Modeling of the behavior of power electronic equipment to grid ripple control signal

X. Yang, S. Dennetière

Abstract - The paper presents time domain simulation for power electronic device equivalent impedance computation at ripple control signal frequency.

The ripple control used by the grid is a low frequency voltage signal superimposed at MV substation. In France, the frequency used by grid ripple control systems is 175 Hz. It is well-known that some customer loads can disturb ripple control signal transmission such as capacitor bank, distributed generator, etc. These equipments can influence or disturb ripple control signal by two main ways: presence of a small impedance or an important interharmonic current injection at ripple control frequency. In transient state, even a symmetrical static converter can produce interharmonic currents.

In site studies, some customer power electronic device (Variable Speed Drive for example) is often modeled by an infinite impedance at ripple control frequency. However site measurements and simulations show that this simplification can cause in some case important error in ripple control signal level assessment.

The main purpose of this study is to define ripple control frequency equivalent impedances of typical converters used in industry. The study shows that a voltage source converter (rectifier with DC capacitor structure) gives a relative small impedance at ripple control frequency. It is recommended to integrate this impedance in performing ripple control signal propagation study by means of frequency domain software.

Keywords: Ripple control, harmonic impedance, time domain modeling, frequency domain modeling, transient voltage, voltage source converter, interharmonic, steady state analysis

I. INTRODUCTION

THIS document provides equivalent impedance simulation of some industrial power electronic devices at ripple control signal frequency. The ripple control system used by the grid is a low frequency voltage signal superimposed at MV substation. Its main roles are to change electrical tariff at customers' kWh meters according to each predefined time schedule and to control some categories of loads within customers' premises (Fig. 1). In France, the frequency used by grid ripple control systems is 175 Hz.

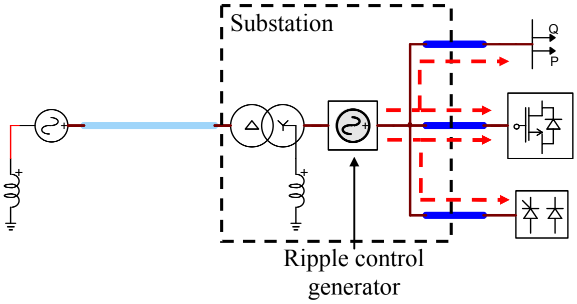

Fig. 1 Ripple control signal flow at a substation

Because more and more high power electric devices are connected to the grid, the ripple control signal may be disturbed by harmonics or inter harmonics generated by these devices. It may also be partially absorbed by some loads whose ripple control frequency impedance at 175Hz is relatively low.

Measurements from a wind mill show that at transient state (voltage fluctuation), the control system of a power electronic device can generate interharmonic current. Fig. 2 shows the RMS voltage sag measured during transient state and Fig. 3 shows the 175Hz component of the current.

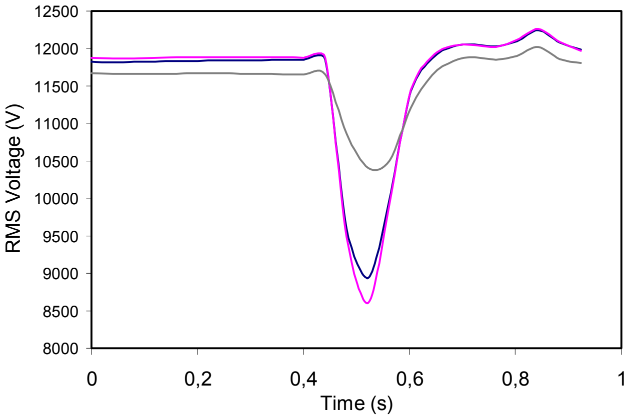

Fig. 2 RMS phase voltage sag during an asynchronous wind generator involvement

---

X. Yang and S. Dennetière are with Electricité de France, Clamart, France.
(e-mail of corresponding author: xavier.yang@edf.fr)

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

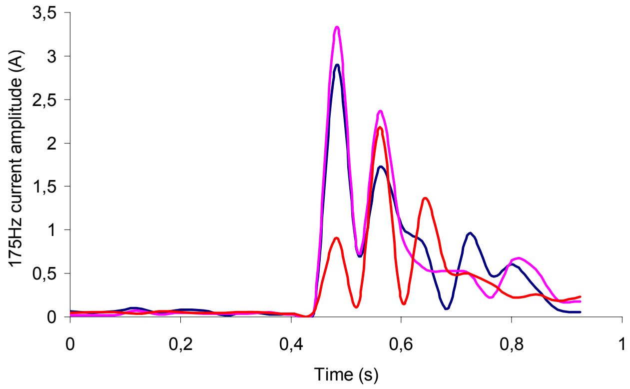

Fig. 3 Transient current at ripple control frequency with an asynchronous wind generator involvement

The field measurements show also that the practical assumption of an infinite 175 Hz impedance at the input of a power electronic device is sometimes wrong. Ripple control signal transmission may be disturbed by two key elements: a small equivalent impedance of customer appliance or an important interharmonic current injection from customer side.

Our study begins with time domain analyses by EMTP-RV on different types of power electronic devices (rectifiers with L or C filter on DC bus). An FFT analysis is performed on time-domain waveforms and the 175 Hz impedance is directly available in the GUI of EMTP. The simulations from case studies show that the 175Hz impedance at the input of a rectifier connected to a capacitive DC filter is much lower than the impedance at fundamental frequency. With the growing use of rectifiers in electrical equipment (VSD, wind generators, etc) it is becoming increasingly important for grid power quality engineers to take into account the low impedance of certain power electronic devices when performing ripple control signal study.

The results of this study provide reasonable impedance values, instead of infinite values used until now. These values should be integrated in frequency domain simulation softwares which are widely used by power quality engineers.

II. RIPPLE CONTROL IMPEDANCE COMPUTATION BY TIME DOMAIN SIMULATION

The general structure of power electronic equipment is presented in Fig. 4.

The first part of the structure is a converter connected to the AC upstream network. It can be either a conventional rectifier with diodes or thyristors or a PWM (Pulse-Width-Modulation) based converter. The DC bus is composed of a DC filter either capacitive or inductive. The third part is a converter connected to the DC side. This converter feeds a load or a generator. It can be either a conventional rectifier with diodes or thyristors or a PWM based converter.

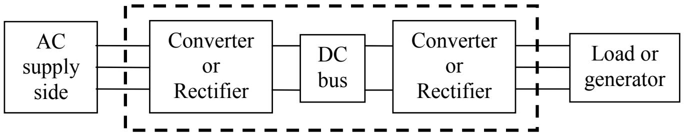

Fig. 4 General structure of power electronic equipments

The analysis of the behavior of power electronic equipments to grid ripple control signal is carried out on the 3 main types of converters structures. The following section explains in details the structure of these converters and their modeling in EMTP-RV. Recommendations given in [7] have been used.

A. *Converter structures and modeling in EMTP-RV*

1) *Type 1: rectifier with inductive filter and load*

This type of converter is often used in DC motor drives and synchronous motor drives, AC phase current is interrupted 60 + 60 degrees owing to the rectifier switching, ie, during the phase current interruption, there is no effect on ripple control signal. This converter is made up of :

- a diode or thyristor based rectifier
- a DC bus inductive filter
- a DC load : DC machine or synchronous machine connected to a current source inverter

Fig. 5 describes this structure in EMTP-RV. The DC load is modeled by a simple resistance. The idealized switching characteristic of diode has been used as recommended in [7]. RC snubbers have been added in parallel with each diode.

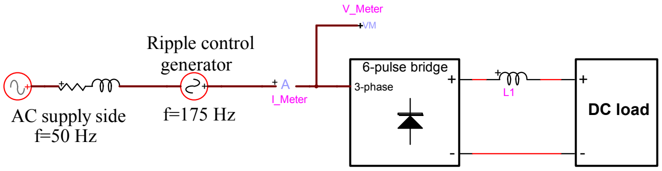

Fig. 5 Example of a Type1 converter

The grid ripple control signal is modeled by a 175 Hz voltage source. To simplify calculations, the amplitude of this source is 1% of the AC power supply amplitude.

2) *Type 2: rectifier with capacitive filter and load*

This type of converter is the most commonly used as electronic variable speed drive. The only difference between Type 1 and Type 2 converters is the DC bus filter : a capacitive DC filter is used in Type 2 converter. During the phase conduction, the DC bus capacitor offers a low impedance to ripple control signal.

Fig. 6 shows the description of a Type 2 converter in EMTP-RV.

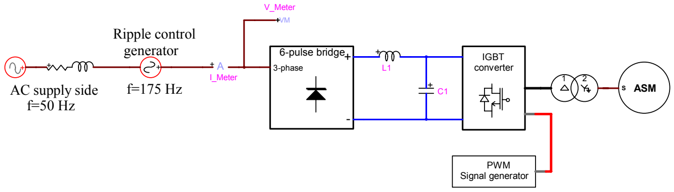

Fig. 6 Example of a Type2 converter

In this case the DC load is made up of an IGBT inverter connected to an induction machine.

The converter and the IGBT model are presented in Fig. 7. The IGBT switch model has been developed starting from the ideal controlled switch model. An ideal diode is placed in series with the switch to ensure conduction of current in only one direction. In order to provide a continuous current flowing path for an inductive load, a reversal diode is used in parallel with the switch. A snubber RC circuit is placed in parallel with the switch to complete the IGBT representation.

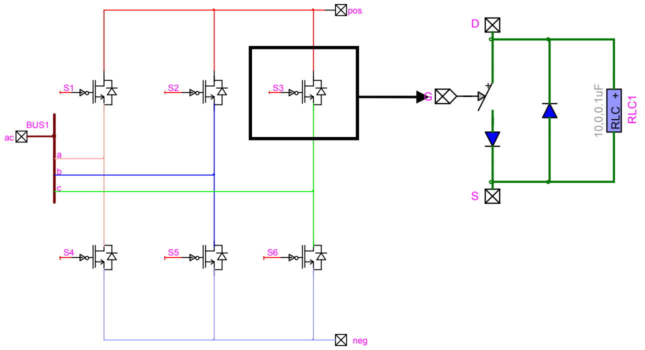

Fig. 7 An IGBT model in EMTP-RV

A single cage induction machine is connected to the IGBT bridge. Parameters of the machine are given in Appendix. The asynchronous machine model is a hard-coded model. It is based on an iterative method and is capable of obtaining a simultaneous solution with network equations at each simulation time-point.

In order to vary the fundamental component of the output voltage for the fixed dc bus voltage, a simple Sine Pulse Width Modulation (SPWM) is used. Carrier frequency is 500 Hz.

3) *Type 3: PWM Rectifier and capacitive filter*

This is the common structure of a PWM rectifier used in VSD. The input AC filter plays equally a role in ripple control signal analysis. Moreover, an unsymmetrical PWM control may cause interharmonic current at ripple control frequency. This type of converter is made up of a PWM rectifier with a capacitive filter. Fig. 8 shows an example of this type of converter in EMTP-RV. The DC load is modeled by a simple resistance.

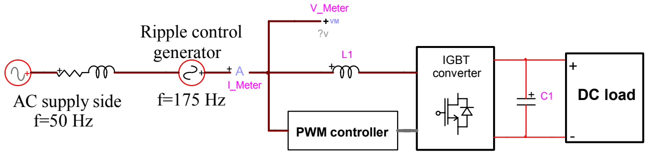

Fig. 8 Example of a Type3 converter

The gating controller is composed of 2 parts:

- A PLL controller that generates filtered 3-phase sinusoidal signals in phase with the input voltage of the converter
- A PWM signal generator based on the sine waveforms generated by the PLL3

4) *"Simultaneous Switching" method in EMTP-RV*

The "Simultaneous Switching" method has been used in these simulations of power electronic. This method enables to solve through an iterative process, control system equations and network equations as explained in [8]. It is a fixed-point method and the maximum number of iterations represents the maximum number of switch state changes that are allowed to occur in a given time-point solution. When this option is turned on the delay between control signals generated by the PWM controller, controlled switches and diodes are eliminated. Fig. 9 shows the DC-bus voltage of a Type 3 converter simulated with and without this option. When this method is not used the delay between control system solution and network solution leads to disoperation of the converter.

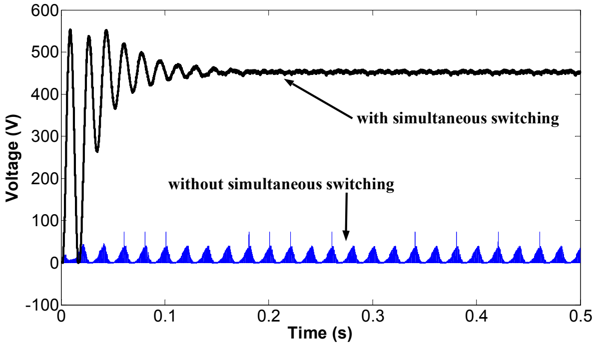

Fig. 9 Simulation of DC-bus voltage, with and without "Simultaneous switching" option

It is noticed that the same circuit could have been also solved without using "Simultaneous switching", but modeling the diodes with non linear functions. Fig. 10 shows closed results between simulation with "Simultaneous Switching" and ideal diode model and simulation without "Simultaneous Switching" and a non-linear resistance (15 segments). The "Simultaneous Switching" method gives accurate results and avoids usage of network elements with complex modeling.

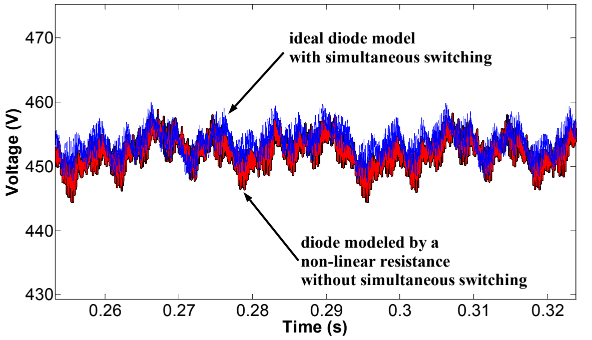

Fig. 10 Simulation of DC-bus voltage with ideal diode (dashed line) and with nonlinear function (solid line)

B. Impedance computation

Time domain simulations have been run for each type of converter. FFT analyses are performed on voltage and current waveforms at AC supply side. The fundamental frequency of this analysis is 25 Hz in order to obtain the power frequency component and the ripple control signal component. Fig. 11 and Fig. 12 give the FFT analysis of current and voltage waveforms of Type 1 converter (L_1=5 mH and a DC load modeled by a resistance of 2 Ω)

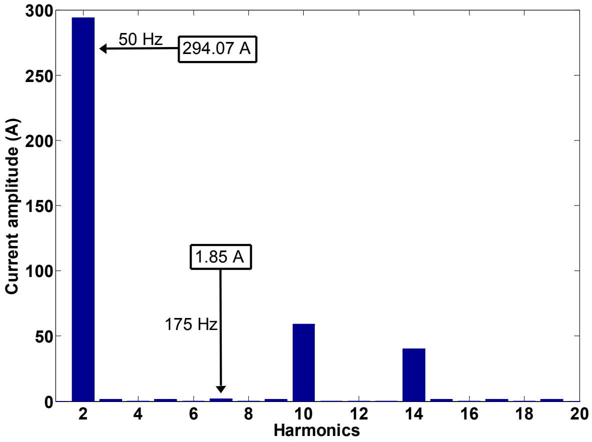

Fig. 11 Fft analysis of current waveform for Type 1 converter

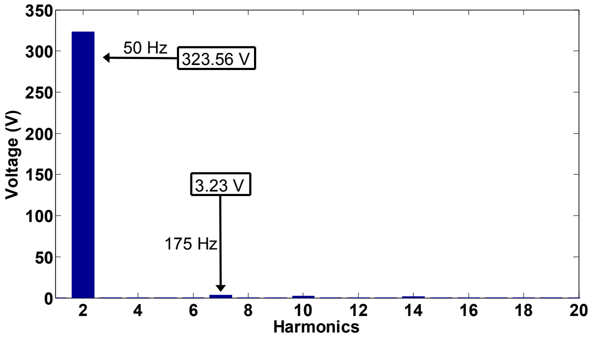

Fig. 12 FFT analysis of voltage waveform for Type 1 converter

50 Hz and 175 Hz impedances are calculated as follow:

$$Z_{50\,\mathrm{Hz}}=\frac{\mathrm{V\_Meter(50\,Hz)}}{\mathrm{I\_Meter(50\,Hz)}}=\frac{323.56\ \mathrm{V}}{294.07\ \mathrm{A}}=1.1003\,\Omega$$

$$Z_{175\,\mathrm{Hz}}=\frac{\mathrm{V\_Meter(175\,Hz)}}{\mathrm{I\_Meter(175\,Hz)}}=\frac{3.23\,\mathrm{V}}{1.85\,\mathrm{A}}=1.7461\,\Omega$$

Impedance computations are given in the following tables. For each type of converter, some parameters are changed (Filter sizing, and DC-load power) and impedances are calculated.

1) Type 1 converter impedances

TABLE I HARMONIC IMPEDANCES OF TYPE 1 CONVERTER

L_1 (mH)	S (kVA)	Z_{50Hz} (Ω)	Z_{175Hz} (Ω)	Z_{175Hz}/Z_{50Hz}
2.5	275	0.5518	0.8718	1.58
5	275	0.5519	1.0269	1.86
2.5	145	1.0999	1.3987	1.27
5	145	1.1003	1.7461	1.59

2) Type 2 converter impedances

TABLE II HARMONIC IMPEDANCES OF TYPE 2 CONVERTER (STEADY-STATE)

C_1 (μF)	S (kVA)	Z_{50Hz} (Ω)	Z_{175Hz} (Ω)	Z_{175Hz}/Z_{50Hz}
15	7	18.6473	10.2492	0.55
75	7	25.1218	9.3010	0.37
100	7	24.9302	5.9339	0.24
100	16	10.5864	5.3457	0.50
225	16	12.5108	5.7683	0.46

TABLE III HARMONIC CURRENTS OF TYPE 2 CONVERTER (TRANSIENT-STATE)

C_1 (μF)	S (kVA)	I_{50Hz} (A)	I_{175Hz} (A)	I_{175Hz}/I_{50Hz}
15	7	43.342	3.042	7.02%
75	7	44.729	2.792	6.24%
100	7	44.855	2.990	6.67%
100	16	88.309	6.039	6.84%
225	16	88.228	6.966	7.90%

These results show that at transient state, this converter generates over 7% 175Hz interharmonic current referred to the fundamental current. This interharmonic current can cause ripple control voltage in crossing network line impedance. In the case of low ripple control voltage level, the presence of transient interharmonic can disturb the ripple control system.

3) Type 3 converter impedances

TABLE IV HARMONIC IMPEDANCES OF TYPE 3 CONVERTER

L_1 (μF)	C_1 (μF)	S (kVA)	Z_{50Hz}(Ω)	Z_{175Hz}(Ω)	Z_{175Hz}/Z_{50Hz}
300	1e3	600	0.2478	0.2657	1.07
500	1e3	600	0.4241	0.4844	1.14
500	5e3	550	0.2684	0.3586	1.33

C. Recommended impedance values

Based on above studies, it is recommended to use a reasonable impedance to represent a power electronic device when doing ripple control signal propagation study. In each case, the lowest value is rewritten in Table V. Among these three kinds of converters, type 2 is the worst case as its equivalent impedance at ripple control frequency is the lowest.

TABLE V RECOMMENDED EQUIVALENT RIPPLE CONTROL IMPEDANCE

Type converter	Recommended equivalent impedance values in ripple control propagation studies
1	$Z_{175Hz}/ Z_{50Hz} = 1.27$
2	$Z_{175Hz}/ Z_{50Hz} = 0.24$
3	$Z_{175Hz}/ Z_{50Hz} = 1.07$

III. CASE STUDY: APPLICATION IN FREQUENCY DOMAIN SIMULATION

A case study is performed by means of ExpertEC (an EDF software for frequency domain power quality studies) which takes into account both power electronic device harmonic source injection and equivalent impedance at 175Hz.

As mentioned above, a symmetrical conventional rectifier does not produce inter-harmonic currents, but, at ripple control frequency, some power electronic device behaviors as an impedance. If this impedance is too small, the ripple control signal may be weakened. A real case is presented in this section. It reveals the impact of power electronic device impedance on ripple control signal propagation. The simplified electric scheme is given in Fig. 13. A 350kW VSD of type 2 is connected on the LV feeder supplied by a typical MV/LV transformer of 1 MVA (a common configuration of a LV substation), another linear load of 100kVA is also connected to the same feeder. The ripple control generator is located in MV side.

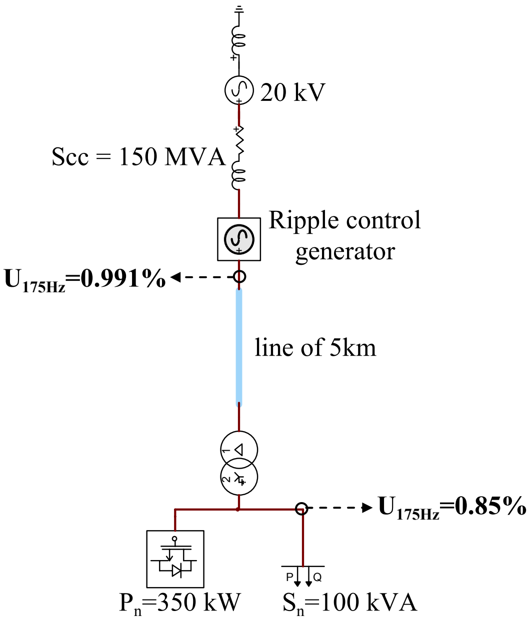

Fig. 13 Ripple control case study: a power electronic device connected to an LV network

In order to estimate different ripple control voltage values at customer side, two simulations have been done: at the first case, the power electronic device is considered as a pure harmonic current source and at the second case, it is simulated as an harmonic current source with a ripple control frequency equivalent impedance ($Z_{175} = 0.24 * Z_{50}$). The table below shows the simulation results: ripple control voltage level at each side of the transformer.

TABLE VI SIMULATION RESULTS

	Equivalent Z_{175Hz}	MV_U_{175Hz}	LV_U_{175Hz}
Case 1	Z_{175Hz} = infinite	0.99%	0.99%
Case 2	$Z_{175Hz} = 0.24 \times Z_{50Hz}$	0.99%	0.85%

If the power electronic device is modeled as a pure current harmonic source, the ripple control voltage level at LV side will be overestimated about 15%.

IV. CONCLUSIONS

The paper presents time domain simulation for power electronic device equivalent impedance computation at ripple control signal frequency. The time-domain simulation results show that the 175Hz impedance at the input of a rectifier connected to a capacitive DC filter (type 2) is much lower than the impedance at fundamental frequency. It is suggested to integrate this impedance in ripple control signal propagation study:

- Some power electronic device can't be modeled as an infinite impedance at ripple control signal study. According to the type of converter, a reasonable impedance value has to be used when doing frequency domain study (see Table V).
- If a power electronic device generates transient or permanent interharmonic current, it must be taken into account in ripple control signal study.
- In frequency domain ripple control signal analysis, a power electronic device should be modeled as harmonic and interharmonic current source with a ripple control impedance in parallel. It is recommended to integrate all these elements into frequency domain simulation software.

The key step here is to be able to define a reasonable ripple control frequency equivalent impedance of a power electronic device. Our study has given some approximate values of three types of converters by means of time domain simulation. Accurate impedance must be determined by taking account of most pessimist case in order to estimate right ripple control signal level, for example, input filter, DC filter, control pattern, and other detail information from device manufacturer.

V. PERSPECTIVES

The authors [6], [9] and [10] give a novel method to get frequency coupling matrix of a voltage source converter derived from Piecewise linear differential equations. This method will be very interesting when several frequencies are studied. If the frequency coupling matrix can be defined directly by engineering parameters such as power, filter, grid impedance etc, it will simplify significantly the ripple control study at any frequency.

VI. APPENDIX

A. Single cage induction machine parameters used in the example of Type 2 converter

Nominal Power : 20 Hp, COSφ = 0.853
Nominal Voltage : 156 V RMS LL
Number of poles : 4
Electrical data: Rs= 0.1062Ω; Xls= 0.2145Ω;
Xm= 5.8339Ω; Rr= 0.764Ω;Xlr= 0.2145Ω
Moment of Inertia : 1.5 kg m^2

VII. REFERENCES

[1] CIGRE Working Group 36-05, "Harmonics, Characteristic Parameters, Methods of Study, Estimates of Existing Values in the Network", Electra, no. 77, July 1981, pp. 35-54.

[2] G. Seguier. “Les Convertisseurs de l’électronique de puissance”, Volume 1, Lavoisier – Tec&Doc 1992, ISBN 2-85206-841-9

[3] IEEE Harmonics Modeling and Simulation Task Force, “Modeling and Simulation of the Propagation of Harmonics in Electric Power Networks: Part I”, IEEE Trans. on Power Delivery, vol. 11, n° 1, Jan 1996, pp. 466-474.

[4] J. Arrillaga, L. Juhlin, M. Lahtinen, P. Ribeiro, A.R. Saavedra "AC System Modeling for AC filter design – an overview of impedance modeling" ELECTRA N°164 February 1996

[5] X. Yang. “Advanced methodology and new tool for multiphase power quality analysis & mitigation”, 18th International Conference on Electricity Distribution CIRED, June 2005, Torino, Italy

[6] P.W. Lehn “Harmonic Modeling of Thyristor Bridges using a Simplified Time Domain Method”, ICHQP 2006, Cascais, Portugal

[7] “Guidelines for modeling power electronics in electric power engineering applications”, Power Electronics Modeling Task Force & Digital simulation Working Group, IEEE Transactions on Power Delivery, Vol. 12, No. 1, January 1997.

[8] M. Zou, J. Mahseredjian et al: “Interpolation and reinitialization in time-domain simulation of power electronic circuits”. Electric Power Systems Research, Volume 76, Issue 8, May 2006, pp 688-694

[9] M. Fauri, “Harmonic modeling of non-linear load by means of crossed frequency admittance matrix”, IEEE transactions on Power Systems, Vol. 12, No. 4, November 2001, page 1632-1638.

[10] C. Saniter, A. R. Wood, R. Hanitsch and D. Schulz, “Modeling the effect of ac system impedance unbalance on PWM converters using frequency coupling matrices”, IEEE Bologna PowerTech Conference Proceedings, June 23-26, 2003.

VIII. BIOGRAPHIES

Dr. Xavier X. Yang (M’07) received his Electrical Engineering Diploma B.S. and a M.S. degrees in Liaoning Technology University (China), and received the Ph.D. from National Polytechnic Institute of Toulouse (France). From 1994 through 2001, Dr. Yang was employed in French Electricity and Energy Consulting Companies in which he was in charge of site measurement and power quality mitigation. He is doing now research works in Electricite de France (EDF) Research & Development. His research interests are in the areas of modeling and simulation techniques for electric power systems, power system harmonics, computer algorithms, fault detection and voltage sag mitigation. He is a member of IEC SC77A Working Group 1 (Harmonics and other low-frequency disturbances) and CIGRE Joint Working Group C4.105 (Benchmarking of Power Quality Performance in Transmission Systems).

Sébastien Dennetière (M'04) graduated from École Supérieure d'Electricité (Supélec) in France in 2002. He received the M.A.Sc. degree from École Polytechnique de Montréal in 2003. From 2002 to 2004 he worked at IREQ (Hydro-Québec) on research and development activities related to the simulation and analysis of electromagnetic transients. In October 2004 he joined the research center of EDF where his interests are currently in the field of insulation coordination and power system simulations.