Sensitivity Studies for AC Railway Networks Design

Pierre FAYET, Philippe AURIOL, Guy CLERC

Abstract-- AC Railway networks design simulation tools, since these networks include moving loads, different catenary types, and some connections between line conductors may exist, implying a specific research on line models.

The results presented were obtained with a new simulation tool which was specifically build for railway networks design. This development was lead in parallel by AMPERE Laboratory and SEMALY.

This tool is composed of three modules:

- Mechanical calculations. Speed, position and mechanical power vs. time are calculated,

- Electrical calculations. Single or dual AT-feeding systems can be simulated. Contact wire to rail and rail to earth potential and currents in each conductor and at the pantograph of a train are calculated. Some other data such as power factor at the substation are also available.

- Thermal calculations. The temperature of the contact wire is calculated.

The work presented here deals with the electrical aspect and is divided into two parts. In the first part, three different line models are compared. The goal of this part is to quantify the error made on the calculated impedances, currents and voltages using one of the three models (Carson, Dubanton, Escane). In the second part, the influence of different parameters is studied in order to quantify the results sensitivity to input data variations.

Parameters such as earth resistivity, rail to earth impedance value (along the line or at the substation) and rail to earth conductance are studied. These studies were made on the 1x25 KV single power supply system. A special attention is given to the rail to earth potential calculation, which must not exceed 50 Volts. This work has also been validated with dual power supply (2x25 Autotransformers system).

Keywords: Conductivity, grounding, impedance matrix, power cables, power system simulation, rail transportation, simulation software.

I. INTRODUCTION

THIS paper presents sensitivity studies made with a simulation tool for designing railway networks. This tool is the result of a specific home development and is composed of three modules (Fig. 1).

P. Fayet is PhD. student at SEMALY and AMPERE laboratory (UMR5005) Ecole Centrale de Lyon / Lyon I University, France.

Ph. Auriol is professor at Ecole Centrale de Lyon

G. Clerc (43B1) is professor at Université de Lyon, Lyon, F-69622, France ; université Lyon 1, Lyon, F-69622, France ; CNRS, UMR5005, CEGELY, Villeurbanne, F-69622, France

SEMALY and Egis Rail are EGIS Group companies.

Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4-7, 2007

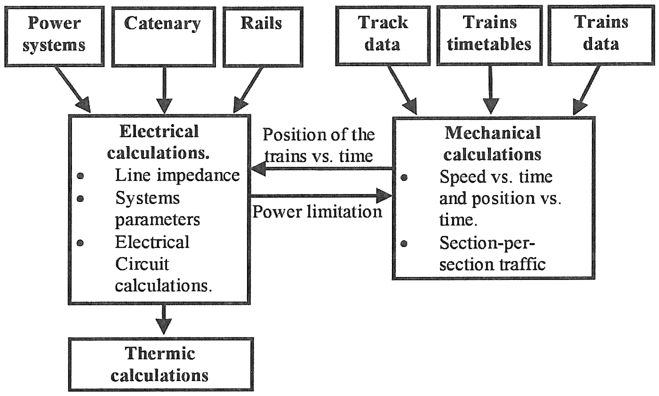


Fig. 1. Functional scheme of the program.

These three modules interact with each other through an SQL database, making data exchange easier between the different modules and allowing the use of data from external simulation softwares.

The work presented in this paper deals with the electrical aspect. A comparison between three different line models is presented (Carson, Dubanton, Escane), in order to quantify the results sensitivity to input data variations. The studied parameters are: earth resistivity, rail to earth impedance value (along the line or at the substation) and rail to earth conductance. These studies were made on the single power supply system. A special attention is given to the rail to earth potential calculation, which must not exceed 50 Volts [1]. Notice that this work has been extended to dual power supply.

II. CIRCUIT DESCRIPTION AND LINE IMPEDANCES CALCULATION

A. Circuit description

The circuit studied in this paper is represented on Fig. 2.

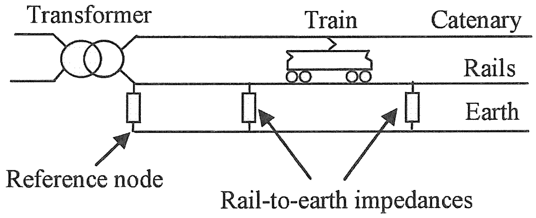


Fig. 2. Electrical circuit used in the studies.

Rail to earth impedances represent the links between the rail and the earth (ground bounds or signalization). These links are regularly spaced. Leakages between rails and earth may also be taken into account for some specific studies. Most of the time, we consider the ballast as an insulating material.

The rail to earth impedance values are set by user.

B. *Line Impedances Calculations*

The French National Railways "classical" catenary is taken as example. This catenary is composed of three overhead conductors. (Fig. 3).

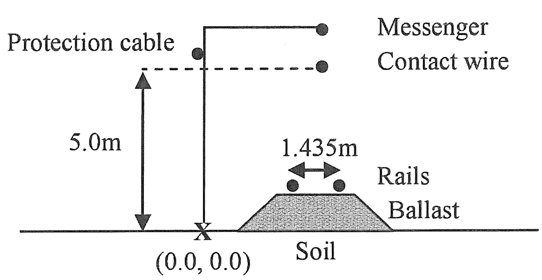


Fig. 3. Conductor cross-section of the French National Railways catenary.

The data of the conductors are given in Table 1. The coordinate origin is taken at the foot of the post.

TABLE I
OVERHEAD CONDUCTORS DATA

Name	Position (x,y),(m)	Diameter (mm)	Material	Resistivity (Ω.m)
Messenger Wire	(3.3,6.55)	10.50	Stranded tin bronze	1.9356e-8
Contact wire	(3.3,5.0)	12.24	Hard drawn copper	3.5120e-8
Protection Cable	(0.0,5.85)	10.89	Aluminium/ steel	4.5639e-8

Three different line models are compared in this paper.

Two of these models (Carson, Dubanton) represent the line as overhead wires with ground return [2] [3] [4] in which the complex depth of earth return is taken into account. In the third model (Escane) [5], the earth is represented as a single conductor. More details about the line models used in these studies are given in VI.

For each line model, the rail self impedance is assumed to be a constant complex value. [6], [7]:

$$Zrail = 0.1e\text{-}3 + j.\omega.0.37e\text{-}6\ \Omega/km.$$

The rails positions are (2.58, 0.40) and (4.02, 0.40).

The rails are connected to the earth by a resistor with 1-km spacing and are considered to be in parallel.

III. COMPARISON BETWEEN LINE MODELS

A. *Impedance calculations*

The graph below shows the results of impedances calculations at harmonic frequencies for the three mentioned line models. The contact wire is taken as example. Figure 6 shows the variation of the internal reactance of the contact wire versus frequency according to Escane's line model. This model differs from the others, and no straight comparison with Carson or Dubanton can be done. As the ground is modelled as a separate conductor, the effects of the image conductors on the conductors impedances are not considered and no correction is made to take the ground into account like in Carson's or Dubanton's model. The real part of the conductors series impedance is considered as a constant, frequency-independent value. This model is accurate enough at low frequencies, as the railway network is modelled as a succession of static states versus time.

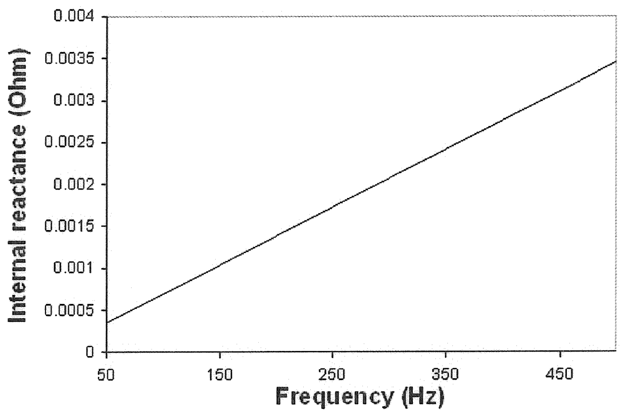


Fig. 4. Internal reactance of the contact wire vs. frequency.

B. *Effects on the calculated line voltages*

The catenary voltages obtained with the different line models are presented on fig. 5. The earth resistivity in this example is set to 1000 $\Omega.m^{-1}$. The active power absorbed by the train is 8 MW ($\cos\varphi = 0.8$).

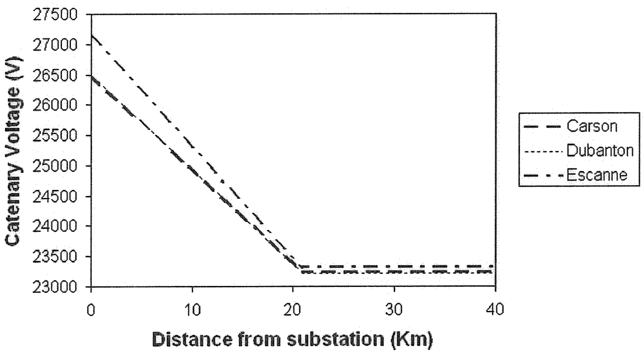


Fig.5. Catenary voltage along the line for different line models.

The voltage difference at the substation between Escane's and Dubanton's models is 624 V. At the train, this difference is 90 V. If we consider 25000V as a voltage reference, the maximal error between the models is 2.5% at the substation and 0.4% at the train.

The different line models give similar results. For the following sensitivity studies, Escane's line model is chosen because this model represents the soil as a separate conductor. The simplified form of the equations make the computations easier (see Appendix) and the connections between the rails and the earth can be accurately modeled. The current driven by the earth can be calculated. The typical shape of this current is represented on the figure below (soil resistivity = 1000 Ω.m).

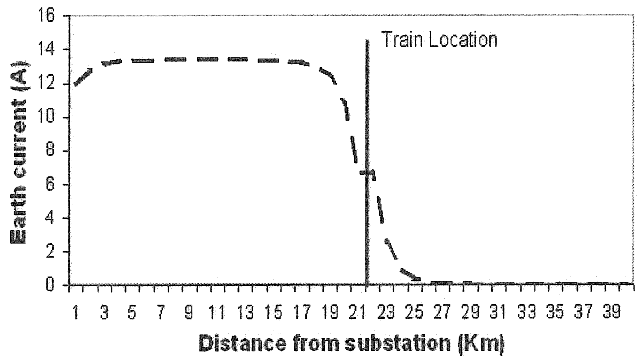


Fig.6. Shape of the earth current.

The repartition of the traction return current between the rails and the earth was also studied. The obtained values correspond to the values used in practice and given in the literature [8].

IV. Sensitivity Studies

A. Influence of the soil resistivity

The simulation tool gives a representation of the distribution of the return traction current between the rails and the earth [9]. This repartition may be influenced by various parameters such as soil resistivity. The earth resistivity typical value is usually 1000 Ω.m. In the following study, the rail to earth impedance values are set to 5 Ω. The rail to earth impedance value at the substation is set to 1 Ω. The active power absorbed by the train is 8 MW and the power factor of the train is 0.8.

Table 2 shows the voltages at different nodes of the circuit versus earth resistivity. For this study, a huge range of earth resistivities was taken. (from 40 Ω.m (clay) to 100000 Ω.m (ice))

TABLE II
INFLUENCE OF EARTH RESISTIVITY

Soil resistivity (Ohm.m)	Catenary–Rails voltage at the substation (V)	Rail to earth voltage at the substation (V)	Catenary–Rails voltage at the train (V)	Rail to earth voltage at the train (V)
40	27132	71.4	23749	91.7
100	27130	58.9	23629	83.5
150	27128	49.6	23565	76.2
250	27126	36.6	23505	64.9
1000	27124	11.6	23463	37.5
2000	27124	6.3	23464	29.2
3000	27124	4.3	23465	26.0
15000	27124	0.9	23467	19.0
25000	27124	0.5	23467	18.2
100000	27124	0.1	23467	17.2

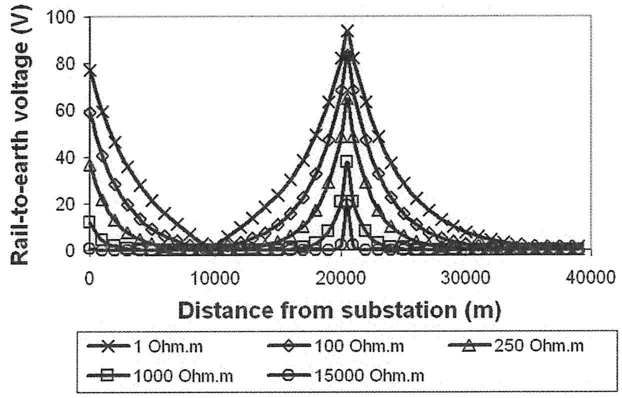


Fig. 7. Rail to earth voltage along the line for different earth resistivities.

Decreasing the earth resistivity increases the part of the return current driven by the earth itself and also the rail to earth voltage values. If the earth resistivity value is set to 40 Ω.m, the current driven by the earth has the following form:

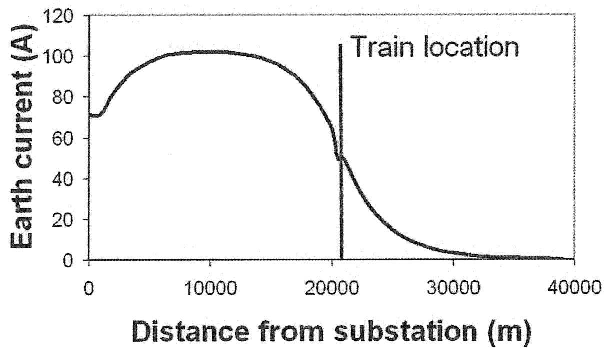


Fig.8. Current driven by the earth with ρ=40 Ω.m.

Fig. 8 shows that the current driven by the earth remains constant in the 8000-12000m area. It means that the current flowing between the rails and the earth between these points are close to zero. Consequently, the rail to earth voltage drops to low values. This is also true for higher earth resistivity values.

B. Influence of the rail to earth impedance value

The rail to earth impedance value at the substation is set to 1 Ω. The soil resistivity is set to 1000 Ω.m. The high voltage power network influence is neglected. The rail to earth resistance value commonly taken as reference is 5 Ω.

TABLE III
INFLUENCE OF THE RAIL TO EARTH IMPEDANCE VALUE

Rail to earth impedance value (Ohm)	Catenary – Rails voltage at the substation (V)	Rail to earth Voltage at the substation (V)	Catenary – Rails voltage at the train (V)	Rail to earth voltage at the train (V)
0.5	27124	11.3	23463	20.0
1	27124	11.4	23463	22.6
2	27124	11.6	23463	27.1
5	27124	11.9	23463	37.5
10	27124	12.1	23463	50.3

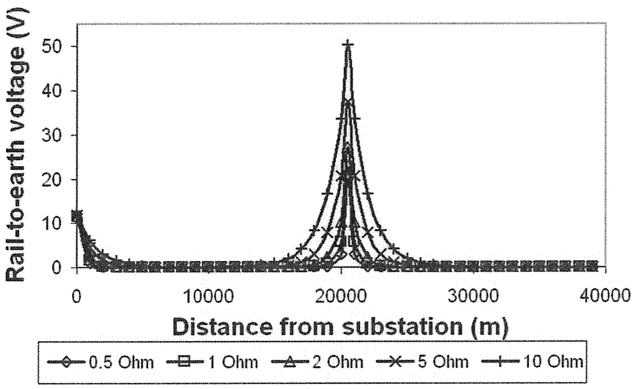


Fig.9. Rail to earth voltage along the line vs. rail to earth impedance value.

A decrease of the rail to earth impedance value along the track decreases the rail to earth voltages along the track.

The rail to earth resistor value at the substation is independent from the others, that is why the rail to earth voltage at the substation remains the same in each case. The rail to earth impedance value has a significant influence on the rail to earth voltage.

C. Influence of the rail-to-earth impedance value at the substation

The rail to earth impedance values along the line are set to 5 Ω. The soil resistivity is set to 1000 Ω.m.

TABLE IV

INFLUENCE OF THE RAIL-TO-EARTH IMPEDANCE VALUE AT THE SUBSTATION

Rail-to-Earth impedance value at the substation (Ω)	Catenary – Rails voltage at the substation (V)	Rails-to-earth Voltage at the substation (V)	Catenary – Rails voltage at the train (V)	Rails-to-earth voltage at the train (V)
0.5	27124	6.3	23463	37.5
1	27124	11.9	23463	37.5
2	27124	21.4	23463	37.5
5	27124	41.3	23463	37.5
10	27124	59.9	23463	37.5

Changing the value of the rail-to-earth resistor at the substation has significant effects on the rail-to-earth voltage at the substation, but not on the rail-to-earth voltages on the whole line.

The voltage around the grounding point of the substation is also a function of the rail-to earth impedance value.

D. Influence of the rail to earth conductance

All the former sensitivity studies were made considering rails laying on an insulating structure. In fact, a rail to earth conductance must be taken into account while some pollution can establish a connection between them.

Rail to earth conductance (G) is given as a metric value, for a single track (two rails). In our tool, it is modeled as distributed impedances.

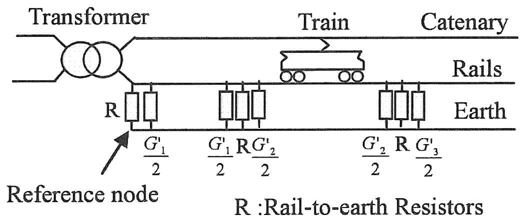


Fig. 10: Electrical circuit used for the rail to Earth conductance study.

All the hypotheses given in III.C remain the same.

A first study was made with and without taking the rail to earth conductance into account (G=0.000001 and 0.5 S/Km)

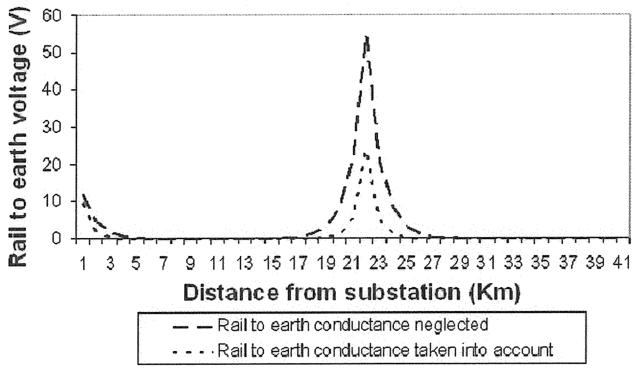


Fig.11: Rail to earth voltage along the line with and without rail to earth conductance

The maximal difference between the two curves given on Fig.11 is 31V at the train location. This corresponds to 44% of the maximal value when the rail to earth conductance is not taken into account. An explanation can be found considering the current driven by the earth.

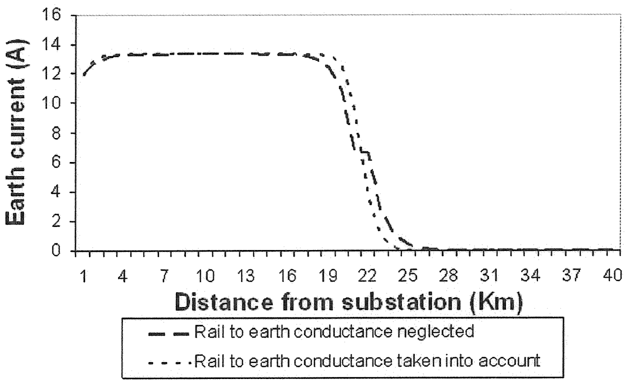


Fig.12: Current driven by the earth with and without rail to earth conductance

We can see that the current distribution in the area of the train changes when the rail to earth conductance is taken into account. In fact, the equivalent rail to earth resistances along the line become lower. The study presented in III.C. shows that rail to earth voltage along the line decreases for low rail to earth resistance values. In the example above, for a 1-Km spacing and a 0.5 S/Km value, the equivalent resistance is 1.43 Ω according to the circuit given on Fig. 14.

Table V presents the results obtained with different values of parameter G. [10]

TABLE V
INFLUENCE OF THE RAIL TO EARTH CONDUCTANCE

Rail to earth conductance value (S/km)	Catenary – Rails voltage at the substation (V)	Rail to earth Voltage at the substation (V)	Catenary – Rails voltage at the train (V)	Rail to earth voltage at the train (V)
0.1	27121	11.3	23351	42.3
0.5	27121	9.5	23351	23.9
1	27121	8.0	23351	16.0
1.5	27121	6.9	23351	12.2
2	27121	6.1	23351	9.9

We can see that the rail to earth conductance has a significant influence on the rail to earth voltage. Rail to earth conductance value must therefore be taken into account for accurate rail to earth calculations.

V. SENSITIVITY STUDIES SYNTHESIS

Table VI gives the differences on each voltage value (catenary-rails, rail to earth, at the load and at the substation) for each parameter varying. These differences are given in percentage as they are divided by the average value of the considered voltages on their ranges.

TABLE VI
SENSITIVITY STUDIES SYNTHESIS

	Catenary-rail voltage at the substation	Rail to earth voltage at the substation	Catenary rail voltage at the train	Rail to earth voltage at the substation
Soil resistivity (0.1, 100000 Ohm.m)	0.03 %	234 %	1.5 %	141 %
Rail to earth impedance along the line (0.1,10 Ohm)	0 %	8 %	0 %	112 %
Rail to earth impedance at the substation (0.5, 10 Ohm)	0 %	38 %	0 %	0 %
Rail to earth conductance (0.1, 2 S/Km)	0 %	61 %	0 %	155 %

VI. CONCLUSION

Three different line models were compared. This comparison shows that the error committed on the catenary to rail voltage remains acceptable. Moreover, the third model allows the user to get precise results on ground currents and on the rail to earth voltage.

Sensitivity studies were made to quantify the influence of each parameter. Both rail to earth conductance and rail-to-earth impedance values have a significant influence on the simulation results. These values must be carefully filled in as input data. Appendix

Theory elements about Carson's model are described in literature [11].

VII. APPENDIX: THEORY ELEMENTS ABOUT LINE MODELS

A. Theory elements about Dubanton's line model

The internal impedance of a conductor is given by:

$$Z_{ii} = R + jL\omega = \left(Rc\left(\frac{1}{4} + \sqrt[6]{\left(\frac{3}{4}\right)^6 + V^6} \right) + \frac{\mu_0 \omega}{2\pi} \arctan \frac{a}{1-a} \right) + j\omega \left(\frac{\mu_0}{8\pi} \frac{\frac{2\alpha^2}{(1-\alpha^2)} \ln \frac{1}{\alpha} - \frac{3\alpha - 1}{1-\alpha}}{\sqrt[6]{1+V^6}} + \frac{\mu_0}{2\pi}\left(\ln \frac{4h}{d} + \ln \sqrt{a^2 + (1+a)^2} \right) \right) \quad (9)$$

where d is the diameter of the considered conductor

$$V = \frac{d}{4\delta} \text{ with } \delta = \sqrt{\frac{\rho}{\pi\mu f}} \quad (10)$$

$$a = \frac{\delta_s}{2h} \text{ with } \delta_s = \sqrt{\frac{\rho_s}{\pi\mu f}} \quad (11)$$

For hollow conductors, $\alpha = \left(\frac{d_1}{d_2}\right)^2$ (12)

B. Theory elements about Escané's line model

In this model, the earth is represented by a rectangular resistor located under the railway track. Its dimensions and also its conductivity can be changed by the user. Thus, the depth of the return currents is under control and physical connections between the ground and any other conductor can be easily taken into account.

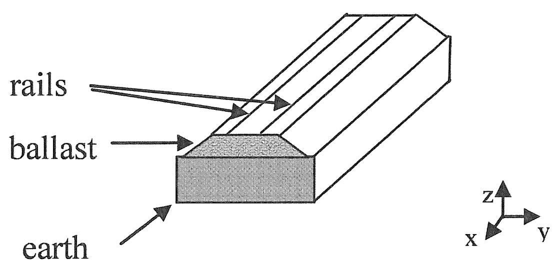


Fig. 13. Earth modelling.

The internal impedance of the conductors is given by:

$$L'_i = \frac{\mu_0}{2\pi}\left(\frac{1}{4} - \ln\frac{a_i}{R_0}\right) \qquad (13)$$

$$M'_{ij} = -\frac{\mu_0}{2\pi}\ln\frac{D_{ij}}{R_0} \qquad (14)$$

VIII. References

[1] *Railway applications – Fixed installations. Part I: Protective provisions relating to electrical safety and earthing,* European norm NF EN 50122-1.

[2] J. R. Carson, "Wave Propagation in Overhead Wires with Ground Return", Bell System Technical Journal, 5, pp.539-554, 1926.

[3] M. Aguet, J. J. Morf, *Traité d'électricité*, volume XII : *Energie électrique*. Georgi, 1981, pp.60-61.

[4] R. Cella, G. Giangaspero, A. Mariscotti, A. Montepagano, P. Pozzobon, M. Ruscelli, M. Vanti "Measurement of AT Electric Railway System Currents at Power-Supply Frequency and Validation of a Multiconductor Transmission-Line Model". IEEE Transactions on power delivery, Vol. 21, No. 3, July 2006.

[5] J. M. Escané, *Réseaux d'énergie électrique. Modélisation : lignes, câbles.* Collection de la Direction des Etudes et Recherches d'Electricité de France. (Eyrolles, 1997).

[6] R. J. Hill, D. C. Carpenter, "Determination of rail internal impedance for electric railway traction system simulation", IEE proceedings – B, vol. 138, No. 6, November 1991

[7] R. J. Hill, D.C, Carpenter, "Modelling of nonlinear rail impedance in AC traction power systems". IEEE Transactions on power delivery, Vol. 6, No. 4, October 1991.

[8] J. Alias, *La voie ferrée, techniques de construction et d'entretien*. (Eyrolles, 1984).

[9] A. Mariscotti, "Distribution of the Traction Return Current in AC and DC Electric Railway Systems". IEEE Transactions on power delivery, Vol. 18, No. 4, October 2003.

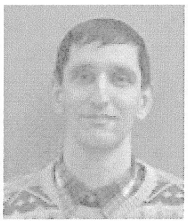
[10] A. Mariscotti, P. Pozzobon, "Determination oh the electrical parameters of Railway traction lines: Calculation, measurement and reference data". IEEE Transactions on power delivery, Vol. 19, No. 4, October 2004.

[11] H. W. Dommel. *Electro Magnetics Transient Program*. Theory book, 1986.

IX. Biographies

Pierre FAYET was born in Roanne, France, on March 9, 1981. He received the science master degree in Electrical engineering from the University Claude Bernard, Lyon I in 2004. Since October 2004, he is Ph. D. Student at SEMALY Rolling Stock and Equipment department in Lyon. His work deals with High Voltage design applied to rail transport.

Philippe AURIOL was born in Beziers, France, on March 15, 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 ECL. His research activities in the midst of the CEGELY (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.



Guy CLERC was born in Libourne, France, on November 30, 1960. He received the Engineer's degree and the PhD in electrical engineering from the Ecole Centrale de Lyon, France, in 1984 and 1989, respectively. He is Professor of Universities. He teaches electrical engineering at the "University Claude Bernard Lyon I" in France. He carried out researches on control and diagnosis of induction machines at CEGELY/UCBL.