HV Substation Overvoltage Computation Taking into Account Frequency Dependent Transients on the Substation Grounding System

S. Sadovic, R. Gacanovic, M. Rascic

Abstract-This paper describes methodology for the computation of the electromagnetic transients in the high voltage substations, taking into account transients on the substation grounding system. Simulation technology is based on the system decomposition. Interconnections between different subsystems are done in each time step using Thevenin equivalents. Frequency dependent impedance of grounding conductors is represented by the parallel combination of resistance-inductance branches, to enable simulation in the time domain. Lightning overvoltage computation is performed for one particular 123 kV high voltage substation.

Keywords: Electromagnetic transients, Frequency dependent, System decomposition, Overvoltages, Grounding, Lightning, Arrester, Protective gap.

I. Introduction

In the computation of the electromagnetic transients in the high voltage substations, transients on the substation grounding system are usually neglected. Taking into account that the high frequency transients generated by the lightning strokes or by the switching operations can produce substantial voltage drops on the grounding conductors, this approximation can sometimes lead to the wrong conclusions regarding overvoltage protection of high voltage substations.

Electromagnetic transients on the grounding conductors are frequency dependent and it is usually very difficult to represent this phenomenon in the standard time domain electromagnetic transients simulations. In this paper, frequency dependent impedance of the grounding conductors is represented by the parallel combination of several resistance-inductance branches, which enables simulation in the time domain. During the computation, transients on the grounding system are separated from that on the other substation elements (phase conductors, equipment, lightning protection system). Interconnection between different subsystems is done in each time step using Thevenin equivalents. This separation enables organization of a very efficient computational procedure.

Introduction of electromagnetic transients on the grounding system in the computation of overvolatges in HV substation is very important in the determination of the real electrical stresses on the substation equipment. Proper functioning of the substation protection, control and communication systems is also related to the level of overvoltages on the substation grounding system. Corrective measures can be undertaken using results obtained by the proposed calculation technology.

II. SUBSTATION GROUNDING SYSTEM MODEL

The substation grounding system can be composed of the horizontal conductors and vertical rods. A phase-domain transmission line model is used in the representation of the grounding conductors [1]. Grounding conductors are subdivided into a number of short segments. The propagation model for each grounding conductor segment is similar to that described in [2]. The difference is that each segment consists of the two *ideal propagation* sections, while the block representing losses and internal flux is inserted in the middle of the segment. An equivalent circuit used for the representation of one grounding conductor segment is given in Fig. 1.

In Fig. 1, Z_g represents the conductor resistance and the conductor inductance, modified for the fraction of the inductance used for the definition of the ideal propagation section surge impedance. This impedance is frequency dependent. The surge impedance Z corresponds to the *ideal propagation* section, which is defined by the capacitance of the conductor and the conductor inductance determined at a very high frequency.

The conductor shunt conductance g is placed at the ends of the impedance Z_g. Determination of the grounding conductor parameters is given in Appendix (for horizontal conductor).

Transients on the *ideal propagation* sections are computed using the lattice diagram method, which is in the considered representation very easily implemented.

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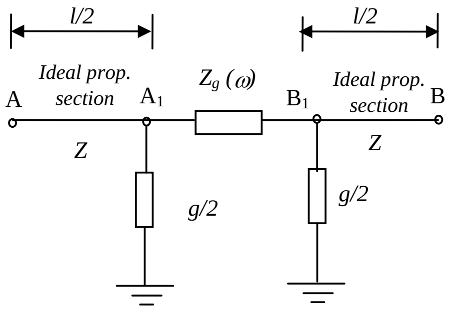

Fig. 1 - Grounding conductor segment

According to Fig. 2, we can define following voltage traveling waves:

U_l - left-hand side traveling wave (from A to A_1)

U_r - right-hand side traveling wave (from B to B_1)

U_l^* - modified left-hand side traveling wave (from B_1 to B)

U_r^* - modified right-hand side traveling wave (from A_1 to A)

At the nodes connecting the segment's ideal propagation sections (nodes A and B), there is no wave reflection because of the same surge impedance. Voltages at these nodes are simple additions of the modified left-hand and right-hand side voltage waves arriving at these nodes, i.e.,

$$U_A = U_l^{*(i-1)} + U_r^{*i} \tag{1}$$

$$U_B = U_l^{*i} + U_r^{*(i-1)} \tag{2}$$

The impedance *Zg* can be approximated by the parallel combination of R-L branches (Fig. 3). In Fig. 3, R_0 represents conductor DC resistance, while R_{Pi} and L_{Pi} correspond to the resistance and inductance of the branch *i*.

For the determination of the equivalent resistance and inductance we use the following equation:

$$(Z_g(\omega_i) - R_0)^{-1} = \sum_{i=1}^{n} (R_{Pi} + j\omega_i L_{Pi})^{-1} \tag{3}$$

n - number of the parallel branches used in the approximation of Z_g

ω_i - frequency sample

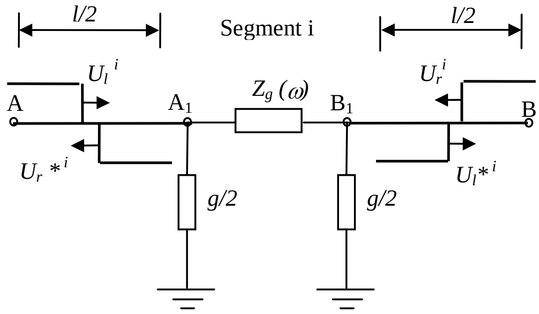

Fig. 2 - Traveling waves on the conductor segment

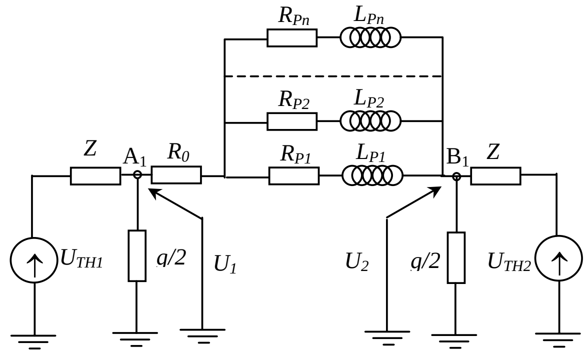

Fig. 3 - Equivalent circuit for determination of the voltages in middle of the segment

To solve equation (3), the Gauss-Seidel iteration method is used. It is enough to use three to five parallel branches (three to five frequency samples) in the approximation of the frequency dependant impedance Z_g

For the determination of the voltages in the middle of the segments, the equivalent circuit given in Fig. 3 is used. Left-hand and right-hand propagation sections are considered as open ended and reduced to the Thevenin equivalents, determined by the surge impedance Z and the Thevenin voltages:

$$\begin{aligned} U_{TH1} &= 2U_l \\ U_{TH2} &= 2U_r \end{aligned} \tag{4}$$

Inductance of the parallel branches L_{Pi} is represented by the equivalent resistance connected in series with voltage source, which represents a past history terms [3]. An equivalent circuit given in Fig. 3 is solved in each time step. It is important to note that if we divide the grounding conductor into segments having the same length, then the circuit given in Fig. 3 is same for all the segments. Only Thevenin equivalent voltages and voltage sources related to the inductance approximation are different.

When the voltages for the middle of the segment are known, the modified voltage traveling waves are determined according to the following expressions:

$$\begin{aligned} U_r^* &= U_1 - U_l \\ U_l^* &= U_2 - U_r \end{aligned} \tag{5}$$

III. INTERCONNECTION OF THE GROUNDING AND SUBSTATION SUBSYSTEMS

A substation subsystem consists of the lightning protection system and of the system, which corresponds to the substation equipment, bus bars and connecting conductors. A substation subsystem is represented by the propagation elements, resistive equivalent branches connected in series with the past history voltage sources, spark gaps, surge arresters, voltage and current sources [3]. According to the standard electromagnetic transients simulation technology in time domain, substation subsystem can be described by the following equation (grounding subsystem excluded):

$$[Y][U]=[I] \qquad (6)$$

[Y] - equivalent conductance matrix
[U] - voltage vector
[I] - current vector which includes voltage and current sources and the sources related to the past history terms

Interconnection of the substation and grounding subsystems is done in each time step. Taking into account that the grounding subsystem nodes, which are used for the interconnection have only *ideal propagation* sections connected to them, equivalent of the substation grounding system can be represented by the set of uncoupled equivalent surge impedance Z_E and the corresponding voltage sources U_E (Fig. 4). Equivalent surge impedance is equal to the parallel combination of the surge impedance of ideal propagation sections, while the equivalent voltage sources are Thevenin voltages.

If we include equivalent of the grounding subsystem in the substation subsystem, the following equation is obtained:

$$[Y]^*[U]=[I]^* \qquad (7)$$

[Y]* - equivalent conductance matrix which includes equivalent of the grounding subsystem
[U] - voltage vector
[I]* - vector of the currents, which includes sources related to the grounding subsystem

Algorithm used for the interconnection of the substation and grounding subsystems is:

- Electromagnetic transients on the grounding subsystem are performed in one time step. Thevenin equivalent voltage sources U_E are determined.
- Substation current vector is updated to take into account grounding subsystem voltage sources.
- Equation (7) is solved. Substation node voltages, including voltages of the interconnection nodes are obtained.
- Grounding subsystem reflected waves are determined, which enables simulation on the grounding subsystem in the next time step.

IV. MODEL VERIFICATION

In order to verify the proposed substation grounding system model, comparison between calculation and the experimental results is done. For this purpose, results of the experimental work done by EdF - Electricite de France are used [4].

Comparison is done for the 15 m long horizontal cooper conductor, buried at 0,8 m (conductor cross section was 116 mm^2). Soil specific resistivity was 70 Ωm and relative dielectric constant was 15. In the simulation, grounding conductor was divided into 0,5 m long short segments. A total number of 4 parallel R-L branches are used. Simulation is done using sigma spx software (described later).

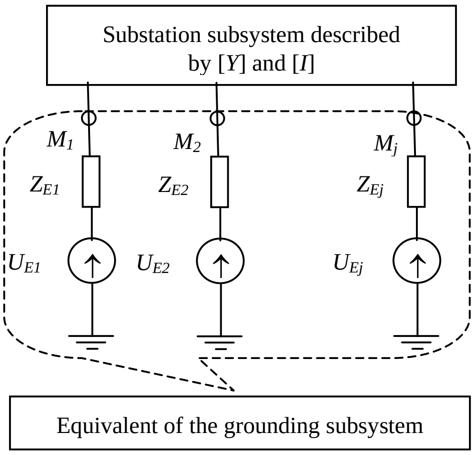

Fig. 4 – Interconnection of the substation and the grounding subsystems

Impulse current shape from the EdF experiment is digitized and used in the simulations. Impulse current shape is presented in Fig. 5.

Voltage shapes are compared for the injection point, which corresponds to grounding conductor end. Results of the simulation and from the EdF experiment are presented in Fig. 6 (Blue - sigma spx calculation / Red – EdF experiment).

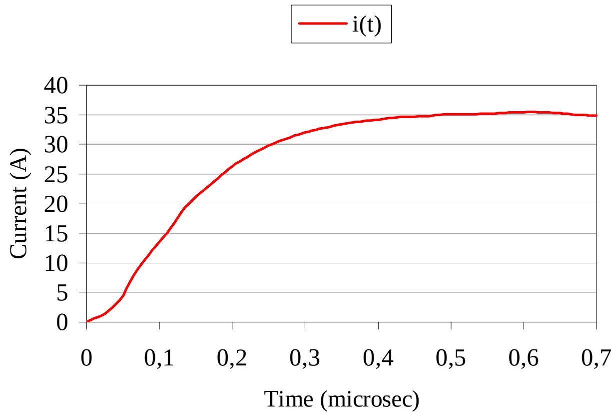

Fig. 5 - Impulse current used in the EdF experiment

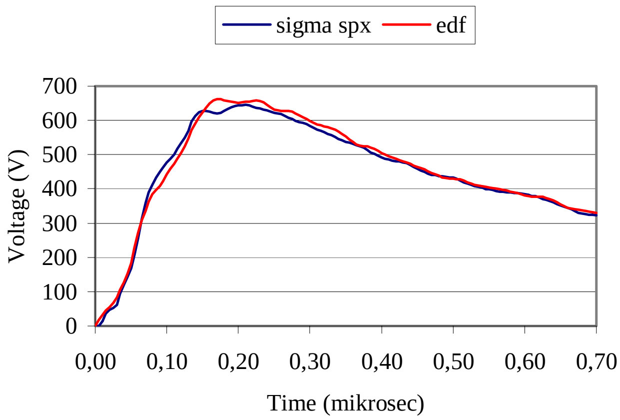

Fig. 6 - Voltage shapes at the injection point (15 m grounding conductor)

V. SIMULATION SOFTWARE

Presented model is integrated into **sigma spx** [5] software packages. This object-oriented package, which uses a full potential of the computer graphics and database management, is developed for the high voltage substations insulation coordination studies. By the introduction of the substation grounding system model, there is no need for the simplification in the computation of the substation electromagnetic transients. The new version of the software has very a powerful preprocessor for the automatic generation of the substation grounding system model.

Substation subsystem and grounding subsystem are created separately. User has to define interconnection between these two subsystems. Substation and grounding subsystems are displayed on the computer screen, with the indication of the corresponding interconnections (Fig. 7).

Software automatically determines all grounding conductor segment data (R-L branches data, ideal propagation data and shunt conductance).

VI. CASE STUDY

In order to show the application of the presented computational methodology, overvoltage protection of one 123 kV high voltage substation is considered. Substation grounding and lightning protection systems are also modeled. The substation diagram, along with some study data is given in Figure 8. Power transformer (PT) is represented by the capacitance of 2 nF, current transformer (CT) has capacitance of 0,4 nF. Station type surge arrester inside substation (SSA) is IEC Class III arrester, which has rated voltage equal to 96 kV. Arrester lead lengths are represented by an inductance of 6 μH. At the substation entrance, IEC Class II polymer housed surge is installed on the substation entrance structure (ESA). This arrester has also rated voltage equal to 96 kV. A substation grounding system is made as a grounding grid having a step of 6 m. A lightning protection system, consisting of the two entrance structures and the two ground wires is also represented in all simulations.

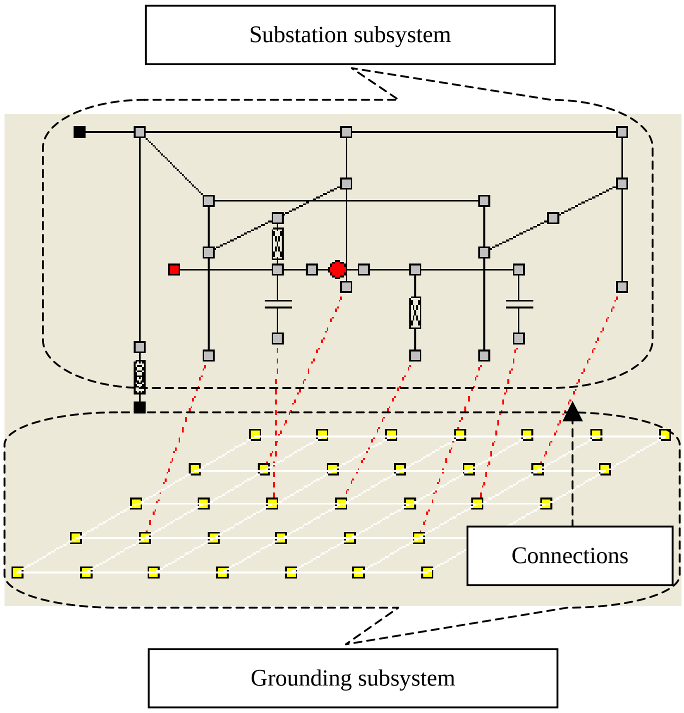

Fig. 7 - Sigma spx software display for one particular case study

The first simulation case corresponds to the situation in which line entrance breaker is in the closed position. Overvoltage surge, having amplitude 750 kV, steepness 1000 kV/μs and tail time of 75 μs arrives into a substation along the phase conductor, which has surge impedance equal 450 Ω. Incoming surge front and tail are linear.

Overvoltage shapes on the power transformer (PT) and on the current transformer (CT) are given in Figure 9.

Fig. 10 presents overvoltage shapes on the grounding system for the nodes B and C (SSA and PT connection nodes).

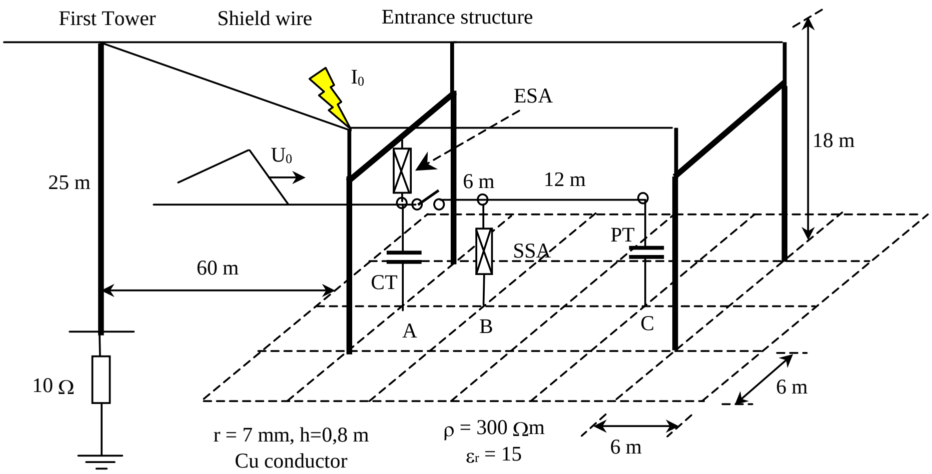

Fig. 8 - 123 kV High voltage substation

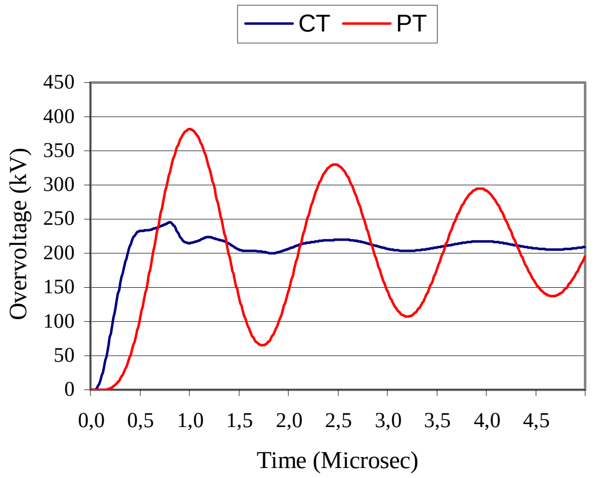

Fig. 9 - Overvoltage shapes on the current transformer and on the power transformer

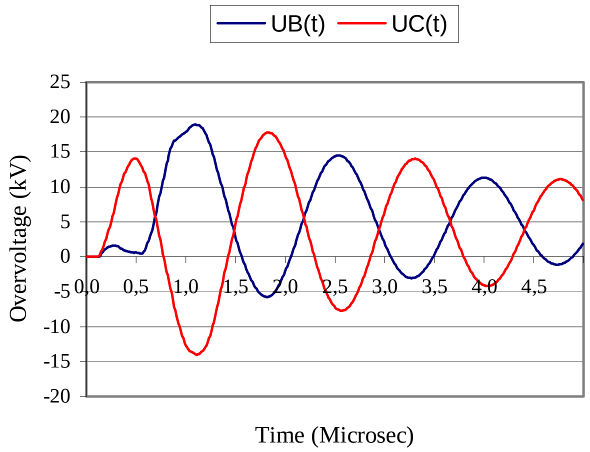

Fig. 10 - Overvoltage shapes at the SSA and PT grounding nodes (Nodes B and C)

The second simulation case is related to the lightning stroke having amplitude 100 kA and front time of 4 μs, hitting lightning protection system (as indicated in Fig. 8). Entrance breaker was in the open position. Overvoltage shape at the grounding side of the current transformer (Point A in Fig. 8) is presented in Fig. 11.

VII. CONCLUSIONS

1. Introduction of electromagnetic transients on the grounding system in the computation of overvolatges in the HV substation is very important in the determination of the real electrical stress on the substation equipment. Proper functioning of the substation protection, control and communication systems is also related to the level of overvoltages on the substation grounding system. Corrective measures can be undertaken using results obtained by the proposed calculation technology.

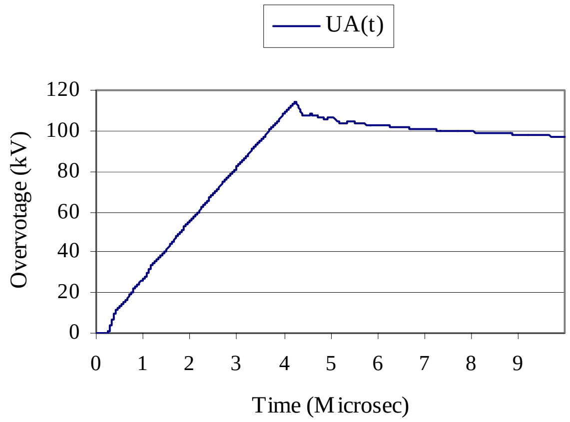

Fig. 11 - Overvoltage shapes at the current transformer grounding side (Node A)Stroke hits lightning protection system

2. To simulate frequency dependent transients on the substation grounding system in the time domain, frequency dependent impedance of the grounding conductor can be represented by the parallel combination of resistance-inductance branches.
3. Introduction of two *ideal propagation* sections into each segment of the grounding conductor gives the possibility for the treatment of each segment separately.
4. The computational decomposition of the system into two different subsystems and use of Thevenin equivalents for their interconnections enable the organization of a very efficient computational procedure.

VIII. APPENDIX

Surge impedance and speed of propagation of the ideal propagation section are:

$$Z = \sqrt{\frac{L_{hf}}{C}} \qquad v = \frac{1}{\sqrt{L_{hf} C}} \tag{A.1}$$

Z – surge impedance (Ω)
v – speed of propagation (m/s)
L_{hf} – inductance at very high frequency (H)

Capacitance of the horizontal conductor [6]:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\frac{2l}{\sqrt{2hr}} - 1} \tag{A.2}$$

C – capacitance of horizontal conductor (F/m)
l – conductor length (m)
r – conductor radius (m)
h – depth of burial (m)
ε_0 – permittivity of free space (F/m)
ε_r – relative dielectric constant

Conductor internal impedance is determined using following formula [7]:

$$Z_i = \frac{\rho m}{2\pi r}\coth(0,777mr) + \frac{0,356\rho}{\pi r^2}$$
$$m = \sqrt{\frac{j\omega\mu}{\rho}} \qquad \text{(A.3)}$$

Z_i – conductor internal impedance (Ω/m)
ω - angular frequency (rad/s)
ρ - conductor resistivity (Ωm)
μ– permeability (H/m)

Earth-return path impedance is determined using an approximate expression [7]:

$$Z_r = \frac{j\omega\mu}{2\pi}(-\ln\frac{\gamma mr}{2} + \frac{1}{2} - \frac{4mh}{3} \qquad \text{(A.4)}$$

Z_r – Earth-return path impedance (Ω/m)
γ - Euler's constant (γ =0,57722)

Frequency dependent impedance, which is placed in the middle of the conductor segment, is given by:

$$Z_g(\omega) = Z_i + Z_r - j\omega L_{hf} \qquad \text{(A.5)}$$

L_{hf} - inductance at a very high frequency (H)
L_{hf} is computed from $(Z_i + Z_r)$ at frequency of 1 MHz.

Shunt conductance is determined using an approximate expression given in [8]:

$$g = \frac{\pi}{\rho \ln \frac{H}{\sqrt{2rh}}} \qquad \text{(A.6)}$$

H is radius of the equivalent cylinder, while for the computation of electromagnetic transients generated by lightning strokes in [8] recommended is to take H = 20 m. In this paper, it is taken that equivalent cylinder radius is equal to the depth of penetration:

$$H = \delta = \sqrt{\frac{2\rho}{\omega\mu}} \qquad \text{(A.7)}$$

Depth of the penetration is determined for the frequencies between 100 and 150 kHz.

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X. Biographies

S.Sadovic was born in Trebinje, Bosnia-Herzegovina in 1947. He received the Diploma engineering degree from the University of Sarajevo (B&H) and Master and Doctor of Science degrees from the University of Zagreb (Croatia) in 1973 , 1977 and 1981 respectively. Since 1973 Dr Sadovic has been with the University of Sarajevo, where he is a Professor of Electric Power Engineering. He was Dean and Vice Dean of Electrical Engineering Department of the same University. In 1993-94 he was with Electricite de France - Research and Development Department. Currently he is a consultant. His research fields include overvoltages and insulation co-ordination, power systems analysis, numerical field computations and computer applications in power engineering.

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