Study, Design and Implementation of Tuned Harmonic Filters: Technical and Economical Overview

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***Abstract*—This paper presents a technical approach, electrical simulations and implementation results for a case study of harmonic disturbances in a manufacturing environment with nonlinear loads (controlled rectifiers of six and twelve pulses), considering the impact of such loads at various levels of the power system. The results of studies and simulations for different load scenarios are compared with the recommended indexes like the IEEE-519, helping the design of tuned harmonic filters. The strong correspondence between the simulation results and the field measurements after the installation of two tuned harmonic filters of 3 Mvar confirms the methodology. Finally, an economic analysis is done by checking the ratio between the cost of installation of the equipment and the cost of penalty by the reactive excess.**

***Keywords*: Power quality, harmonic distortion, harmonic filtering, power factor, reactive compensation.**

I. Introduction

AMONG various solutions for harmonic filtering [1], the passive filtering is the most economical and effective enough for many industrial applications.

In recent decades several articles related to the harmonic distortion or disturbances have been published, describing the increase of losses and energy consumption [2], the fail and wrong operation of protective device [3-5], measurement errors and billing [6-7], failures in capacitor banks [8-9], and many others problems. In Brazil it was reported the overload and shutdown of harmonic filters for 3rd/5th orders of the Itaipu DC link in Ibiúna-SP [10].

It's a consensus that it's necessary to keep harmonic distortion bellow some limit values. Much has been discussed around the world about the impact of harmonic distortion in the electrical system. Indexes and limits were proposed in Brazil [11-13], including technical guidance (Internal Rules of Utilities) [14], in U.S. [15], in European [16-18], and other countries.

During the modernization of a large industrial plant (a manufacturer of steel parts for the automotive industry) it was conducted a study and evaluation of the electrical power system through electrical power measurement and harmonics, at various points of the plant, from low voltage buses (220 to 480 V), medium voltage feeders (6.6 kV and 11.9 kV), forming a database of measured information, including all electrical power data and harmonics spectrum.

From the field measurement and the characteristics of the various components of the installation, as the Thevenin equivalent of the feeder, transformers, induction furnaces and other loads, was used the PTW32 software for the mathematical representation of the facility and construct the respective electrical model. Several simulations were made, as fundamental and harmonic load flow, harmonic resonance, and then these results was compared with the initial measurements, validating the model.

With the new configuration of the electrical installation and loads, including two twelve-pulses induction furnaces and a high-voltage substation of 138 kV with two transformers of 10 MVA, it was run various simulations of the harmonic load flow, comparing the resulting harmonic distortion with the IEEE Std 519 [15], whose result is the basis for the design and implementation of the harmonic filters, connected to the medium voltage bus.

This article is organized as follows: Section II presents a brief theory on the analysis of power system, the problem formulation in terms of harmonic distortion and harmonic filter planning. Section III presents a study of the plant, in which there is a high number of non-linear loads producing high harmonic distortion. The system needs reactive compensation, for the elimination of penalties for excessive reactive consumption, and installation of tuned harmonic filter for mitigating the harmonic effects. Section IV presents the final results of reactive compensation and harmonic filtering, comparing the simulated results with field measurements, and still presenting the economic aspects of the installation. Finally, follows the conclusion of the article.

II. Power System Analisis for Harmonic Study

Based on the Kirchoff law it is possible to analyze the circuit. The sum of the currents entering in a node is equals the sum of the currents coming out of this node. This principle allows the calculation of the harmonic voltages and is used for designing passive harmonic filters. Looking at Fig. 1, we obtain the following relations:

- For the nominal frequency, the utility is the only source of energy and, therefore, the fundamental voltage at the transformer output is proportional to the voltage drop in the sum of the utility impedance and the transformer.
- For harmonic frequencies, the resulting voltage in the output of the transformer is proportional to the product of the harmonic current by the impedance seen by the busbar.

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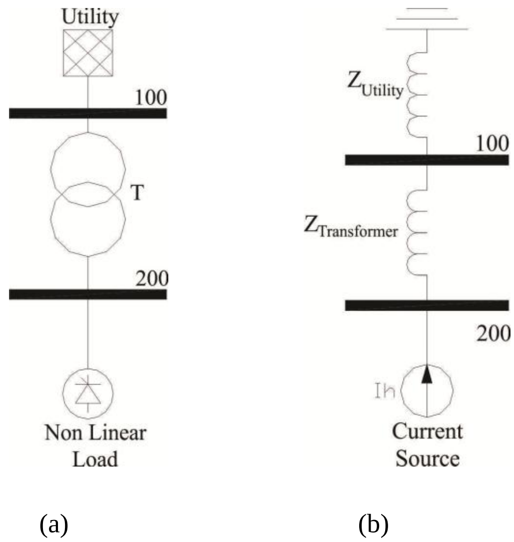


Fig. 1. Typical facility instalation. (a) Simplified one-line diagram; (b) Equivalent electric circuit for current harmonic source.

According with Arrilaga [19], the distribution of voltages and currents through a power system can be represented by linear elements, containing one or more sources of harmonic currents, and it's usually obtained by nodal analysis.

For a generic industrial plant, like in Fig. 2, with harmonic current sources, the harmonic voltages of each busbar can be calculated by the following matrix:

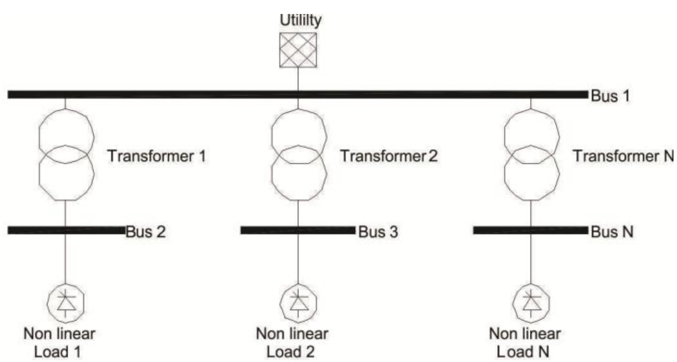


Fig. 2. Generic industrial installation with *n* buses

$$\begin{bmatrix} V_{1(h)} \\ V_{2(h)} \\ V_{n-1(h)} \\ V_{n(h)} \end{bmatrix} = \begin{bmatrix} Z_{11(h)} & Z_{12(h)} & Z_{1n-1(h)} & Z_{1n(h)} \\ Z_{21(h)} & Z_{22(h)} & Z_{2n-1(h)} & Z_{2n(h)} \\ Z_{31(h)} & Z_{32(h)} & Z_{3n-1(h)} & Z_{3n(h)} \\ Z_{n1(h)} & Z_{n2(h)} & Z_{nn-1(h)} & Z_{nn(h)} \end{bmatrix} . \begin{bmatrix} I_{1(h)} \\ I_{2(h)} \\ I_{n-1(h)} \\ I_{n(h)} \end{bmatrix}, \quad (1)$$

Where:
Vn(h) are the harmonic voltages of the *n* busbar;
Znn(h) are the own impedances of the *n* busbar in the *h* order;
Zn n-1(h) are the mutual impedances of the busbars in the *h* order;'
In(h) are the harmonic currents in the *n* busbars;
h = are the harmonic components.

- The resonance phenomena

Circuits that have inductive and capacitive components, present the resonance phenomena with more or less amplification. This phenomenon manifests itself when the capacitive reactance equals the inductive reactance (predominantly associated to the transformer, in industrial installations).

If there are harmonic currents in the system that match the resonant frequency, the harmonic voltage levels will be maximized, for an parallel resonance, or reduced, for a series resonance, as is the case of shunt passive harmonic filters.

In industrial installations inductive loads are predominant, if there are no power capacitors, and the impedance grows proportionally to the frequency and there is no resonance.

Fig. 3 (a) shows a schematic of a typical industrial installation with a step-down transformer and a capacitor for power factor correction. In (b), the equivalent diagram, from which the following relationships can be obtained:

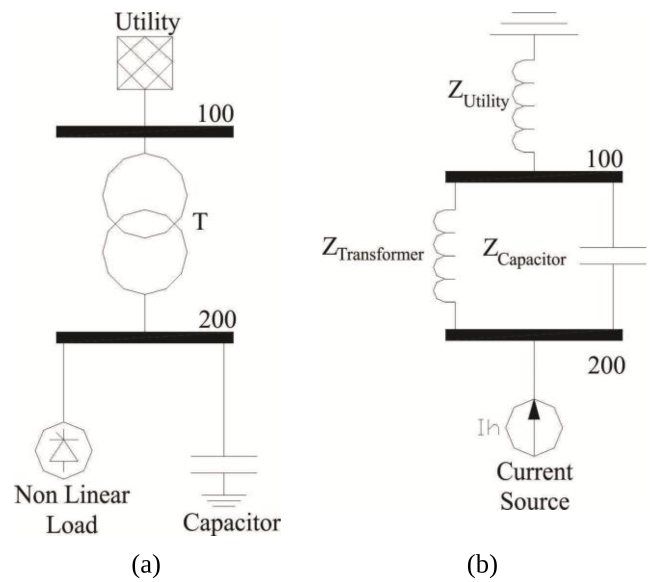


Fig. 3. Electrical circuit with capacitor, for harmonic load flow. (a) One-line diagram; (b) Equivalent electric circuit.

In resonance:

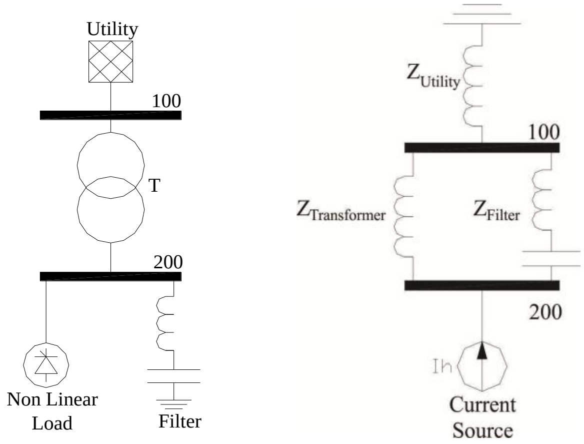
$$XL = XC \rightarrow 2\pi\, f\, L = \frac{1}{2\pi\, f\, C} \quad (2)$$

There is a frequency at which these two impedances are equal and therefore the resonance frequency is:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

In this case, a parallel resonance occurs between the impedance of the transformer and the capacitor. The parallel resonance circuit can be seen in Fig. 3 (b).

If a low-pass filter replaces the capacitor, Fig. 4, with capacitor and inductor in series, there is also the phenomenon of parallel resonance between the filter and transformer, but the series resonance is more pronounced. The frequency response of the three conditions are shown in Fig. 5.



(a) (b)

Fig. 4. Electrical circuit with single tuned filter, for harmonic load flow. (a) one-line diagram; (b) Equivalent electric circuit.

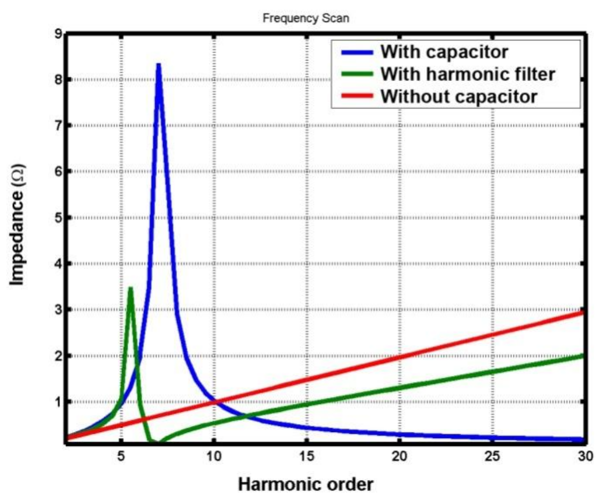


Fig. 5. Graphic representation of resonance phenomena

- Harmonic filtering

The quality factor (Q) of a filter defines the relationship between the center frequency of the RLC filter and its bandwidth, i.e., determines the range of deviations of the frequency around the center frequency tuning. In this aspect, the filter may have high or low quality factor. A low-pass filter has a high quality factor (Q), and is well tuned in one frequency (for example, the 5th). The quality factor is typically between 30 and 60. A damped filter or high-pass, has a low quality factor (Q) with typical value in a region between 0.5 and 5, and has a low impedance in a wide range of frequencies. It is generally used to eliminate higher harmonic orders (e.g., 11th, 13th and 17th orders).

A tuned filter like a low-pass filter is a series RLC combination and is tuned in a harmonic frequency (usually in a low-order).

Its impedance is given by:

$$Z_f = R + j\left(\omega L - \frac{1}{\omega C}\right), \quad (4)$$

Where:

Zf is filter impedance (Ω)
R is the ohmic resistance of the filter (Ω)
ωL is the reactive inductance of the filter (Ω)
ωC is the reactive capacitance of the filter (Ω)

In the resonant frequency (*fr*) the impedance of the filter is minimum and its value is R.

To express the impedance of the filter in terms of the quality factor (Q), the following relationships can be used:

$$X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \quad (5)$$

$$Q = \frac{X_0}{R} \quad (6)$$

Where:
X_0 is the inductance on the resonant frequency
C is the capacitance (F);
L nominal inductance of the reactor (H);
Q is the quality factor of the filter
R is the resistance of the filter (Ω)
ω is the tuned frequency of the filter (rad/s)
ωn is the natural frequency of the system (rad/s)

III. Computational Simulations

The industrial facility considered in this article, as in Fig. 6, presents linear loads, as induction motors, and nonlinear loads, as fully-controlled rectifiers. The main part of the load consists of six-pulse thyristored induction furnaces, with a heat treatment consisting of resistive loads, whose power modulation is made by two-phase thyristored rectifiers, motor and other loads.

From field measurements of the electrical power and harmonics, with the goal of knowing the load profile and the harmonic spectrum, it was built a database and an one-line diagram in the PTW32 software, seen in Fig. 6. Table I summarizes the information of the transformers and loads, while Table II shows the harmonic spectra of the loads. The twelve pulse transformers and the furnaces will be added to the plant from at the first scenario.

In the base case, simulations were performed with fundamental load flow and harmonic load flow, the latter being performed with and without capacitor banks, in order to compare the two situations, if the simulation results are close to measured values. Fig. 7 shows simulation results, considering the following assumptions:

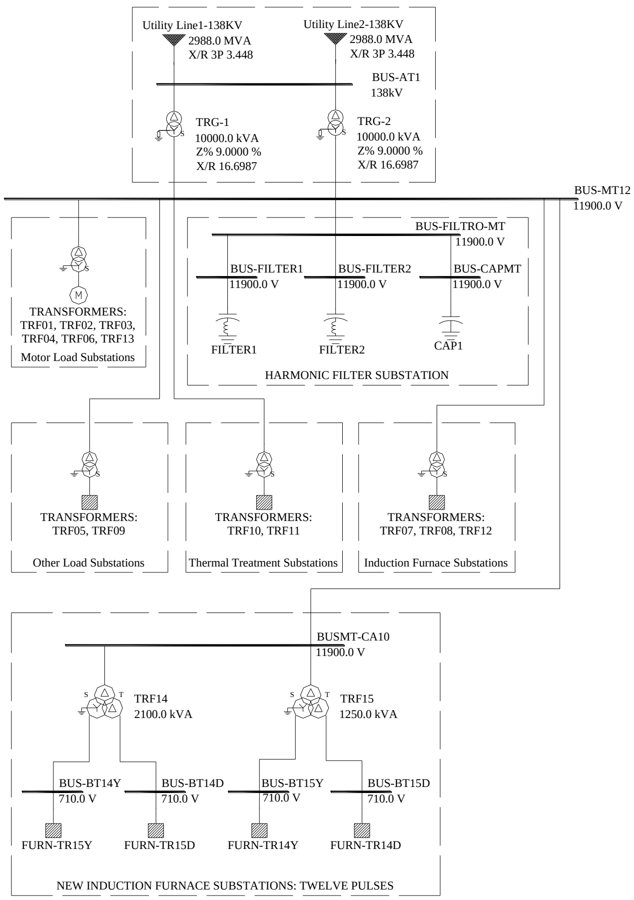


Fig. 6. One-line diagram of the power plant.

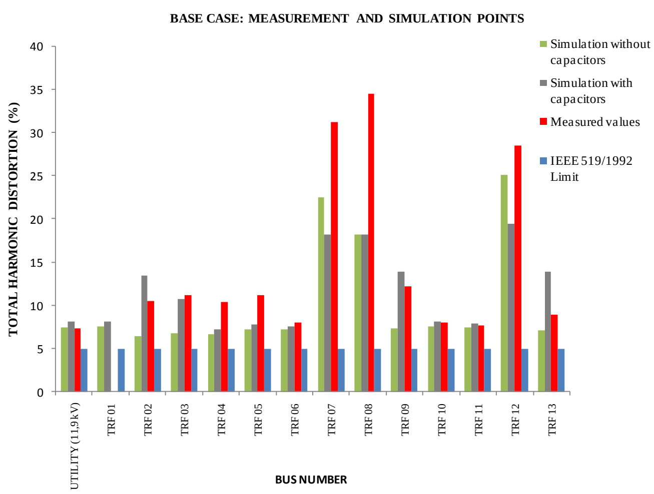


Fig. 7. Data Measured and simulation, compared with the limits of the IEEE Std 519.

The plant is fed initially at 11.9 kV on medium voltage (old substation), with the twelve pulse transformers and induction furnaces numbers 14 and 15 off line.

TABLE I

TRANSFORMER, LOAD AND UTILITY DATA PER TRANSFORMER

Busbar	Busbar Voltage (kV)	Power (MVA)	Impedance (Z %)	X/R	Load (P + jQ) kVA	Load Type
Utility	3226,000	138,000	-----	8,00000	----	----
TRG-1	11,9	10,000	9,00	16,69760	----	----
TRG-2	11,9	10,000	9,00	16,69760	----	----
TRF 01	0,22	0,110	3,70	3,39390	0,00	----
TRF 02	0,46	2,500	5,57	10,47320	1200,18 + j 806,52	Motor
TRF 03	0,46	1,500	5,80	6,54010	229,60 + j 160,16	Motor
TRF 04	0,46	0,300	4,64	4,14980	144,50 + j 89,55	Motor
TRF 05	0,22	0,300	4,97	4,14980	88,20 + j 17,91	Mixed
TRF 06	6,00	1,000	5,25	5,71130	231,00 + j 235,67	Motor
TRF 07	0,48	1,500	5,44	6,54010	496,80 + j 774,33	Induction Furnace Six Pulses
TRF 08	0,48	1,500	5,45	6,54010	372,60 + j 719,21	Induction Furnace Six Pulses
TRF 09	0,46	1,500	6,10	6,54010	252,21 + j 68,20	Mixed
TRF 10	0,44	1,500	5,80	6,54010	762,49 + j 108,64	Resistive two-phase thyristor
TRF 11	0,44	1,500	5,81	6,54010	1049,19 + j 149,50	Resistive two-phase thyristor
TRF 12	0,75	1,500	6,76	6,54010	450,50 + j 720,8	Induction Furnace Six Pulses
TRF 13	0,44	1,500	6,63	6,54010	444,00 + j 494,52	Motor
TRF 14[a]	0,71	2,10	---	---	1600,80 + j 627,40	Induction Furnace Twelve Pulses
TRF 15[a]	0,71	0,71	---	---	951,30 + j ,72,80	Induction Furnace Twelve Pulses

[a]Not measured; calculation in function of load characteristics (new substation); For three-winding transformers, the characteristics will be informed below.

TABLE II

HARMONIC SPECTRUM OF THE NON-LINEAR LOAD

Load	Furnace		Furnace		Furnace		Furnace		Furnace	
Harmonic Order	TR7	Angle (º)	TR8	Angle (º)	TR10	Angle (º)	TR11	Angle (º)	TR12	Angle (º)
1	100	257,28	100	0,26	100	9,52	100	4,86	100	64,86
2	0,9	9,73	0,8	18,49	0,1	5,85	0,1	9,94	0,5	113,45
3	2,4	211,59	1,9	179,19	0,4	227,2	0,5	306,15	1,9	10,44
4	0,7	319,04	0,6	155,94	0,2	46,35	0,2	131,27	0,5	177,23
5	23	29,19	23	178,29	4,1	153,2	2,6	40,78	23	288,96
6	0,4	178,9	0,3	54,73	0,7	294,55	0,2	185,75	0,3	189,65
7	11	184,61	11	179,06	1,9	303,62	0,9	1,65	10	191,43
8	0,4	4,22	0,2	175,75	0,3	138,03	0,1	120,36	0,1	308,99
9	2,5	150,76	2,2	358,37	0,2	186,12	0,1	78,78	1,9	251,18
10	0,4	287,97	0,6	314,15	0,1	49,92	0,1	303,33	0,2	68,23
11	10,6	316,39	10,7	355,7	0,5	175,26	0,2	337,96	10,3	167,79
12	0,5	80,71	0,4	176,08	0,1	309,37	0,1	92,74	0,1	352,15
13	6,5	110,77	6,5	357,82	0,2	354,38	0,1	18,27	6,1	72,11
14	0,5	212,84	0,2	95,49	0,2	199,61	0,1	240,35	0,1	177,02
15	2,4	85,77	2,3	172,42	0,1	325,34	0,1	121,35	2	124,02
16	2	183,09	0,4	36,36	0,1	315	0,1	257,47	0,3	338,2
17	7,5	239,8	7,6	173,09	0,15	90,81	0,1	199,22	7,2	43,71
18	1,3	148,49	0,5	333,97	0,15	231,08	0,1	137,69	0,2	262,86
19	4,8	31,93	4,1	178,46	0,15	208,1	0,1	152,22	4,4	313,72
20	0,2	315,66	2	156,14	0,1	131,57	0,1	102,22	0,7	33,28
21	2,7	358,04	1,4	14,06	0,1	21,89	0,1	261,86	1,8	358,31
22	0,3	330,99	2	309,02	0,1	105,64	0,1	48,17	1	112,49
23	6,4	163,13	7	345,89	0,1	186,22	0,1	309,36	6,6	279,35
24	0,2	29,67	0,5	72,97	0,1	273,03	0,1	16,32	0,2	303,12
25	3,5	324,95	3,9	350,51	0,1	294,87	0,1	231,92	3,5	195,06
26	0,3	112,55	0,5	106,88	0,1	184,25	0,1	303,65	0,2	63,76
27	2,6	288,08	2,7	162,43	0,1	271,29	0,1	61,9	2,8	236,01
28	0,3	74,09	0,4	108,58	0,1	307,41	0,1	326,81	0,3	337,77
29	5,8	87,4	6,3	164,56	0,1	331,25	0,1	203,55	5,5	154,82
30	0,1	358,8	0,3	246,72	0,1	115,1	0,1	152,96	0,4	296,49
31	3,4	248,2	3,2	166,25	0,1	186,51	0,1	254,98	2,8	68,22

With the simulation results, it can be seen that in the busbars where there are induction furnaces (transformers 7, 8 and 12) the harmonic voltage values are lower than measured. This is explained by the occurrence of the "Notch" effect during the commutation of the rectifier of the induction furnace. The values of harmonic distortion in all busbars are below of the limits recommended by IEEE 519 [15].

- Scenario 1: Migration the substation to the 138 kV voltage with contingency of losing one 10 MVA transformer

Continuing the simulation, the power plant is now fed by one 10 MVA transformer (contingency situation without one of the two transformers) and more two twelve-pulses induction furnace; the transformers data are in table III, containing transformers' data and the harmonic spectrum; the fig. 8 contain the harmonic spectrum. Consider a contingency scenario, in which occurs:

- Loss of one 10 MVA transformer;

The introduction of three electrical degrees phase-shift on transformer secondary windings of twelve pulses furnaces (sides Δ and Y) is made in order to simulate the impact of an asymmetry in the thyristors firing angle control.

Performing the simulations of the fundamental and harmonic load flow, the results are shown in Fig. 9.

Comparing the results with the standard [15], as shown in Fig. 9, there is a harmonic voltage distortion violation, except on the Utility busbar. This clearly indicates the need of harmonic filters. If the two transformers in 138 kV substation are connected, the distortion results would be less severe. This occurs mainly due to the change of the nodal impedance of the busbars due to the shutdown of one transformer 10 MVA/138 kV.

When a shutdown of a 10 MVA transformer occurs, there is a theoretical reduction of 50% in short-circuit level at the 11.9 kV busbar and, consequently, a change in self and mutual impedances of the busbars and a higher voltage harmonic distortion.

TABLE III
TREE WINDING TRANSFORMED DATA

Transformer nº	Winding	%R	%X	kVA Base
Transformer TRF14	Primary-Secondary	0,834	6,23	1050
	Primary-Tertiary	0,833	7,81	1050
	Secondary-Tertiary	0,833	7,81	1050
Transformer TRF15	Primary-Secondary	0,84	5,84	625
	Primary-Tertiary	0,84	7,31	625
	Secondary-Tertiary	0,84	7,31	625

The induction furnaces can operate with less than 50% of the nominal load and, in this condition, the reactive power consumption grows a lot. The table IV presents some operational conditions and, as can be seen, the power factor in the half load power is very small.

Considering the operation of the furnaces with less than 50% load, based on table IV, and performing the fundamental load flow, the complex power measured by the utility is:

$$S = 6310 + j\,6568 \text{ kVA} \quad (7)$$

Resulting in a 0.69 power factor.

Brazilian utilities impose a penalty in the energy bills when the power factor is lower than 0.92. Considering the result of the simulations, where the power factor is lower than the limit and the harmonic distortion is higher that the recommended indices, the technical solution is to use a tuned harmonic filter.

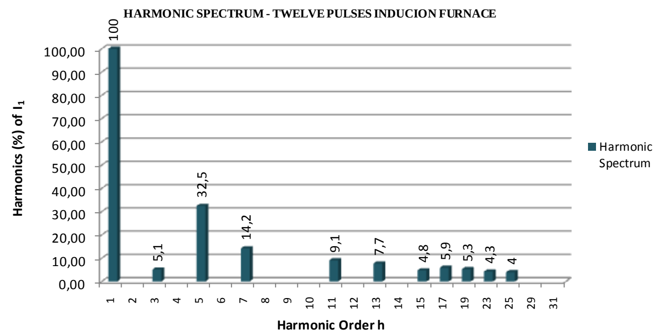


Fig. 8. Typical harmonic spectrum of Metaltrend twelve pulses induction furnace.

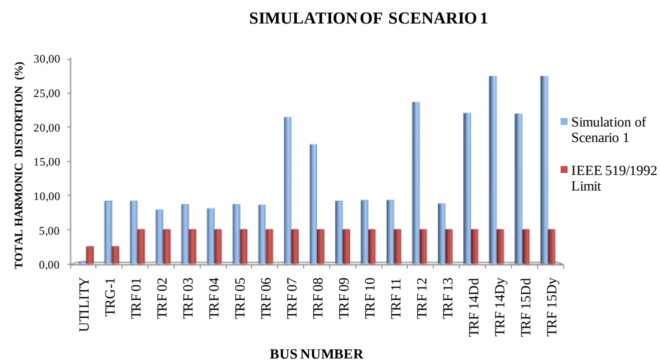


Fig. 9. Simulation of Scenario 1, compared with the limits of the IEEE Std 519.

TABLE IV
TWELVE PULSES FURNACE - CHARACTERISTIC LOAD, HARMONIC AND POWER FACTOR

Situation	Load			
	Average		Full	
Total Power (kW)	308		1500	
PF	0,41		≥ 0,92	
Apparent power per winding (kVA)	375,00		2000,00	
	305,00		813,00	
	(A)	(%)	(A)	(%)
1st order Current	252	100,00%	757	100,00%
3nd order Current	9	3,60%	39	3,60%
5nd order Current	148	59,10%	246	59,10%
7nd order Current	83	33,20%	107	33,20%
11nd order Current	3	1,00%	69	1,00%
13nd order Current	13	5,00%	58	5,00%
15nd order Current	10	4,00%	36	4,00%
17nd order Current	15	5,90%	45	5,90%
19nd order Current	13	5,30%	40	5,30%
23nd order Current	11	4,30%	33	4,30%
25nd order Current	10	4,00%	30	4,00%

These filters supply capacitive reactive energy in the fundamental frequency, removing the penalty in the energy bills, and, in a second manner, are part of the tuned harmonic filter.

Considering an elevation of power factor around 0.95 the following formulation can be used:

$$Q_C = [\tan(\text{acos}(0.69))-\tan(\text{acos}(0.95))].P\ (\text{kvar}) \rightarrow \quad (8)$$
$$Q_C = 0.422\text{x}6310 = 4544\ \text{kvar};$$

Where Q_C is the energy of the power capacitor to elevate the power factor to 0.95.

Considering that the no load loss of the transformers must be compensated, it could be used 2% of the total apparent power of the transformers; as there are 42.2 MVA of transformer, a 844 kvar of capacitors can be used. As it must be used power of capacitor commercial values, and considering the calculated 5388 kvar, it is defined a stage of 3000 kvar per filter. In other words, two equal stages of 3 Mvar.

The IEEE Std 1531 [20] recommends that the low-pass harmonic filter must be tuned between 2 to 4% below the natural frequency of the harmonics generated by nonlinear loads. The predominant harmonic on six-pulse converter is the 5th order and, therefore, the adopted tuning for the filter is the 4.8th harmonic order.

Continuing the design, after defining the power capacitor, it is necessary calculate the inductor of the tuned filter. Using the equation (2) and re-writing with the capacitor value:

$$X_L = X_C \rightarrow 2\pi\ f\ L = \frac{1}{2\pi\ f\ C}\ \text{and how:} X_C = \left(\frac{V_N^2}{Q_C}\right) \rightarrow X_C = \left(\frac{11{,}9^2}{3000}\right) \rightarrow$$
$$X_C = 47{,}20\Omega;$$
$$X_L = 2\pi fL \rightarrow 2\pi fLh = \frac{X_C}{h} \therefore L = \frac{X_C}{2\pi fh^2} \quad (8)$$
$$X_C = 47{,}20\Omega \rightarrow L = \frac{47{,}20}{2.\pi.60.4{,}80^2} \rightarrow L = 5{,}40\,\mu H \quad (9)$$

With the capacitor and inductor calculated, one define the quality factor *(Q)* of the filter. For minimizing the losses, a quality factor of 50 can be use with good results. From the equation (6):

$$R = \frac{X_0}{Q} = \frac{2.\pi.60.5{,}40^{-3}.4{,}80}{50} \rightarrow R = 0{,}195\Omega \therefore R = 20m\Omega \quad (10)$$

After filter design it's necessary to re-run the previous studies and identify the worst case for determining the parameters of the tuned filter, like: nominal voltage of the capacitors, rms current of the reactor and power dissipation of the resistor, if used. The fig. 10 shows the simulation of the worst case, including the contingency, with one tuned harmonic filter. There is also the result without the contingency, comparing the results with the IEEE 519 limits.

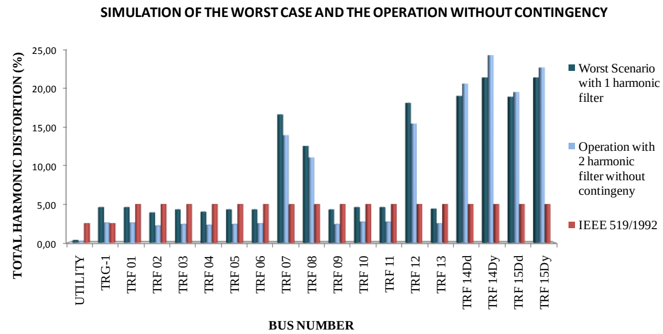


Fig. 10. Simulation of the worst case with contingency and the normal operation, compared with the limits of the IEEE Std 519.

As can be seen, even with contingency, all busbars, except the one that feeds the induction furnace, have the total harmonic distortion below the IEEE 519 limits. Without contingency, the fundamental power flow, result in 0.99 power factor for the utility, solving the problem of penalties.

IV. FINAL RESULT OF HARMONIC FILTERING AND THE ECONOMICAL OVERVIEW

With the last simulation results, without contingency, it is possible to compare the results with the field measurements, after the tuned harmonic filter installation. This allows to prove the power system modeling, the effectiveness of the power factor compensation and the mitigation of the harmonic voltage. The fig. 11 shows the active power and fig. 12 shows the harmonic voltage measured at the 11.9 kV busbar. Fig. 13 shows the simulation and the field measurement of the harmonic current of one stage of the harmonic filter.

As a final part of the simulation, Fig. 14 presents the total power loss including fundamental and harmonic contributions without harmonic filter, and including the loss with two tuned filters, without contingency. By the simulation, the conclusion is that the installation of harmonic filters in the 11.9 kV busbar reduces the total losses. Considering a reduction of 4.89 kW at the power demand with the installation of two tuned harmonic filter, in one month, the total energy saved is around 3000 kWh.

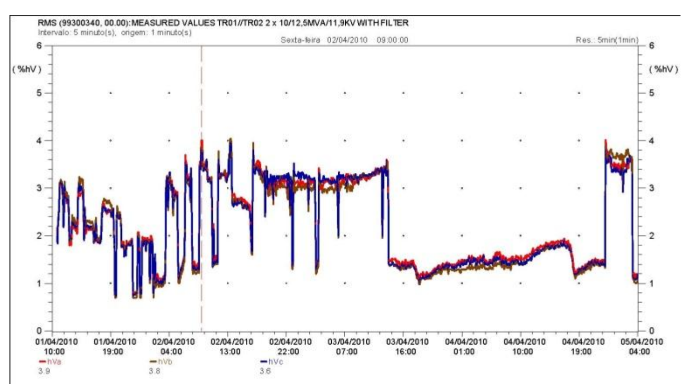


Fig. 11. Active power measured on 11,9 kV busbar, with tuned harmonic filter turned on.

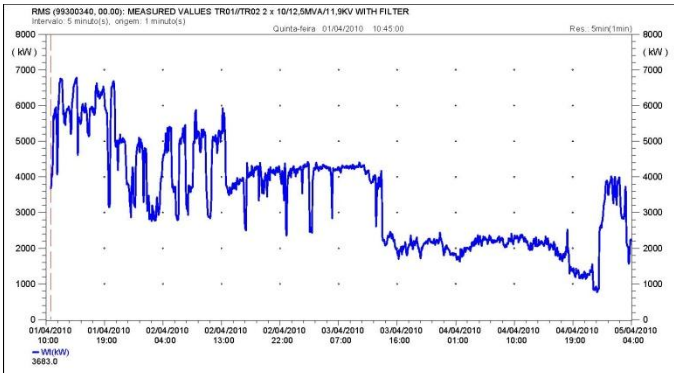


Fig. 12. Total harmonic distortion measured on 11,9 kV busbar, with tuned harmonic filter turned on.

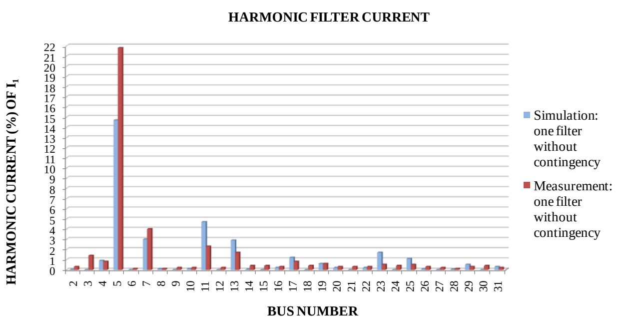


Fig. 13. Comparing the harmonic current of the filter: simulation without contingency and with the normal operation (suppressing the fundamental).

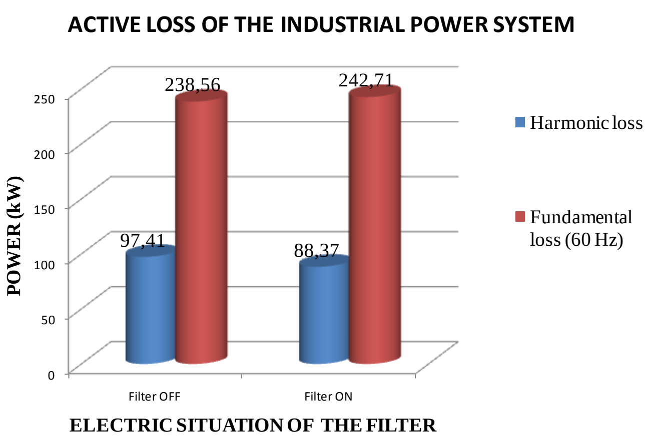


Fig. 14. Active loss in the power system for two situations: filters off line and filters connected.

- Economic overview

In industry, all types of project must have an ROI (Return on Investment) or normally known as Pay-Back. The base of this article is a study, project and implementation of a two single tuned harmonic filters whose the Pay-Back occurs in less than six months. The factory was fined with more than seventy thousand U.S. dollars in the beginning of tests of the two new twelve pulses furnace, which made the project indispensable, in technical and economic terms. The table V summarizes the investment, penalty and the ROI.

The fig. 15 shows the tuned harmonic filter of the 11.9 kV substation, on the filters room.

TABLE V
PROJECT COST AND PAY-BACK

Total cost of project and implementation	US$ 685.669,78
Total cost of penalty on energy bills with taxes	US$ 114.640,43
Pay-Back (months)	5,99

Fig. 15. Filters room, and the two tuned harmonic filters.

V. CONCLUSIONS

The paper has presented a brief theory of power system harmonics simulation, how to treat the non-linear loads, how to understand the problem of harmonic propagation and the possibility of aggregate harmonic solution with power factor correction. Finally, was presented an economical overview of the cost of installation of two tuned harmonic filters comparing with the penalty on the energy bills, concluding that on this real case, the goal of technical and economical solution was obtained.

VI. REFERENCES

[1] W. G. Chang, Shou-Yung Chu, Hung-Lu Wang, "A new method of passive harmonic filter planning for controlling voltage distortion in a power system", IEEE Trans. Power Delivery, vol. 21, pp. 305-312, December, 2005.

[2] V.E. Wagner, J.C. Balda, D. C. Griffith, A. McEachern, T. M. Barnes, D. P. Hartmann,D. J. Phileggi, A. E. Emannuel, W. F. Horton, W. E Reid, R. J. Ferraro, W. T. Jewell, "Effects of Harmonics on Equipment", IEEE Transactions on Power Delivery, vol. 8, N 2, April, 1993.

[3] W. A. Kramer Elmore, C.A. Zocholl, "Effect of Waveform Distortion on Protective Relays", IEEE Transactions on Industry Applications, V. 29, 03-04/1993.

[4] Alexander Kusko, Marc T. Thompson, Power Quality in Electrical Systems, McGraw-Hill, 2007, pp. 45-46.

[5] Recep Yumurtaci, Kayhan Gulez, Altug Bozkurt, Celal Kocatepe, Mehmet Uzunoglu, "Analysis of Harmonic Effects on Electromechanical Instantaneous Overcurrent Relays with Different Neural Networks Models", International Journal of Information Technology Vol. 11 No. 5, 2005.

[6] V. Rozenshtein, "The Harmonics Influence in Energy Measurement and its Utilization for Power Quality Improvement," IEEE Power Engineering Review, October 2002.

[7] Alessandro Ferrero, "Measuring electric power quality: Problems and perspectives", Journal of the International Measurement Confederation (IMEKO) Elsevier, Volume 41, Issue 2, February 2008, Pages 121-129, Advances in Measurements of Electrical Quantities.

[8] N. D. Rao , S. I. Sporea and A. Sawma, "Analisys of Resonance Problems and Harmonic Filter Design in Power Factor Correction Capacitor Applications", IEEE Canadian Conference on Electrical and Computer Engineering, 1998.

[9] Wei-Jen Lee, K. Narayanan, T. Maffetone and P. Didsayabutra, "The design of a capacitor bank early warning system", IEEE Transactions on Industry Applications, Volume: 39 Issue: 2, page(s): 306 – 312, Mar/Apr 2003.

[10] R. A. A. Gonçalves, E. M. Brandi, J. S. Luz, J. R. Medeiros, A. R. Saavedra, "Elo de Itaipu - Filtros de 3/5 Harmônicos da Estação Inversora de Ibiúna – Necessidade, Especificação e Projeto", XIII ERIAC, Décimo Terceiro Encontro Iberoamericano do Cigré, 2009.

[11] Critérios e Procedimentos para o Atendimento a Consumidores com Cargas Especiais- Revisão 1" ; Nov/97; GGOI/SCEL e GCPS/CTST.

[12] "Termo de Referência – Grupo de Trabalho Especial de Qualidade de Energia Elétrica"; GAT-Junho/1999.

[13] Resolução Normativa nº 345, de 16 de dezembro de 2008; Agência Nacional de Energia Elétrica - ANEEL; Aprova os Procedimentos de Distribuição de Energia Elétrica no Sistema Elétrico Nacional - PRODIST, e dá outras providências.

[14] GED 110 - Atendimento a Cargas Geradoras de Harmônicos em Sistemas Primários de Distribuição - GED 110, CPFL.

[15] IEEE Std 519-1992 Recommended Practices and Requeriments for Harmonic Control in Electrical Power Systems.

[16] IEC 61000-2-2 ELECTROMAGNETIC COMPATIBILITY (EMC) Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public lowvoltage power supply systems.

[17] IEC 61000-2-4 Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances.

[18] IEC 61000-3-6 Electromagnetic compatibility (EMC) Part 3: Limits. Section 6: Assessment of emissions limits for distorting loads in MV and HV power systems. Basic EMC publication

[19] Arrillaga, Jos.; Watson, Neville R.; Power System Harmonics; Jonh Wiley & Sons; Second Edition, John Wiley & Sons, 203, pp. 143-189.

[20] IEEE STD 1531 - Guide for Application and Specification of Harmonic Filters

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