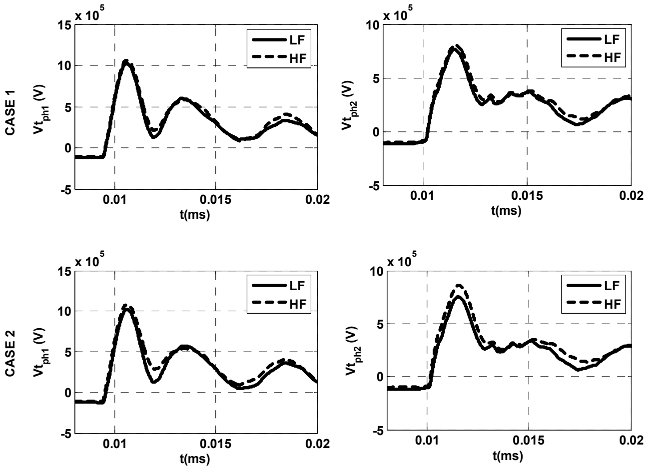

Fig. 9. Vt when Tower₁ is struck by lightning, case 1 (first line) and 2 (second line).

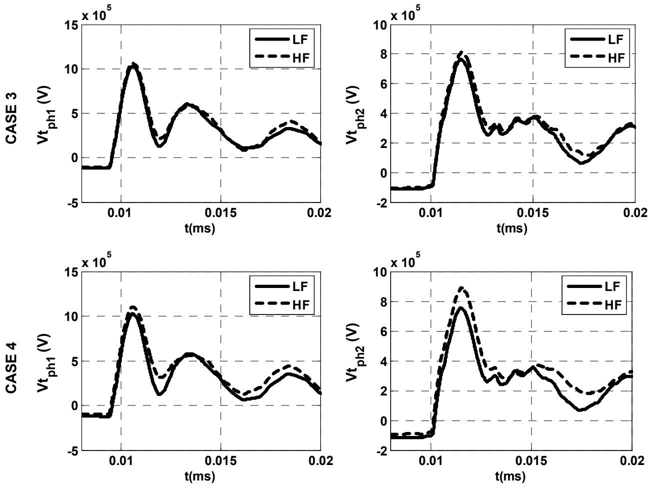

Fig. 10. Vt when Tower₁ is struck by lightning, cases 3 (first line) and 4 (second line).

D. GROUNDING RISE POTENTIAL OF THE GRID

We present in the following figures, for the four cases we are analyzing, the scalar potential of terminals 1 and 2, when modeling the grid either with one resistor only ('LF') and with the Electromagnetic model ('HF').

When Tower₁ is struck, a part of the lightning current is circulating in the shield wire and terminal 1. As a consequence, V_2 and V_1 increase, which may result in EMC problems.

In this case, the values of V_1 and V_2 computed with the two approaches (HF and LF) are quite different. With the LF approach, neglecting the inductive behavior of the grid leads to underestimate fast transients values of V_2 (cf. Fig. 7). Concerning V_1, it is overestimated with LF model because we do not take into account the fact that high frequency transients on terminal 2 are not completely transmitted to terminal 1 (cf. Fig. 8).

As a conclusion, for EMC studies corresponding to grounding terminals voltages, it might be important – in general – to take into account the high frequency behavior of the grounding grid.

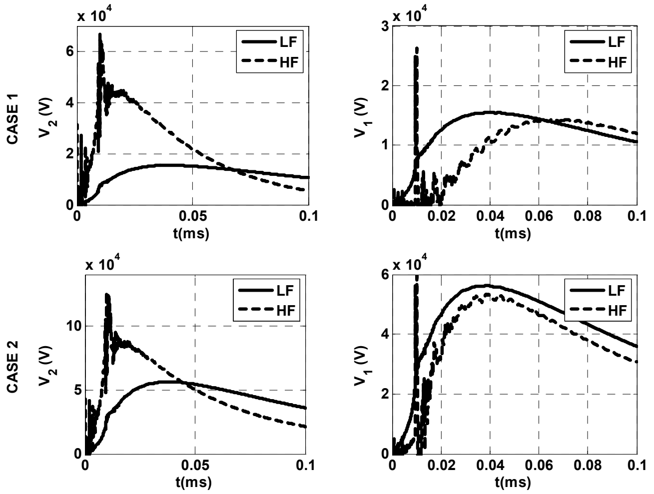

Fig. 11. Grounding rise potential of terminals 1 (V_1) and 2 (V_2) when Tower₁ is struck by lightning, case 1 (first line) and 2 (second line).

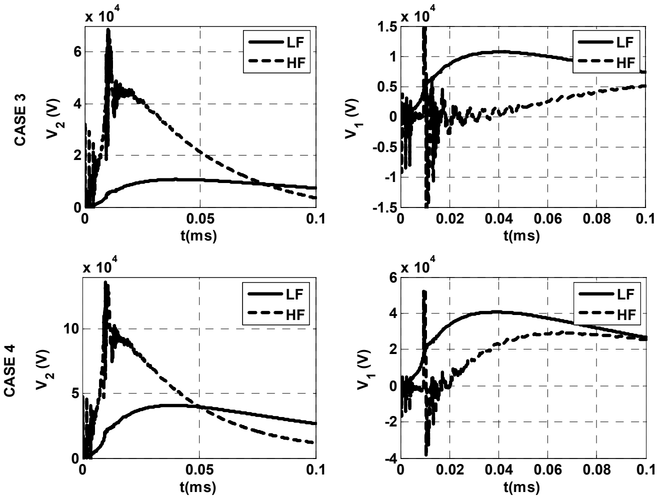

Fig. 12. Grounding rise potential of terminals 1 (V_1) and 2 (V_2) when Tower₁ is struck by lightning, cases 3 (first line) and 4 (second line).

IV. CONCLUSIONS

When studying transients in power systems, the choice of the appropriate models for each part of the network and the substation is a critical step. For grounding grids, several approaches are proposed, from the simplest, which is from a theory point of view accurate only for low frequencies, to the most complex and accurate. The choice of one particular model is not straightforward and should be the best compromise between accuracy and complexity. To evaluate the inaccuracies due to the use of the simplest model, we have chosen two approaches:

- the simplest , which consists indeed of a static resistor;
- one of the most accurate: the Electromagnetic model.

On an insulation coordination point of view, we have shown that for the cases considered, the choice of the model of the grounding grid does not influence in a significant way the computed values for the fast front overvoltage stressing the transformer.

When computing the potential of two points of a grid of a substation in the vicinity of a tower struck by lightning, we have shown instead that using the simplest model leads:

- to underestimate the potential rise of a point of a large grounding grid connected to a shield wire conducting a lightning current; this is due to the neglected inductive behavior of the grid;
- to overestimate the potential rise of a point of a large grounding grid which is not directly connected to a current source; this is due to the poor coupling between two distant points of the grid in high frequency.

These results point out the necessity to model accurately the high frequency behavior of the grounding grid when carrying out EMC studies, for which the ground potential rise of a grid is of concern.

To conclude, the choice of a very simple or a more accurate model for the grounding grid of a substation when computing lightning consequences depends on the type of study: the high frequency behavior of the grid should – in general – be taken into account if the potential of the grounding system are the variables of interest (as for some EMC studies).

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VI. BIOGRAPHIES

Xavier Legrand was born in France, in 1980, and received the M.S.degree in electrical engineering from Institut National des Sciences Appliquées de Lyon, France, in 2004. He is currently working towards the Ph.D. degree in Research and Development Section of EDF, with the AMPERE Laboratory at Lyon. His research interests include effects of lightning on aerial and underground transmission lines, grounding systems of lines and substations, and numerical computing of transients in power systems.

Alain Xémard was born in France on December 20, 1961. He graduated from the National Institute of Applied Sciences in Lyon, France, with an engineering degree in electrical engineering in 1985. His research interests include insulation coordination, and development of tools for electromagnetic transient calculation. He has been working at the Research Division of EDF since 1992. He is convener of the CIGRE WG C4 301 dealing with insulation coordination.

Philippe Auriol was born in Beziers, France, in 1947. He received the Engineer degree in Electrical Engineering from the Institute National Polytechnique de Grenoble in 1970, and the Ph. D. degree in electrical engineering from the University of Lyon, France, in 1977. Joining the Ecole Centrale de Lyon in 1971, he has been full Professor since 1981, and is currently Head of the Electrical Engineering Department of the Ecole Centrale de Lyon. His research activities in the midst of the AMPERE Laboratory (CNRS unit n°5005) include power network transients and high voltage equipments, lightning phenomena and EMC.Prof. Auriol is a Senior Member of French SEE, and Distinguished Member of the CIGRE.

Carlo Alberto Nucci was born in Bologna, Italy, in 1956. Degree with honors in Electrical engineering in 1982 from the University of Bologna. Researcher in the Power Electrical Engineering Institute in 1983. Associate professor in the same University in 1992, full professor, chair of Power Systems, in 2000. He is author or co-author of more than 200 scientific papers published on reviewed journals or presented at international conferences. He is member of the IEEE Working Group 'Lightning performance of Distribution lines'; in CIGRE he serves as chairman of the Study Committee C4 ‘System Technical performance' and is member of CIGRE Working group C.401 'Lightning', of which he is also convener. He is Fellow of the IEEE and of the IET. His research interests concern power systems transients and dynamics, with particular reference to lightning impact on power lines, system restoration after black-out and distributed generation. He is the chair of International Steering Committee of the IEEE PowerTech and of the IEEE PES Italian Chapter PE31 in Region 8.

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