

# Treatment of Measured and Calculated Harmonic Currents in Filters of the Itaipu HVDC System

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**Abstract** – This work presents a methodology for the treatment of harmonic currents measured in a 3<sup>rd</sup>/5<sup>th</sup> harmonic filter located at the Foz do Iguaçu Converter Station of the High Voltage D.C. System of Itaipu. The methodology has been based on the statistical treatment applied both to field measurements and EMTP/ATP (Alternative Transients Program) digital simulations. By comparing the amplitude medium value and the dispersion of the harmonic currents, for different configurations and loading conditions of the HVDC System, the methodology has been of assistance to identify some factors that may affect the levels of the harmonics. Experience obtained with this work indicates the importance of three-phase representation to study the harmonics in the system studied as the level varies substantially between the phases.

**Keywords** – harmonic current, 3<sup>rd</sup>/5<sup>th</sup> harmonic filter, statistical treatment, field measurements, EMTP/ATP digital simulations, HVDC Systems

## I. INTRODUCTION

The Itaipu Hydro Plant is a bi-national venture situated at the Paraná River between Brazil and Paraguay. Due to the different frequencies in the two countries, half of the 18 generators are 60 Hz, and the other half is 50Hz. However most of the generated power has to be transmitted to the Brazilian grid, and for this reason a 6300 MW, +/- 600 kV DC link was constructed. The DC line connects the Converter Station at Foz do Iguaçu to a major substation near São Paulo, 800 km away, where the power is converted to 60 Hz. In November 1999, there was an emergency which caused the disconnection of the 3<sup>rd</sup>/5<sup>th</sup> harmonic filters at the Foz do Iguaçu Converter Station. Even though the harmonic overload protection did not indicate any anomaly, the tripping of the filters was decided once it was observed that some filter reactors were actually burning.

In order to monitor the levels of harmonics, it was decided to install meters in the affected reactor of one of the 3<sup>rd</sup>/5<sup>th</sup> harmonic filters. The equipment was installed and remained in operation several months, generating vast quantities of data.

The objective of this paper is to describe the methodology adopted to study the phenomena, which consisted of two main steps: a. Statistical treatment of the measured data, and b. Digital simulations to investigate possible factors affecting the harmonic levels.

## II. METHODOLOGY

### II.A Field Measurements

A modern digital meter was installed to measure the currents flowing through the 3 phases of the reactor. The meter was connected to the secondary of the reactor CTs. The instrument processes the data using FFT with a fixed two-cycle window which is synchronized through the detection of zero crossing. The sampling rate is 32 points per cycle with 1% accuracy [1], and the measurements are updated at 5 second intervals. The meter remained installed during several months and this allowed the monitoring of the harmonic levels under different operating conditions of the DC Link. As an example, Figures 1 and 2 show respectively the 3<sup>rd</sup> and the 5<sup>th</sup> harmonics as a percentage of the fundamental for a 24 hr period.

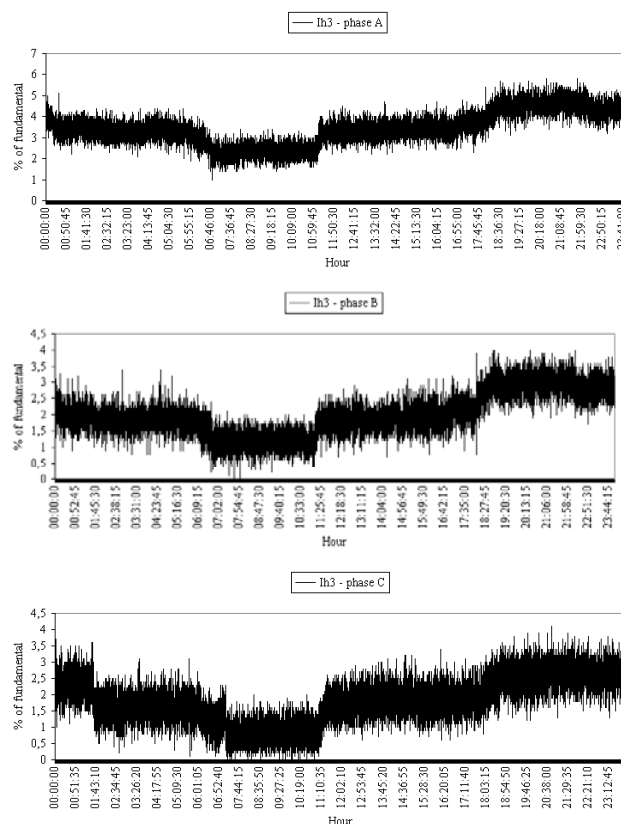


Figure 1 – 3<sup>rd</sup> Harmonic Components of Measured Currents on phases A, B and C – 24 hour period

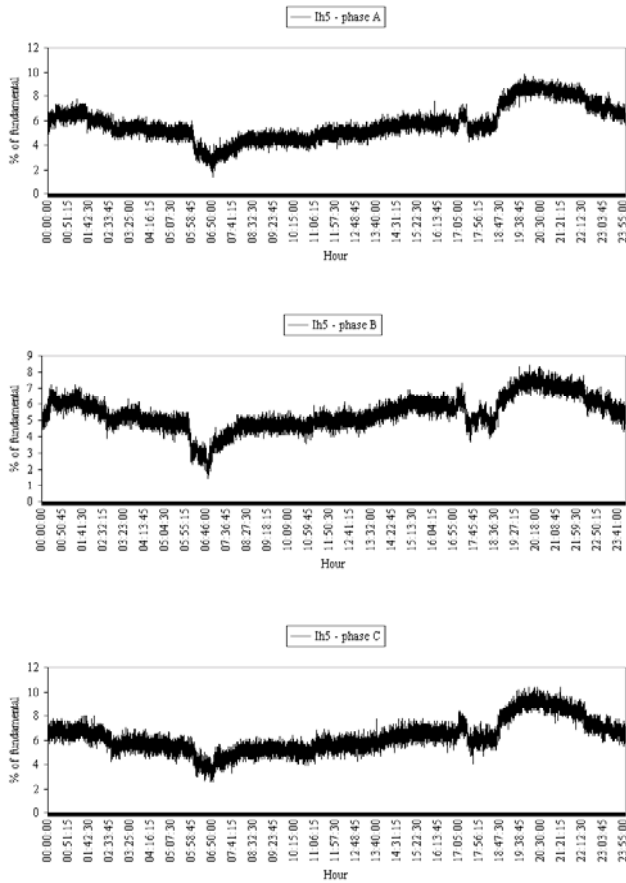


Figure 2 – 5<sup>th</sup> Harmonic Components of Measured Currents on phases A, B and C – 24 hour period

It is apparent from these Figures that the level of harmonics varies considerably from one phase to the other. The influence of the system load curve on the harmonics can also be observed, specially in Fig 2 where it can be seen that the level of the 5<sup>th</sup> harmonic raises substantially during the period from 19:00 to 23:00hs..

Considering the vast quantity of data generated by the metering campaign, as well as the fairly wide variations in harmonic levels as observed above, it was decided to introduce a statistical methodology to assist with the analyses of the harmonic behavior. Experience with the operation of the DC Link over the years since its installation in 1983, has shown that for any given load condition, steady-state operation can be considered to remain fixed during a period of about 7.5 minutes. Since the meter registers quantities at 5 second intervals, this would correspond to 90 samples.

Figures 3 and 4 show respectively the 3<sup>rd</sup> and the 5<sup>th</sup> components over a given 7.5 minutes operating condition. This condition was chosen to start at 18:57:00hs.

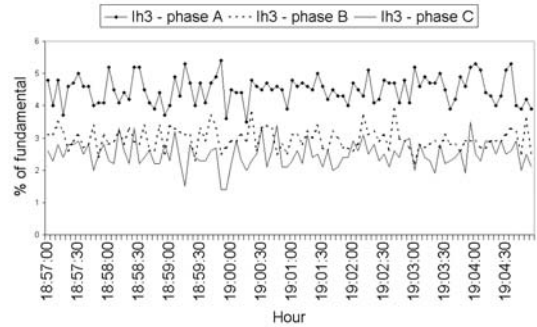


Figure 3 – 3<sup>rd</sup> Harmonic Components of Measured Currents on phases A, B and C – 7.5 minutes of a steady-state operating condition

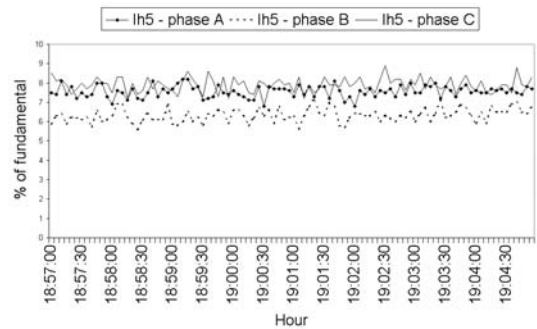


Figure 4 – 5<sup>th</sup> Harmonic Components of Measured Currents on phases A, B and C – 7.5 minutes of a steady-state operating condition

It is clear from these Figures that, although the system is at steady state, there is a random variation of the harmonic levels.

## II.B Statistical Treatment

Student's t-distribution was selected to process the data. This choice has been based on observations of the behavior of the harmonic variations and on the fact that it was desired to attain a confidence interval for each harmonic level having a confidence coefficient of 90%. There was no prior knowledge of the standard variation, as well as the  $\sigma^2$  value for the variable distribution [2,3,4].

The following calculations were performed for each operating condition:

1. Calculation of the sample mean:

$$\bar{I} = \left( \frac{1}{n} \right) \sum_{i=1}^n I_i \quad , \text{ where } n=90 \quad (1)$$

2. Standard deviation :

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (I_i - \bar{I})^2} \quad (2)$$

3. From the tables for Student's t-distribution, for confidence coefficient of 90%, and 89 degrees of freedom (90 samples):

$$t_{89;0.95} = 1.662 \quad (3)$$

4. Confidence interval:

$$L = n^{-1/2} \cdot S \cdot t_{n-1, 1-\alpha/2} \quad (4)$$

5. Lower confidence limit:

$$\bar{I} - L \quad (5)$$

6. Upper confidence limit:

$$\bar{I} + L \quad (6)$$

It can be seen from the above expressions that the confidence interval may vary, as it depends on the sample statistics. It is well-known that Student's t-distribution will approach the Normal distribution  $N(0,1)$  as the number of degrees of freedom increases [2].

### II.C Digital Simulations

Fig 5 shows a single line diagram of the system including the DC Link, the filters at both ends of this link, the 50 Hz synchronous generators at the Itaipu Power Plant and associated transformers, the connection with the ANDE (Paraguay) System; a positive-sequence equivalent was connected to the Ibiuna Substation to represent the South/South-East Brazilian grid.

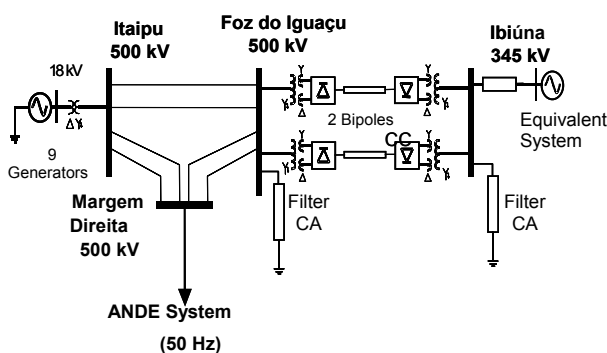


Figure 5 - Single-line diagram of Itaipu DC link and main interconnections

A full three-phase representation was adopted for the AC network and equipment, so that the effects of unbalances on harmonic levels could be observed in the simulations.

The simulations were made using the EMTP/ATP Program with a  $2.5 \mu\text{s}$  time step and a total simulation time of 4.5 s. Before each simulation, the EMTP/ATP was run to initialize the link, following a procedure specially developed for this purpose [5]. The harmonics were determined using a window covering the time interval between 1.0 and 4.5s, in order to ensure steady state conditions. For each simulation, the currents flowing in the three phases of the reactor under study were stored for post-processing. Analyses of the stored data revealed that the variations on harmonic levels that were observed in the measurements, were also present in the simulated results. This was somewhat surprising, and will be discussed in Section III of this paper. In order to compare the calculations with the measured data, it was necessary to develop routines that would replicate the processing of the data as performed by the digital instrument. The routines were written using MATLAB v 5.2 [6] and will be briefly described below.

#### 1. Routine CALCHARM

**Step 1.** Detect a positive-going current zero on phase A and record the values for the calculated currents in phases A, B and C at every time step over two cycles. This will correspond to 320 values for each phase.

**Step 2.** Call routine SPECTRALSG to perform a FFT[7] on the calculated values and store the results corresponding to the fundamental, 3<sup>rd</sup> and 5<sup>th</sup> harmonics

**Step 3.** Repeat steps 1 and 2 for the duration of the simulation time, that is  $t_{\text{max}} = 4.5$  seconds. Thus 90 values of the 3 quantities will be stored for each phase.

For any given operating condition, the above routine will supply the data needed for the statistical analysis described in the previous section. Therefore measured and calculated results can be compared to verify the accuracy of the simulations [9].

#### 2. Routine "SPECTRALSG"

This routine performs a Fast Fourier Transform on the calculated currents and is based on the method described in [8], except that the number of samples can have any value and is not necessarily a power of 2, as in [9].

As can be seen Figure 6 shows an example of the results obtained using the above routines. It is seen that the level of 3<sup>rd</sup> harmonic on phase A current presents fluctuations around some average value and can therefore be submitted to the statistical treatment using Student's t-distribution.

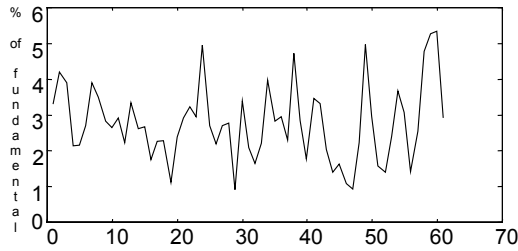


Figure 6 – Phase A current 3<sup>rd</sup> harmonic. Simulated results for a given steady-state operating condition.

### III. RESULTS

From the available data measurements, the following four different DC Link Power operating conditions were selected for discussions here. In all cases, the two bypoles were operating and only one of the 3<sup>rd</sup>/5<sup>th</sup> filter was connected.

Case 1 - Day: 23/04/2000, 6:45 am – 2330 MW

Case 2 - Day: 29/01/2000, 6:45 am – 2790 MW

Case 3 - Day: 29/01/2000, 7:00 pm – 3600 MW

Case 4 - Day: 23/04/2000, 7:00 pm – 5590 MW

As an example, Figures 7 to 12 show the results for Case 4 simulations, in which the system is heavily loaded (0.89 pu on the basis of the DC link power).

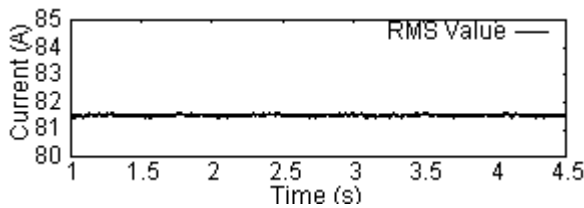


Figure 7 – Phase A Current in 3<sup>rd</sup>/5<sup>th</sup> Harmonic Filter

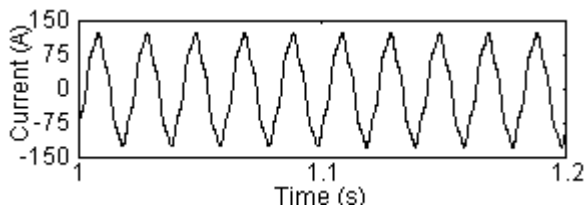
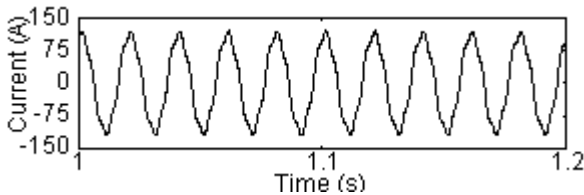


Figure 8 – Phase B Current in 3<sup>rd</sup>/5<sup>th</sup> Harmonic Filter

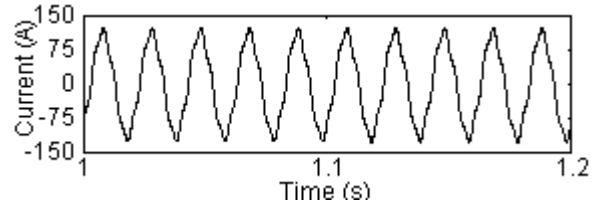


Figure 9 – Phase C Current in 3<sup>rd</sup>/5<sup>th</sup> Harmonic Filter

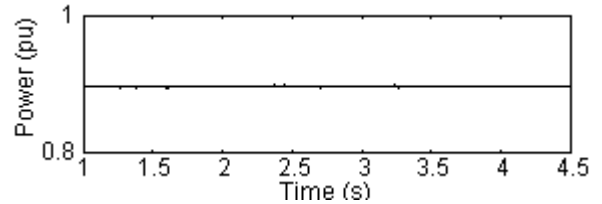


Figure 10 – DC Link Power = 5590 MW (0.89 pu)

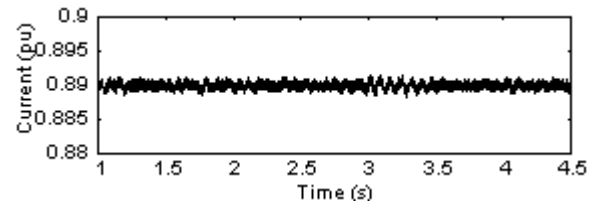


Figure 11 – DC CURRENT

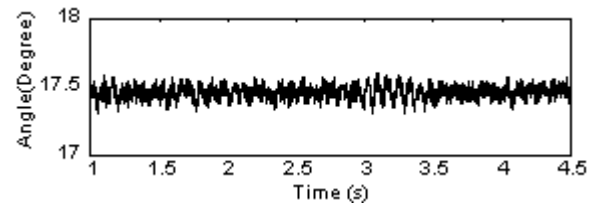


Figure 12 – FIRING ANGLE

It is seen in Figure 12 that the firing angle presents a kind of random oscillation around an average value. This is a consequence of the actual variations in the DC current, as shown in Figure 11: at each firing time, the firing angle control adjusts to bring the current to the set value; at each subsequent firing time, the value of the current is slightly different from the previous value, so the firing angle is changed accordingly by the control and so on, thus producing a random behavior. This phenomenon has been observed before, and is analysed in some detail in [10].

A comparison between simulations and measurements can be seen in Table I in the Appendix, where the results for the 4 cases are summarized.

The results shown in Table I refer to four load conditions on the DC Link. The calculated values for the two conditions presented in this table are generally much higher than those given by the metering equipment.

However for cases 3 and 4, when the DC Link Power operating conditions are 3600 MW and 5590 MW, respectively, there is clearly good agreement between the simulated and measured results.

The authors did not have access to the complete data of the ANDE (Paraguay) system, but were able to identify that the level of harmonics were strongly affected by the excitation characteristics of the transformers at the “Margem Direita” busbar shown in Figure 5. However, it was not possible to identify the actual condition that could have caused the burning of the reactor. None of the cases that were examined showed 3<sup>rd</sup>/5<sup>th</sup> harmonic levels that would justify the damage that occurred.

#### IV. CONCLUSIONS

This work has shown that Student’s t-distribution is suitable to describe the statistical behavior of harmonic levels in a Power System, and can be applied to both measured and calculated results.

The fairly wide variation on the harmonic levels observed in the three phases of the system has been useful to stress the importance of 3-phase modeling to examine the phenomena.

The proposed methodology has been applied to the study of harmonic behavior in filters connected to a HVDC System, but it can be readily applied to other kinds of equipment.

#### ACKNOWLEDGMENTS

The authors would like to thank Mr. Guilherme S. Luz for his assistance with the Itaipu DC Link simulations, and to Professors Edson H. Watanabe and José Luiz R. Pereira for discussions on harmonics.

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Table I Statistical Treatment – Digital Simulation (S) X Measurements (M)

Case	Power Elo CC (MW)	Ih3A (% fund.)		Ih3B (% fund.)		Ih3C (% fund.)		Ih5A (% fund.)		Ih5B (% fund.)		Ih5C (% fund.)	
		Average	Conf.	Average	Conf.	Average	Conf.	Average	Conf.	Average	Conf.	Average	Conf.
S	2330	2.23	0.23	2.28	0.28	2.26	0.25	6.41	0.17	5.97	0.18	6.86	0.16
M		2.44	0.07	1.13	0.07	1.06	0.07	2.67	0.07	2.46	0.07	3.52	0.08
S	2790	2.92	0.17	1.79	0.14	2.21	0.12	6.53	0.15	6.17	0.11	6.98	0.12
M		2.94	0.07	1.70	0.05	2.03	0.06	3.84	0.05	4.17	0.05	4.38	0.07
S	3600	3.67	0.14	2.39	0.16	2.21	0.15	6.42	0.16	6.18	0.16	6.72	0.14
M		3.79	0.05	2.42	0.05	2.37	0.06	6.33	0.06	6.09	0.06	6.41	0.07
S	5590	4.58	0.28	2.83	0.23	2.75	0.25	7.53	0.17	6.37	0.18	7.89	0.16
M		4.51	0.07	2.96	0.06	2.49	0.07	7.55	0.05	6.29	0.06	7.91	0.06