Practical Modeling of Large Rectifier Loads for the Estimation of Low-order Non-characteristic Harmonics

M.O. Roux   A. Coutu   G. Beaulieu

Abstract-- The paper reports modeling efforts undertaken to ensure adequate estimation of low-order harmonics injected into the AC network by an important rectifier load. For this purpose, measurement results obtained from a large aluminium smelter were compared to the simulation results of a detailed time-domain model developed in EMTP-RV. Using the EMTP-RV time-domain model, it can be shown that rectifiers do not act like constant current sources at low-order non-characteristic harmonics. This type of model is useful to evaluate harmonics for a given configuration of the installation and of the network. However, it may become too laborious to use such a time-domain model for doing sensitivity analysis in order to determine the worst conditions. A model that takes into account the damping and frequency displacement effects on resonances of converters is presented in the paper.

Keywords: Harmonics, Voltage Unbalance, Rectifier Loads, Converter Impedance, Damping, Resonances, EMTP-RV.

I. Introduction

The power supply of large smelter plants consists mainly of a number of power rectifiers connected in parallel. Typically, these converters are important sources of characteristic harmonics which are usually almost eliminated by phase-shift cancellation and appropriate filtering (also needed to compensate for the reactive power). However, low-order non-characteristic harmonics (mainly third) due to network voltage unbalance (negative-sequence) may not be negligible especially if resonance conditions exist [1]. These non-characteristic harmonics should be estimated properly to ensure compliance with the emission limits allowed on the network [2]. This paper proposes a simple and practical approach for rectifier load modeling for the estimation of low-order non-characteristic harmonics. The model parameters are derived from results of EMTP-RV simulations.

II. Basics

The assumptions that the AC voltages are perfectly balanced and undistorted (fundamental frequency only) are often made in the literature when describing harmonic generation of converters [1]. However, those conditions are never fully satisfied in practice, thus non-characteristic harmonics are produced.

Even if these uncharacteristic harmonics are usually small (compared to characteristic harmonics) due to normally small voltage unbalance (negative-sequence component) on the network, resonance between capacitor banks and/or AC filters and the network can amplify such harmonics to unacceptable levels.

In this situation, problems could be experienced from low-order non-characteristic harmonics produced by large rectifier loads and HVDC converters.

Unbalanced voltages result in odd-triple harmonic current generation on the ac side of converters [1]. Only the third harmonic is significant with the level of unbalance normally encountered in HV networks. Fig. 1 shows the Discrete Fourier Transform (DFT) of the AC network current obtained by simulation of a large rectifier load supplied by a network whose voltage unbalance factor (V_2/V_1) is 2% with all other conditions being near ideal.

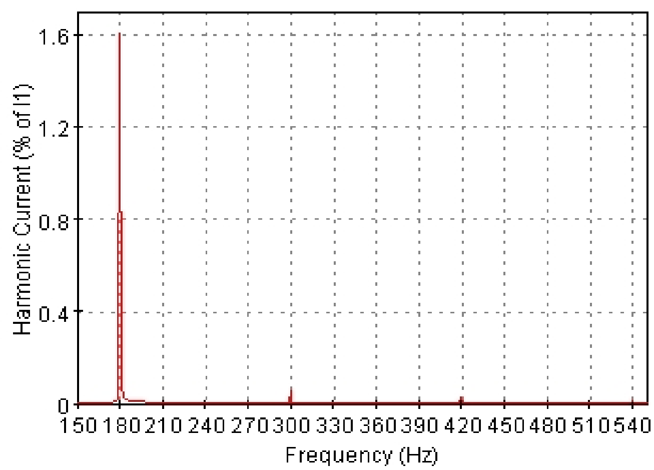

Fig. 1. Harmonic content of network current under voltage unbalance for near idealized conditions (DFT analysis) of a 48-pulse rectifier load

The effect of voltage unbalance on harmonic generation is twofold:

1) Phase-to-phase voltage differences cause variations in the commutation periods of a six-pulse bridge in a way that modifies the shape of each pulse which then produces specifically odd-triple harmonics [1].

2) The voltage unbalance is transferred to the DC side by the commutating process, producing a 2^{nd} harmonic voltage component on the DC voltage which drives 2^{nd} harmonic current in the DC circuit [3]. The six-pulse bridge then converts this second harmonic current into 60 Hz negative-sequence and 3^{rd} harmonic currents injected in the AC system.

In this study, only the first mode of third harmonic generation was considered since the inductance of the DC circuit in the smelter plants being investigated was found to be so high that it prevented any significant second harmonic current in the DC side.

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The paper will also concentrate on the 3rd harmonic because the main incentive for this study was to find a solution to an actual problem at this harmonic. For the sake of simplicity, only the supply system voltage unbalance as being the dominating cause of third harmonic generation will be considered. Other sources of third harmonic such as transformer and saturable reactor asymmetries are not considered.

Nevertheless, such asymmetries may need to be taken into account when a comprehensive harmonic assessment is needed for a large rectifier plant.

Finally, conduction asymmetries between half bridges (odd-numbered and even-numbered valves) can also be present in large rectifier installations and cause even harmonics. This aspect will be discussed in section IX.

III. Ideal Model

Like other potential source of disturbances, it is required that the operator of a large rectifier plant (i.e. an aluminum smelter) conducts a detailed harmonic study (characteristic and non-characteristic harmonics) to ensure compliance with emission limits allowed at the connection point to the network.

It has been common practice in the industry to assess non-characteristic harmonics in the same way as for characteristic harmonics i.e. by modeling converters as ideal constant current sources of harmonics (see Fig. 2). The magnitudes of the current sources are estimated based on measurements made on similar installations worldwide or by analytical approximations [4,5]. Fig. 2 shows a simple representation of this model which will be referred as the ideal model in this paper.

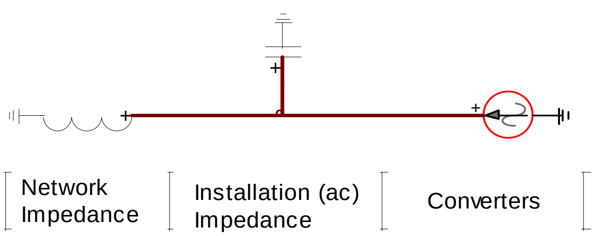

Fig. 2. Ideal model (constant current sources)

As we will see later when comparing the results obtained with the ideal model against a detailed time-domain model and actual measurements, converters do not behave as ideal constant current sources for low-order non-characteristic harmonics. The ideal model may lead to overestimate the emissions of 2nd, 3rd and 4th harmonics.

IV. Time-Domain Model

A detailed time-domain model of the aluminium smelter plant was implemented in EMTP-RV to investigate our assumption that the ideal model may be inadequate in some situations. A more advanced assessment of the 3rd harmonic emissions was performed.

A. AC System

The supply network Thevenin impedance along with power transformers, harmonic filters and substation auxiliary loads were modeled by using passive elements.

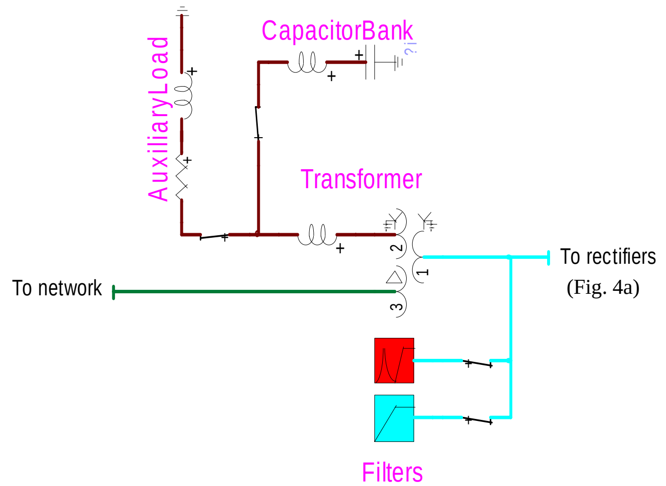

Fig. 3. AC system modeling (EMTP-RV)

B. DC Load

The four 12-pulse diode rectifiers are simulated as shown in figures 4a and 4b. The 48-pulse operation was obtained by the use of ideal phase-shifting transformers introducing phase-shifts of 7.5 degrees between each 12-pulse rectifier. A simple script was programmed to automatically calculate the transformer parameters for a given phase-shift.

A simplified model consisting of the total resistance and inductance of the bus-bars in series with a counter electromotive force (EMF) representing the aluminum potline was used.

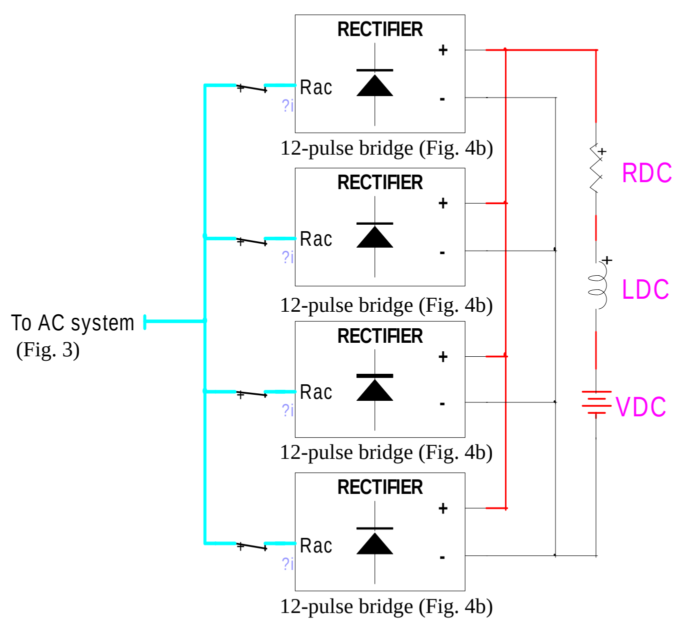

Fig. 4a. 48-pulse rectifier load modeling (EMTP-RV)

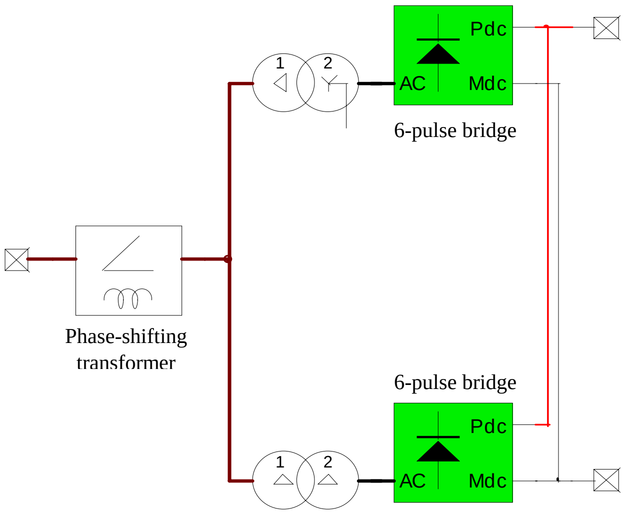

Fig. 4b. 12-pulse diode rectifier modeling (EMTP-RV)

The process operates at constant DC current obtained via the control of the DC voltage. A coarse control is obtained by the tap changers of power transformers which control the AC voltage at rectifiers to appropriate levels. In addition, a fine control is achieved via saturable reactors in series with each diode. Although they do not directly contribute to 3rd harmonic currents, it will be shown that significant asymmetries between the saturable reactors may increase the 3rd harmonic generation. At first, these reactors were not modeled in the study since a perfect symmetrical operation of the rectifiers was assumed.

V. Validation Against Field Measurements

In order to validate the EMTP-RV time-domain model of the whole smelter plant, simulation results were compared with a number of field measurements at the supply system point of connection. Some of the measurements suggested that important asymmetries may be caused by the saturable reactors when operated in the unsaturated part of their V-I characteristic. Only measurements in which the reactors were fully saturated were used for comparison with the time-domain model. For these cases, a good agreement was observed between the measurement and simulation results considering that measurements also include some level of disturbances originating from the network.

Considering the worst resonance condition between the network and the plant filters/capacitors (this is the case of interest from the point of view of assessing emissions), the time-domain model gave third harmonic currents within 10 % of the measured values for similar operating conditions. Comparison of the results also remained consistent for the different sets of measurements. At the opposite, the ideal model overestimated the measurements by a large margin for highly resonant cases. For low resonant cases, the two models gave similar results.

VI. Comparison with the Ideal Model

The third harmonic emission calculated with the ideal current source model was then compared with the results obtained with the EMTP-RV time-domain model. Multiple configurations (number of filters and capacitor banks energized) of the plant were tested. Three configurations representing different cases of amplification near 3rd harmonic are considered hereafter and correspond to situations of low, moderate and peak resonance.

Comparison between the ideal and the time-domain model showed good agreement for cases of low amplification, but very important differences for cases of high resonance. Compared to the time-domain model, the ideal model overestimated the 3rd harmonic current by up to 450 % when a near peak parallel resonance condition exists between the network and the smelter plant.

Moreover, Fig. 5 shows the 3rd harmonic current generated by a rectifier using the EMTP-RV time-domain model. Each curve corresponds to three different amplification factors (low, moderate and peak). It shows that the 3rd harmonic current generated by each rectifier reduces as the third harmonic impedance increases.

This result clearly demonstrates that the converters can not be modeled by ideal current sources for assessing 3rd harmonic emissions because the current generated by the rectifiers is influenced by the AC system harmonic impedance.

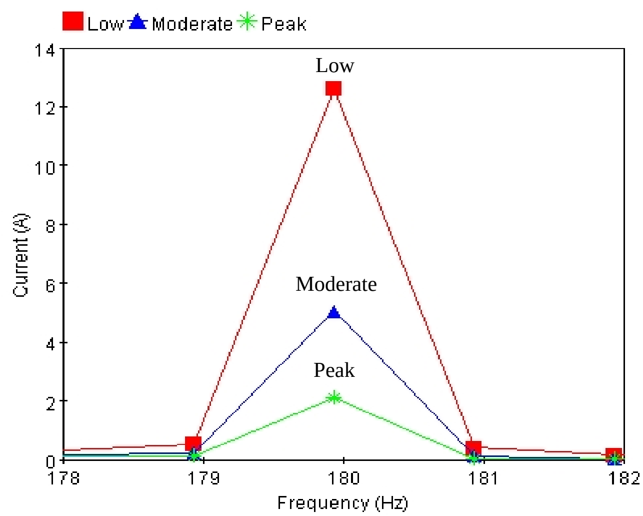

Fig. 5. Discrete Fourier Transform (DFT) analysis of the third harmonic current generated by one rectifier

VII. Development of a More Adequate Model

The EMTP-RV time-domain model of the aluminum smelter is useful to evaluate non-characteristic harmonics for a particular configuration, but it could become laborious when used for determining the worst case. Indeed, no simple procedure exists for automatically finding the maximum emission given a tolerance on the passive elements for instance.

There is a need for a simple model of converters able to properly account for the actual effects on damping and frequency displacement of resonances as the detailed time-domain converter model does. In addition, such a model should permit to easily assess the worst condition of third harmonic resonance using the normal frequency-domain procedure.

At Fig. 6, a model is proposed which consists of adding an equivalent converter-load impedance in parallel with the ideal harmonic current source for a given non-characteristic harmonic order (3rd harmonic in this case).

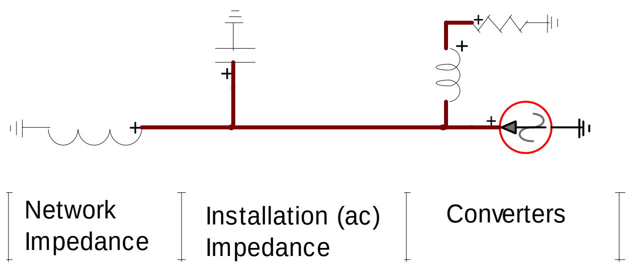

Fig. 6. Proposed model for low-order non-characteristic harmonics

Using the EMTP-RV time-model, we determined the model parameters for the considered smelter plant. The maximum value of the 3rd harmonic current generated by the rectifiers for a specified level of voltage unbalance was determined by injecting an ideal unbalanced voltage source (without impedance) alone at the rectifiers AC input. The value so-obtained does not depend on the network impedance and is used to determine the ideal current source. Also, the 3rd harmonic impedance of the converter-load equivalent was determined by dividing the third harmonic voltage by the corresponding current measured at the input of the rectifiers.

As shown on Table I, the results of the 3rd harmonic current emission into the supply network given by the proposed model are indeed very similar to those obtained by the time-domain representation of converters thus validating the proposed model. It can also be seen that the worst case of 3rd harmonic generation appear under moderate AC resonance.

TABLE I
COMPARISON OF THE 3 MODELS FOR THE 3RD HARMONIC CURRENT EMISSION INTO THE SUPPLY NETWORK

	3rd Harmonic Current (V_2/V_1 = 2 %)		
Case	Ideal model (A)	EMTP-RV model (A)	Proposed model (A)
1 – peak resonance	98.1	22.1	22.5
2 – moderate resonance	34.4	23.3	23.0
3–low resonance	16.5	17.2	17.5

VIII. DAMPING AND FREQUENCY DISPLACEMENT EFFECTS

Using the time-domain EMTP-RV model, this paper previously explained that the converters should not be considered as constant current sources for assessments of the third harmonic. From a frequency-domain standpoint, it could be said that converters are damping [6,7] and displacing the AC system parallel resonance. The harmonic impedance for different resonance cases as viewed from the converter AC side are plotted in figures 7 and 8 for the ideal and proposed frequency-domain models respectively.

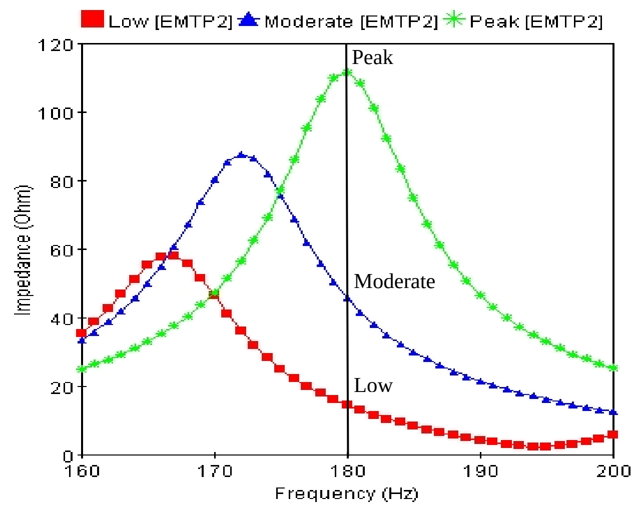

Fig. 7. Ideal model frequency scan

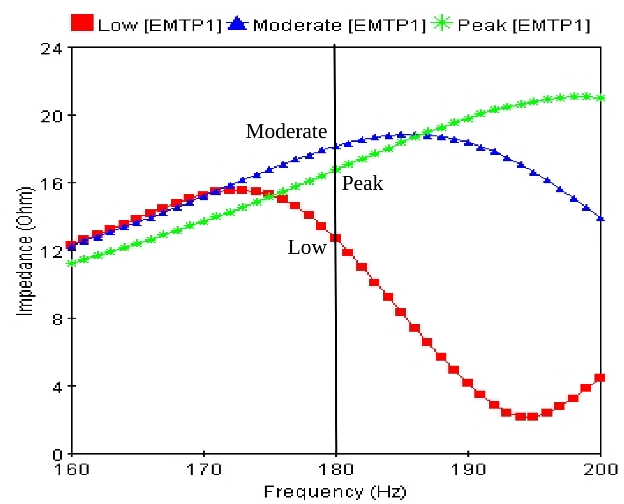

Fig. 8. Proposed model frequency scan

From these figures, it can be observed that the harmonic impedance is modified by the damping and frequency displacement effects of converters. Fig. 7 shows three totally different cases of amplification when ideal current sources are used to estimate 3rd harmonic generation of large rectifier loads. Fig. 8 illustrates the impact of considering an equivalent converter-load impedance in parallel with the ideal harmonic current source. With this proposed model, the third harmonic impedance of each case can be considered here as almost similar which agrees with the results of Table I.

IX. Even Low-order Harmonics Generalization

As mentionned previously, the paper mainly concentrates on the third harmonic because the study was conducted to solve an actual problematic case with this harmonic. It was later examined if the approach could be extended to the evaluation of second and fourth harmonics. Asymmetries between half bridges (odd-numbered and even-numbered valves) are necessary to produce even harmonics.

One way to simulate even harmonic generation is to take into account the effect of saturable reactors. They can lead to important harmonic generation in the case of asymmetrical characteristics (see Fig. 9) between the different reactors associated with each diode. It is possible to emulate the effect of saturable reactors for a given control current by modifying the minimum ignition voltage (so-called forward voltage) of diodes in EMTP-RV.

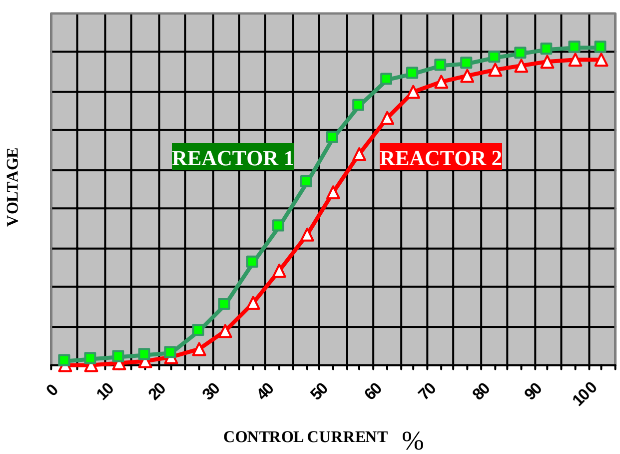

Fig. 9. Asymmetrical characteristic of two saturable reactors

Fig. 10 shows a Discrete Fourier Transform (DFT) analysis of the network current obtained in simulation near a large rectifier load for a network voltage unbalance factor of 2 % and considering an arbitrary level of saturable reactor asymmetries.

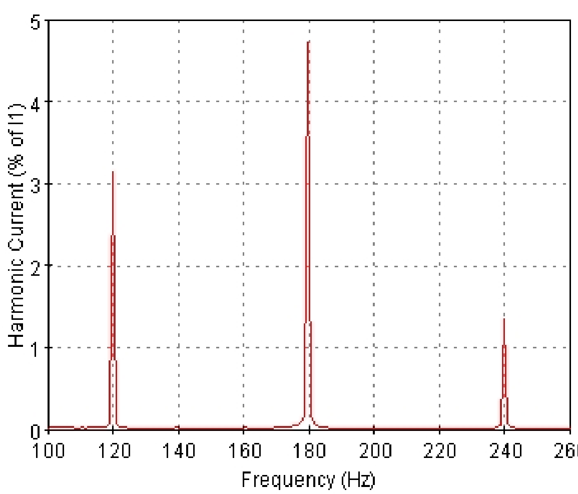

Fig. 10. Harmonic content of network current waveform under unbalanced voltages and saturable reactor asymmetrical characteristics (DFT analysis)

For low-order non-characteristic even harmonics (2nd and 4th), the results obtained with the time-domain and the proposed model are very similar (see Table II).

TABLE II
Validation of the Proposed Model for 2nd and 4th Harmonics

Case (#)	2nd Harmonic Current		4th Harmonic Current	
	EMTP-RV model (A)	Proposed model (A)	EMTP-RV model (A)	Proposed model (A)
1	5.4	5.3	2.5	2.6
2	5.8	5.6	3.2	3.3
3	6.0	5.8	3.1	3.4

X. Conclusions

Converters are important sources of characteristic and non-characteristic harmonics. Phase-shift cancellation and appropriate filtering are normally sufficient to reduce characteristic harmonics to appropriate levels. However, non-characteristic harmonics should also be estimated properly to ensure compliance with the emission limits allowed on the network. Ideal current sources (based on field measurements or mathematical approximations) are commonly used in the industry to represent converters for low-order (2nd, 3rd and 4th) non-characteristic harmonic assessments. This simplification sometimes leads to the overestimation of harmonic generation.

To this effect, modeling efforts reported in this paper were undertaken to find a simple and practical approach to rectifier load modeling for the estimation of low-order non-characteristic harmonics. Measurement results obtained from a large aluminium smelter plant were compared to simulation results from a time-domain model developed in EMTP-RV. This validation has shown good agreement between the two sets of results and gave great confidence in the time-domain model.

Using EMTP-RV time-domain model, it was shown that converters are not ideal harmonic current sources for low-order non-characteristic. Second, third and fourth harmonic currents generated by the rectifiers are effectively influenced by the AC system resonant impedance. In the frequency domain, it can be said that converters are damping and displacing the parallel resonance between the network and the AC side of the installation.

Even if time-domain models are practical to evaluate non-characteristic harmonics for a given configuration, it can be laborious and time consuming (tolerance not easily taken into account) to evaluate the worst harmonic conditions. A model that takes into account the damping and frequency displacement effects of converters is proposed. Based on the ideal model often used in the industry, the proposed model allows the assessment of low-order non-characteristic harmonics with an adequate accuracy. The paper proved that low-order non-characteristic harmonic (2nd, 3rd and 4th) assessments should take into account converters damping and frequency displacement effects on high resonances.

XI. Acknowledgment

The authors gratefully acknowledge the contribution of our colleague J. Lemay for his help on this study.

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XIII. Biographies

Marc-Olivier Roux received his B. Eng. Degree in Electrical Engineering from École Polytechnique de Montréal in 2003. He joined the system studies group of Hydro-Quebec TransÉnergie. He has been working on multiple projects involving high voltage equipment specifications such as series compensation, shunt capacitor banks and production integration. He also prepared multiple technical guides on various subjects like ground potential elevation, joule effect de-icing, inrush currents, harmonics and system modeling.

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