Power Quality Analysis Based on EMTP Simulations - Harmonics Case Study

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***Abstract* - This paper presents an application of the electromagnetic transients program (EMTP) in a distribution system study, where the harmonics injected into a distribution feeder by induction furnaces were the prime concern for this power quality problem. This case is taken from a harmonic problem experienced by ELEKTRO - Eletricidade e Serviços S. A., an electric utility in the southeast of Brazil. The three-phase power system with a digital model of the induction furnaces as power electronics based loads was simulated with the EMTP over a time span which was long enough to reach steady state. Voltage and current waveforms were then analyzed with a Fourier analysis program to obtain the harmonic content of the distorted waveforms. Field measurements at the point of common coupling between the utility and the industry are presented as well. Electromagnetic transients programs are more accurate in representing non linearity effects of the supply system, and allow more detailed modelling of power electronic loads and devices, than steady-state harmonic programs. Power electronics and power quality have such a strong correlation that can only be fully described and analyzed with the use of time domain simulation techniques.**

I. INTRODUCTION

The problem of harmonic analysis in power systems is usually studied with steady-state solution techniques, which use linear solutions at the harmonic frequencies. The characteristic harmonic spectra of non-linear loads are assumed to be known, and are modeled as current sources at the respective harmonic frequency. In reality, the harmonic current sources are not exactly known, because they depend on the behaviour of the power system as well. For example, harmonics from transformer saturation clearly depend on the voltage magnitude and waveform at the transformer terminal.

Only time-domain simulations of the EMTP type [1], [2] can address the interaction between the power system and the harmonic sources, which can result in non-characteristic harmonics as well. PSPICE may also be useful, but does not have as many power component models as the EMTP. Time domain simulations can also be useful to develop other types of power quality studies [3], such as fault analysis, transient impulses caused by switching utility capacitors banks, diagnosing the effects of special loads into the system, troubleshooting the failure of sensitive loads, evaluating the application of “Custom Power” devices as solutions for power quality problems, etc.

Induction heating has gained wide acceptance in industries because this type of heating process is clean, quick and efficient. On the other hand, the use of power electronic devices for induction heating introduces harmonic currents causing voltage distortions in the electric supply network. The dynamic interaction of these harmonics with the electric system in terms of system configuration, loading and other conditions, may result in linear resonances, or even in undesirable steady-state conditions, which all can result in misoperation, failure and life reduction of equipment, with consequent economical losses. Induction furnaces are power electronics-based loads, where the heat in the electrically conducting workpiece to be melted is produced by circulating currents through electromagnetic induction. Series or parallel-resonant inverters are typical configurations used to supply energy to the induction coil, at a selected frequency, which can be in a range varying from the power system frequency to a few hundred kilohertz [4]. The operation of these induction furnaces has produced distortions in the current and voltage waveforms, and has created incompatibility problems between these special loads and other sensitive loads connected to the same distribution feeder [5]. Changes in the configuration of the power supply system as well as application of harmonic passive filters, have minimized the effects, but have not completely eliminated the harmonics power quality problem. Field measurements have been made for different operating conditions to evaluate the effectiveness of the already installed harmonic passive filters.

II. HISTORY OF THE HARMONIC PROBLEM

This section summarizes the actions taken by ELEKTRO - Eletricidade e Serviços S. A., in assisting an industrial customer to deal with harmonic problems created by the operation of induction furnaces in a distribution system. The problem emerged after a customer complained that its sensitive loads (computer-based loads) were suffering from the poor quality of the utility-supplied power. Coincidentally, this customer was connected to the same feeder where one of the industrial plants of the same customer has been operating induction furnaces. At that

time, a harmonic problem was detected and the sensitive load was connected to a feeder supplied from another substation. It was also recommended to the customer to provide corrective filtering of the injected harmonic currents from the induction furnaces. Since there was no clear Brazilian regulation about this issue at that time, and because of the economic costs involved, the solution was postponed by the customer.

Two years later, the utility installed a 9.0 MVAr capacitor bank in the same substation supplying this customer. Resonance effects caused overcurrents in this capacitor bank, which led the utility to change the capacitor digital overcurrent protection relays to electromechanical relays. After that, the protection fuses of the customer's capacitor banks started to blow. The utility's capacitor bank was turned off until another 25/30MVA-138/13.8kV transformer was later installed in the substation. Then, measurements were made after the utility capacitor bank was connected to a different bus bar from the feeder that supplies the induction furnaces customer.

In August 1995, new measurements were made at the substation, especially on the feeder supplying the induction furnaces [5]. Sometimes later, the customer installed 4th and 5th order harmonic tuned passive filters, with an economic motivation imposed by a new Brazilian power factor legislation, which essentially changed from a minimum monthly average power factor of 0.85 to a minimum hourly average of 0.92 (inductive limit from 06:00am to 12:00 midnight and capacitive limit from 12:00 midnight to 06:00am). Recent measurements have been made to verify the system overall performance on this feeder and in the respective distribution substation.

III. HARMONIC MEASUREMENTS

Harmonic measurements were recently made at the point of common coupling (PCC) between the utility and the induction furnace customer, with modern monitoring equipment of the type "Dranetz/BMI-PQNode 8010 and 8020". With this equipment it is possible to monitor power quality phenomena such as voltage sags, voltage swells, outages, "cold load pick-up", transient impulses, waveshape faults, harmonic distortions and frequency deviations [6].

The following figures illustrate some of the harmonic measurements made in March/April 1998. Fig. 1 shows the phase "A" measured current and Fig. 2 shows the measured voltage between phases A and B, with their respective harmonic amplitude spectrum. Both measurements were taken at a particular time when the induction furnace operation was with the 4th and 5th order harmonic passive filters turned off (see Fig. 5). Figs. 3 and 4 illustrate the same measurements, but during an operation condition when the 4th and 5th harmonic passive filters were turned on (see Fig. 6).

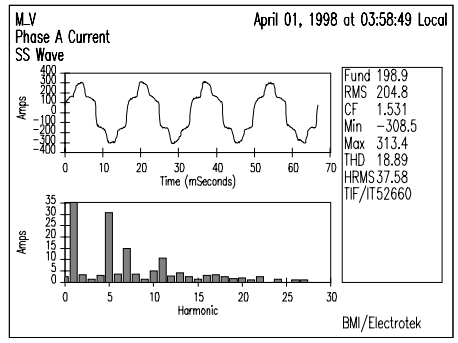

Fig. 1: Phase "A" current measured with harmonic passive filters turned off.

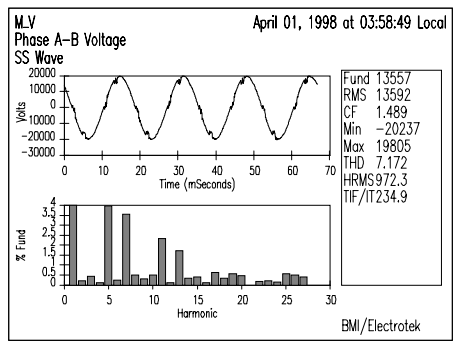

Fig. 2: Phase-to-phase "A-B" voltage measured with harmonic passive filters turned off.

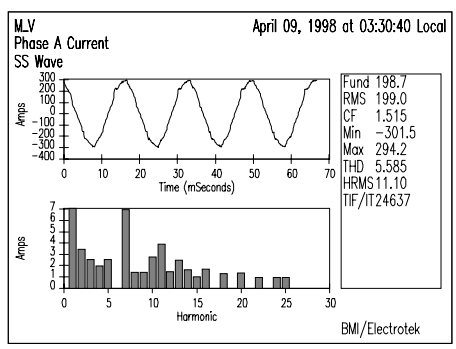

Fig. 3: Phase "A" current measured with harmonic passive filters turned on.

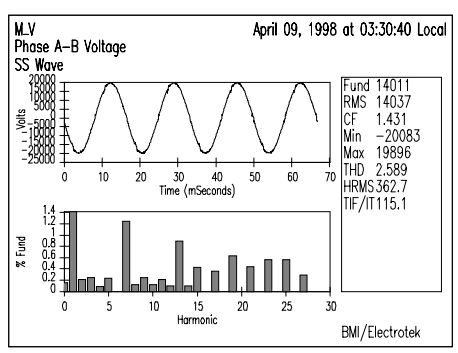

Fig. 4: Phase-to-phase "A-B" voltage measured with harmonic passive filters turned on.

The melting process inside the induction furnaces affects the Total Harmonic Distortion (THD) of the measured voltage at the point of common coupling very strongly. Fig. 5 shows the THD historic trend during one regular day of work, with the 4th and 5th harmonic passive filters turned off from about 12:00 midnight to 06:00am. This THD trend presents a characteristic variation along the day, depending on the load cycle at the industry. During the time when the harmonic filters were turned off (from about 12:00 midnight to 06:00am) it is easy to verify a substantial increase in the THD values. Fig. 6 presents the THD historic trend for another operation condition, with the 4th and 5th harmonic filters turned on during all the time.

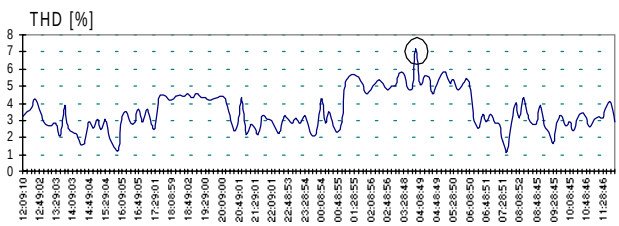

Fig. 5: THD Harmonic trend with harmonic passive filters turned off from 12:00 midnight to 06:00am.

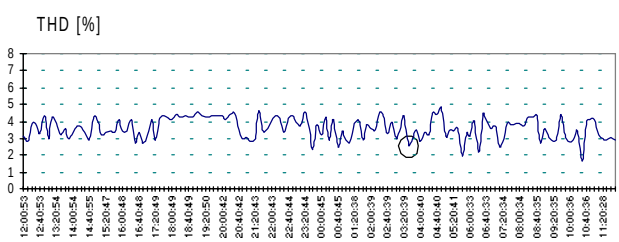

Fig. 6: THD Harmonic trend with harmonic passive filters turned on all the time.

From these charts it is possible to conclude that passive filters can minimize the harmonic voltage distortions, but not eliminate them completely.

On the absence of a specific Brazilian harmonic legislation some other recommendations have been used to guide utility system planning and operation practices in supplying power to special loads. In [7] for example, there are some criteria and global voltage harmonic limits, which were based on the experience of Brazilian power utilities, as well as on standards from CIGRÉ (Conférence Internationale des Grands Réseaux Electriques à Haute Tension - International Conference on Large High Voltage Electric Systems), IEC (International Electrotechnical Commission) and IEEE (The Institute of Electrical and Electronics Engineers).

IV. INDUCTION FURNACES DIGITAL MODELLING

A three-phase detailed modelling of the distribution system, including the linear and non-linear loads, transformer saturation effects, unbalanced conditions, power electronic loads, automatic control devices, frequency dependent characteristics of the system and of the loads, and so on, would be the ideal and recommended database for an electromagnetic transient simulation, in order to analyze power quality phenomena. This would require a complete and well-organized database of the system and load parameters, which is rarely available in practice. For distribution system planning and operation, such details are usually not required, unless some specific power quality problem emerges as urgent and important. Typically, neither some important data is available, nor appropriate models exist to represent the physical behaviour by digital simulation. One must therefore use simplifications, which may make the simulations unrealistic. Therefore, the development of more accurate models is needed for power quality studies.

For this case study, some realistic data was available, and some simplifications had to be made for other data. The actual system under study is shown in Fig. 7. A Thévenin equivalent circuit with a series connection of coupled resistances and inductances was used to represent the 138kV transmission system based on the given three-phase short-circuit power (2881.3MVA, angle of -78 degrees) and single-line-to-ground short-circuit power (1734.1MVA, angle of -77.7 degrees), from which the positive and zero sequence impedances at the frequency of 60Hz can be calculated. In reality, these impedances are frequency-dependent. How important this frequency dependency is has to be studied in more detail. The transformer model used was based on three single-phase pairs of coupled impedances. The distribution line was modelled as a three-phase coupled π-circuit, with positive and zero sequence parameters at 60Hz. For the frequencies of interest here, a π-circuit representation is reasonably accurate. For higher frequencies, a distributed-parameter line model would have to be used, either with constant parameters or with frequency-dependent parameters. The data for all the distribution feeders with their respective loads, and all the capacitor banks for power factor correction were available. Not enough information was available though for the induction furnaces. A digital model based on [4] was therefore used: a current-source, parallel-resonat inverter for induction heating, as shown in Fig. 8. The resonant inverter is used to create variable frequency at the induction coil. The six-pulse controlled rectifiers on the AC side of each induction furnace were supplied through a 13.8/0.48kV-3.0MVA-5.9% three-phase unit transformer in delta/wye-grounded connection. Saturation effects were not considered in this case. Resistance, inductance and capacitance actual values were available for the 4th and 5th order harmonic passive filters.

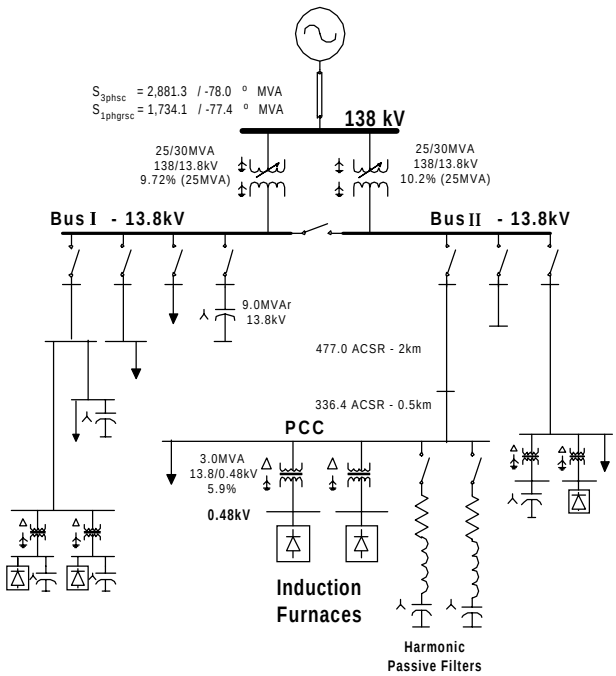

Fig. 7: Distribution substation.

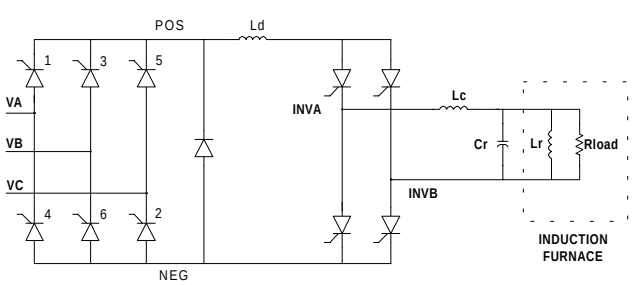

Fig. 8: Current-source, parallel-resonat inverter for induction heating.

EMTP-based programs can perform time-domain transient analysis or frequency-domain analysis. A frequency-domain analysis was done for this case, and the system impedance as a function of frequency, seen from the point of common coupling (PCC) of the induction furnace, was plotted as shown in Fig. 9.

Not only the impedance at multiples of the fundamental frequency was evaluated, but over the continuous frequency range as well, by using a small step increment (Δf) in the frequency variation input parameters. It was small enough to allow linear interpolation between calculated points.

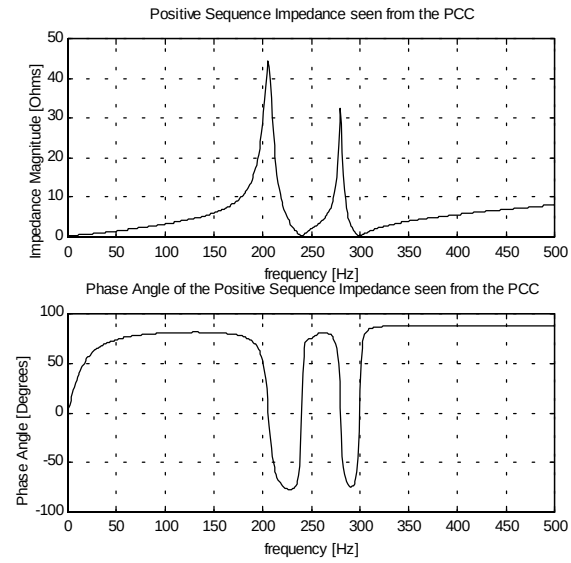

Fig. 9: Amplitude and phase of the positive sequence system impedance at the PCC, with harmonic filters.

The two minimum impedance values at 240Hz and 300Hz shown in Fig. 9 correspond to the effects of the 4th and 5th order harmonic filters. Fig 9 also shows the zero crossings of the phase angle of the system impedance, from inductive to capacitive and vice-versa, thus indicating parallel (maximum impedance) or series (minimum impedance) resonant conditions, respectively.

Next, the three-phase distribution system with the digital model of the induction furnaces as power electronics based loads was simulated as a transients case using the MicroTran$^{(R)}$ version of the EMTP, until a time when steady state was reached. Voltage and current waveforms were then processed through a Fourier analysis program to obtain the harmonic content of the distorted waveforms.

For this simulation, all the distribution feeders were represented. The induction furnace operation condition selected for this case corresponds to the time of maximum total harmonic distortion (THD) measured at the point of commom coupling (PCC), without the harmonic filters (see Fig. 5).

Figs. 10 and 11 show the current and voltage waveforms respectively, with their harmonic contents, at the point of common coupling (PCC) between the utility electric system and the customer facilities, for the induction furnaces operation with the 4th and 5th order harmonic passive filters turned off. Figs. 12 and 13 show the current and voltage waveforms, but for induction furnace operation with the 4th and 5th order harmonic passive filters turned on. This operation condition corresponds to the time of minimum total harmonic distortion (THD) measured from about 12:00 midnight to about 06:00am at the point of commom coupling (PCC), but in this case with the harmonic passive filters turned on (see Fig. 6).

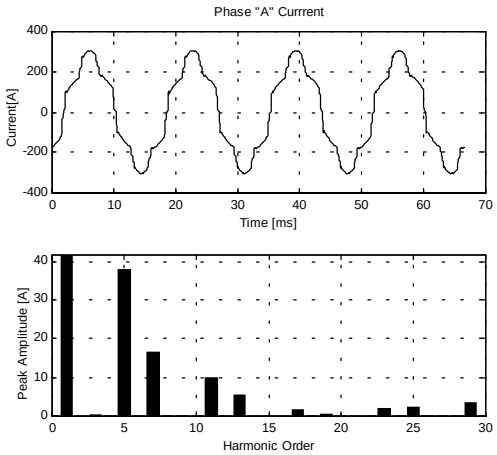

Fig. 10: Phase ”A” current simulated with harmonic passive filters turned off.

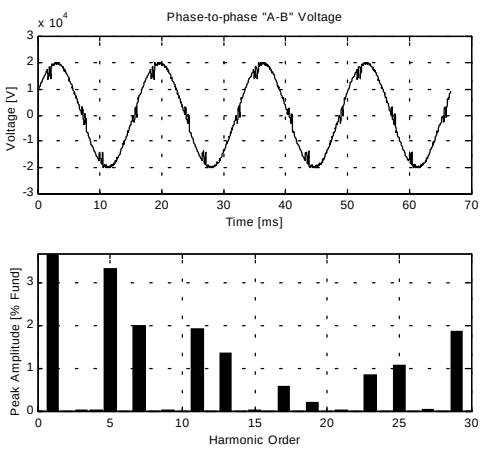

Fig. 11: Phase-to-phase “A-B” voltage simulated with harmonic passive filters turned off.

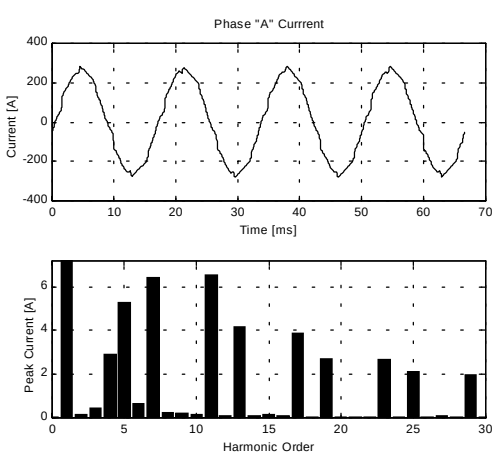

Fig. 12: Phase “A” current simulated with harmonic passive filters turned on.

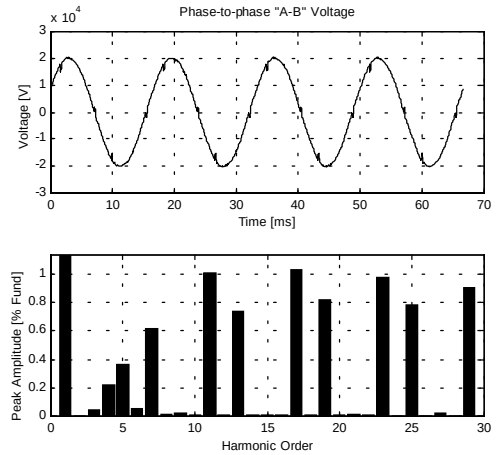

Fig. 13: Phase-to-phase “A-B” voltage simulated with harmonic passive filters turned on.

Some care must be taken when defining the time step size (Δt), which corresponds to the inverse of the sampling frequency, for the transient simulation. Relatively large step sizes introduce errors into the results of a time-domain simulation and consequently into the post-processing frequency-domain analysis. The explanation is that the differential equations of inductances and capacitances in EMTP-based programs are solved with the trapezoidal integration rule, thus producing errors which are a function of the frequency and the time step size (Δt) [2].

New solutions to this harmonic problem can be investigated, as for example the possible use of active filters [8], [9] to minimize harmonic distortions. Such power electronic device should be able to inject a shunt compensated current, as shown in Fig. 14, at the point of commom coupling, thus improving the quality of power at the interface of industrial and utility power systems.

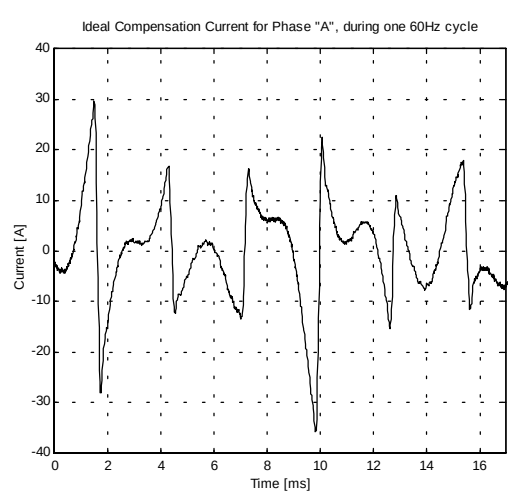

Fig. 14: Instantaneous ideal compensation current to be “injected” by a shunt active filter.

V. CONCLUSIONS

This paper presented an application of the electromagnetic transients program (EMTP) to the analysis of a power quality issue in a distribution system, where harmonic distortions in the voltage and current were produced by induction furnaces. The history of this harmonic resonance problem was described.

A digital model of the induction furnaces as current-source, parallel-resonant inverter loads, together with three-phase representations of the supplying distribution system were used in a time-domain simulation. After reaching a time considered as steady state, the simulated results were processed through a Fourier analysis program to get the harmonic contents of the voltage and current waveforms at the point of common coupling. Field measurements were also presented. A comparison between the actual measurements and the EMTP simulation is shown in Table I and Table II.

TABLE I: Field measurements and EMTP simulation with the harmonic passive filters turned OFF.

Parameters	Phase "A" Current [A]			Phase "A-B" Voltage [V]		
	Measured	Simulated	|Error%|	Measured	Simulated	|Error%|
Fund	198.9	201.8	1.5	13,557	13,776	1.6
RMS	204.8	204.2	0.3	13,592	13,814	1.6
CF	1.531	1.491	2.6	1.489	1.444	3.0
Min	-308.5	-304.4	1.4	-20,237	-19,950	1.4
Max	313.4	304.4	2.9	19,805	19,950	0.7
THD%	18.89	15.42	18.4	7.172	7.487	4.4
HRMS	37.58	31.11	17.2	972.3	1,031.4	6.1
TIF/IT	52,660	64,416	22.3	234.9	320.1	121.4

TABLE II: Field measurements and EMTP simulation with the harmonic passive filters turned ON.

Parameters	Phase "A" Current [A]			Phase "A-B" Voltage [V]		
	Measured	Simulated	|Error%|	Measured	Simulated	|Error%|
Fund	198.7	190.2	4.3	14,011	14,211	1.4
RMS	199.0	190.4	4.3	14,037	14,219	1.3
CF	1.515	1.474	2.7	1.431	1.422	0.6
Min	-301.5	-279.5	7.3	-20,083	-20,130	0.2
Max	294.2	280.7	4.6	19,896	20,220	1.6
THD%	5.585	5.110	8.5	2.589	3.224	24.5
HRMS	11.10	9.72	12.4	362.7	458.2	26.3
TIF/IT	24,637	36,910	49.8	115.1	219.9	91.1

The differences in the total harmonic distortion (THD) values are due to the high frequency harmonic components which are present in the simulation results. The knowledge of manufacturer data of the induction furnaces and their operation condition, such as the natural resonant frequency, would allow the improvement of the EMTP simulation. Considering unbalance conditions could also improve the simulation results. EMTP-based simulations can be useful tools for harmonic analysis, based on the fact that very detailed effects can be taken into account. Once the system is modelled inside an EMTP-based software, any type of studies can be performed. With the development and improvement of models, EMTP-based programs will become valuable tools for electric utility companies and industrial customers in evaluating power quality issues.

VI. ACKNOWLEDGMENTS

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