Passive Filtering of Harmonics in an Industrial Plant: A Documented Case

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Abstract – Harmonic resonance, in a low voltage industrial plant with heavy non-linear loads, may occur when the system's natural frequency corresponds to the frequency of this source of harmonic current. A case of parallel harmonic resonance that resulted in the misbehavior of the plant is verified by means of measurements and computer simulation. Based on this information, estimations of voltage and current harmonic content were made and passive filters were designed, built and inserted in this plant to eliminate the parallel resonance.

I. Introduction

Industrial plants, by themselves, almost always present a low power factor and some power factor correction procedure must be implemented in order to maintain reliability and to comply with regulatory standards. "On shelf" solutions intended to comply with such standards may sometimes result in unexpected behavior by the plant and in some cases may be disastrous.

In fact, if non-linear loads are present (as a heavy portion of the total load) and someone tries to compensate for the power factor by just adding capacitor banks, as required for linear loads, parallel resonance conditions could possibly be present.

The present work deals with this case. An industrial plant, fed by a 1 MVA delta-wye three-phase transformer, (13.8kV/380 V RMS and 60 Hz), with a capacitor bank for reactive power compensation, that was running with no problems, experienced a lot of trouble (switchgear tripping, capacitor failures, relay overture due to no apparent reason) after an important load increment.

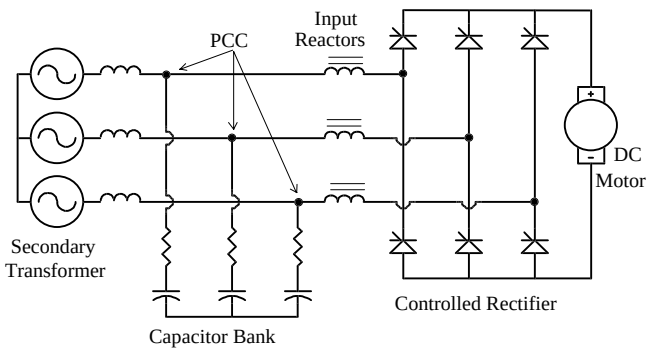

Fig. 1 - Industrial plant: simplified representation.

Several controlled rectifiers feeding DC machines (DC drives) and some other converters are responsible for most of the power load.

Roughly, the industrial plant may be represented as shown in Fig. 1, where three voltage sources model the mains (the secondary side of the three-phase transformer). A controlled rectifier (with an input reactor) feeding a DC motor represents the total load, and a three-phase automatically commutated capacitor bank provides power factor compensation. Fig. 2 shows a one-phase diagram of such a system, including some parameter values.

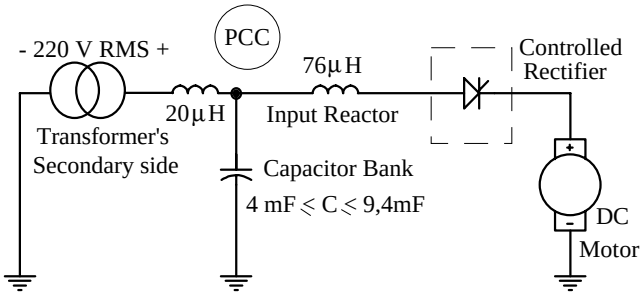

Fig. 2 - Industrial plant: one-phase diagram.

In order to determine the reasons for this anomalous behavior, some measurements were taken, as shown in Figs. 3 – 5, using a light load condition.

Fig. 3 presents the phase voltage v_T, the line current i_T and the instantaneous power p_T in a phase of the secondary side of the transformer. It is easy to notice the high level of distortion for this voltage and current, much higher than the recommended levels.

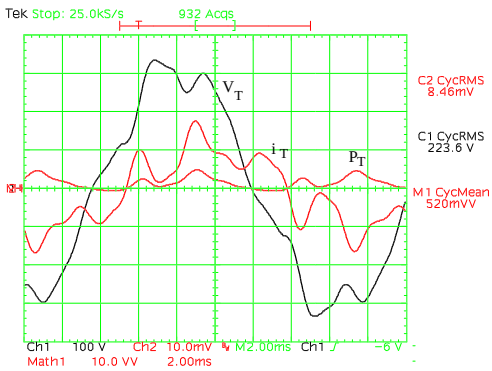

Fig. 3 – Phase voltage v_T, line current i_T and instantaneous power p_T in a phase of the secondary side of the transformer. Active Power = 52 kW, Apparent Power = 189.16 kVA, PF = .275. (100 V/div. (223.6 V_{RMS}) and 1000A/div. (846 A_{RMS})).

Fig. 4 shows the phase voltage v_C at PCC (Point of Common Connection) and the line current i_C in a phase of the capacitor bank. Fig. 5 presents the phase voltage v_1, the line current i_1 at the input of the controlled rectifier (to the left of the input reactor) and one-phase instantaneous power p_1.

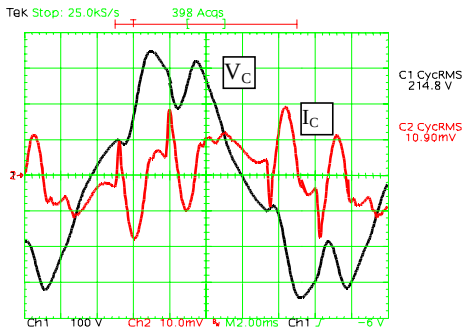

Fig. 4 – Phase voltage v_C and line current i_C in the capacitor bank (100 V/div. (214.8 V_{RMS}) and 400A/div. (436 A_{RMS})).

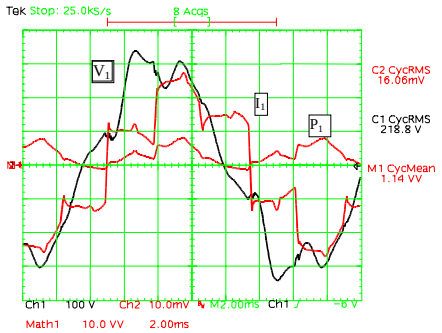

Fig. 5 – Phase voltage v_1 and line current i_1 at the input of one controlled rectifier (to the left of the input reactor) and one-phase instantaneous power p_1. Active Power = 22.8 kW, Apparent Power = 70.28 kVA, PF = .324 (100 V/div. (218.8 V_{RMS}) and 200A/div. (321.2 A_{RMS}).

At a normal load condition, voltage and current wave shapes were worse and the transformer was always overloaded, even when the active power was at the normal expected value.

II. Passive Filtering

Based on the information obtained by the analysis of several measurements, it was possible to model this electrical plant and to simulate some particular situations, in order to adjust the parameters of the model and to get more information about critical operation. It was possible to determine the parallel harmonic resonance conditions that resulted, in practice as well as in computer simulation, when the seventh module of the three-phase automatically commutated capacitor bank was inserted to correct the power factor displacement. These resonance conditions were due to the seventh harmonic or 420 Hz (coincidentally the order of the harmonic was the same number as capacitor modules inserted).

To overcome this problem, passive filters were designed to trap harmonic currents of orders 5, 7, 11 and 13. This was done by adding four three-phase passive filter sections, in a wye connection, with separated floating common points as shown in Fig. 6. Notice that for the 5th, 7th and 11th order the passive filters are formed by RLC series topology in a shunt connection at the PCC (Point of Common Connection). For the 13th and higher order harmonics a low impedance path was provided by a high-pass filter, obtained by bypassing the reactor with a low resistance resistor.

So these passive filters replaced the three-phase automatically commutated capacitor bank; in fact, the high-pass filter section incorporates the automatically commutated capacitor bank with different values for the capacitance, to match the design of the whole filtering system.

III. Basic Filter Design and Specification

First of all it is necessary to obtain the ratio between the short circuit current capacity at PCC and the load nominal current at the fundamental frequency as stated in (1) to (3). With this value one can get the maximum allowed level K_h (relative to I_L) for each harmonic current at PCC, according to IEEE519-1992 Std [1].

$$\frac{I_{sc}}{I_L} = \frac{Vs \quad / Z_s}{I_L} \qquad (1)$$

$$Z_s = \sqrt{R_s^2 + (\omega L_s)^2} \qquad (2)$$

$$\omega = 2\pi f \qquad (3)$$

Where:

V_s: RMS voltage [V] at PCC (in this case, the secondary side of the main transformer).

I_L: RMS fundamental current [A] at PCC.

R_s, L_s: Series equivalent resistance [Ω] and inductance [H] of the main transformer (seen at the secondary side).

ω: Fundamental angular frequency [rad/s].

f: Fundamental frequency [Hz]

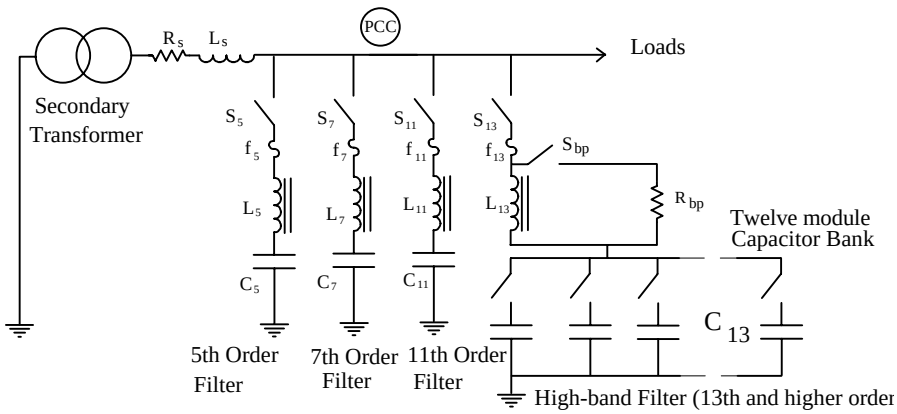

Fig. 6 - One-phase diagram of the plant with passive filters.

A. RLC filter design

At the tuned frequency f_h=h*f (where h is the harmonic order) the hth order filter behaves as a pure resistance R_h and the whole system can be approximately represented by a current divider shown in fig. 7, where the current source represents the harmonic current drawn by the linear load.

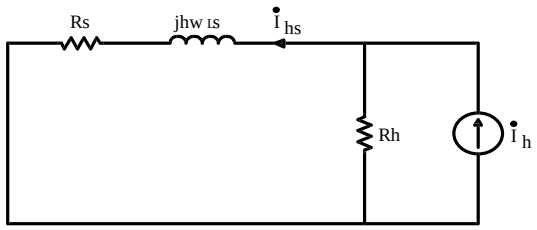

Fig. 7: Equivalent circuit of the electric system at the hth harmonic frequency.

Through circuit analysis, expression (4) should be reached. This expression defines the value of the equivalent resistance R_h of the filter inductor R_h. Expressions (5) and (6) are used to determine the value of the inductance L_h and of the capacitance C_h, respectively.

$$R_h = \frac{K_h I_1}{(I_h^2 - K_h^2 I_1^2)}\left[R_s K_h I_1 \pm \sqrt{\left[(R_s I_1)^2 + (h\omega L_s)^2 (I_h^2 - K_h^2 I_1^2)\right]}\right] \quad (4)$$

$$L_h = \frac{R_h Q}{h\omega} \quad (5)$$

$$C_h = \frac{1}{h^2 \omega^2 L_h} \quad (6)$$

Where:

R_h: Series equivalent resistance [Ω] of the hth order filter.

K_h: Maximum allowed level (relative to I_L). for the hth order harmonic current at PCC, according to IEEE519 - 1992 Std [1].

I_1: RMS fundamental current [A] at PCC.

I_h: RMS h^{th} order harmonic current at PCC.

h: harmonic order.

R_s, L_s: Series equivalent resistance [Ω] and inductance [H] of the main transformer (seen at the secondary side).

ω: Fundamental angular frequency [rad/s].

Q: Inductor quality factor, usually $20 \leq Q \leq 50$ for this kind of application.

Filters were designed by following general procedure [2]-[4] for electrical devices, and by paying attention to the presence of harmonics.

B. Basic specification

 # Three-phase reactors

All reactors must be specified considering the fundamental current and the current harmonic content and also the quality factor required for this kind of application.

Inductance: L_5 = 93 μH, Quality factor at 300 Hz: Q_5 = 50, Voltage insulation: 700 V peak, Total nominal current: 500 A_{RMS}, 60 Hz nominal current: 400 A_{RMS}, 300 Hz nominal current: 300 A_{RMS}.

Inductance: L_7 = 112 μH, Quality factor at 420 Hz: Q_7 = 50, Voltage insulation: 700 V peak, Total nominal current: 210 A_{RMS}, 60 Hz nominal current: 110 A_{RMS}, 420 Hz nominal current: 180 A_{RMS}.

Inductance: L_{11} = 53 μH, Quality factor at 660 Hz: Q_{11} = 50, Voltage insulation: 700 V peak, Total nominal current: 150 A_{RMS}, 60 Hz nominal current: 100 A_{RMS}, 660 Hz nominal current: 110 A_{RMS}.

Inductance: L_{13} = 15 μH, Quality factor at 780 Hz: Q_{13} = 50, Voltage insulation: 700 V peak, Total nominal current: 470 A_{RMS}, 60 Hz nominal current: 460 A_{RMS}, 780 Hz nominal current: 50 $A_{RMS,}$ 1020 Hz nominal current: 40 $A_{RMS,}$ 1140 Hz nominal current: 30 A_{RMS}.

 # Capacitors (Three-phase banks)

Capacitors have a two-fold function, so they must be specified for a higher voltage than the nominal voltage in order to be able to handle the reactive power distortion (harmonic filter function) as well as the linear reactive power (displacement factor correction function).

C_5 = 3*165 kVAr, 380 V_{RMS}.
C_7 = 3* 70 kVAr, 380 V_{RMS}.
C_{11} = 3*60 kVAr, 380 V_{RMS}.
C_{13} = 3*100 kVAr, 380 V_{RMS}.

 # Bypass resistor (3 units)

R_{bp} = 92.5 mΩ, 1.5 kW.

 # Fuses, switches, cables and other devices were rated according to general rules, taking harmonic currents into account.

IV. Experimental Results

The designed filters were built and after their installation, several measurements were taken when the industry was running at nominal load, in order to verify the performance of the whole system. In Figs. 8-20 and Tables 1-5 one can see the improvement in the quality of the voltage and current.

Notice how the harmonic voltage level, which complies with IEEE Standards [1], allowed the plant to work with no further problems and how the transformer operates at a Power Factor greater than 0.9 using more or less 60% of its nominal power. One can also notice the effectiveness of the filter sections in carrying most of the tuned frequency current.

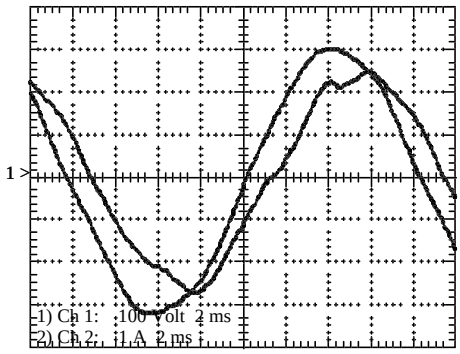

Fig. 8 – Phase voltage and line current on the secondary side of the transformer (100V/div, 1000A/div, 2mS/div).

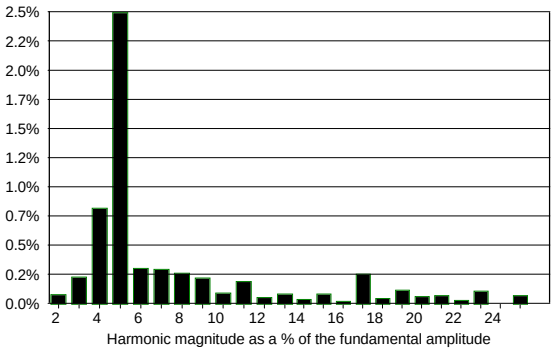

Fig. 9 – Harmonic voltages in the secondary side of the transformer.

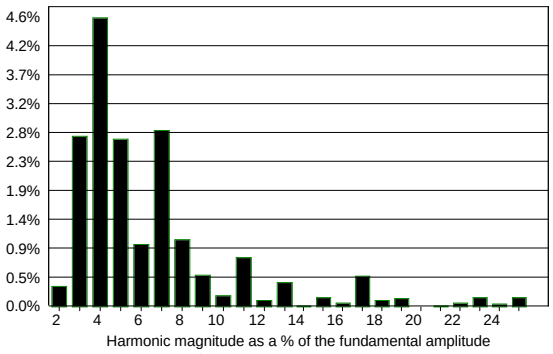

Fig. 10 – Harmonics of line current in the secondary side of the transformer.

Table 1 –Electrical data concerning one-phase of the secondary side of the transformer.

Voltage V RMS	*Current A RMS*	*Power kW*	*Voltage THD*	*Current THD*
220	*880*	*177*	*2.71%*	*6.95%*

Power Factor	*Displacement Power Factor Degrees*	*Instantaneous Power kVA*	*Reactive Power kVAr*
.911	*25.2*	*194*	*80*

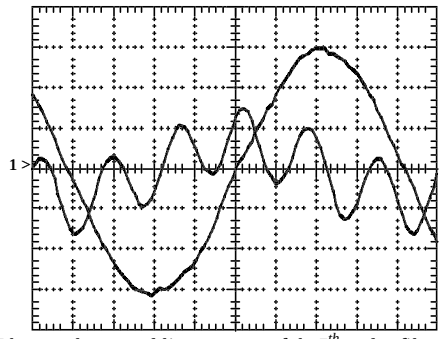

Fig. 11 – Phase voltage and line current of the5th order filter (100V/div, 300A/div, 2mS/div).

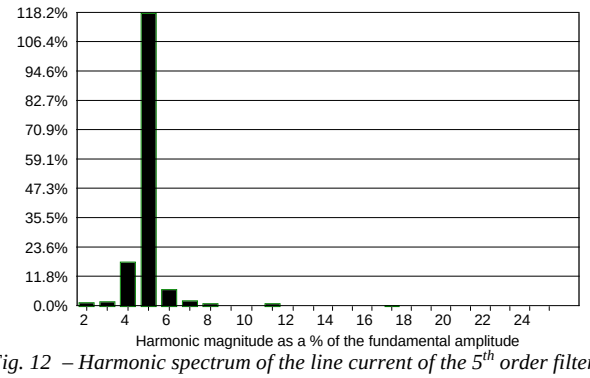

Fig. 12 – Harmonic spectrum of the line current of the 5th order filter.

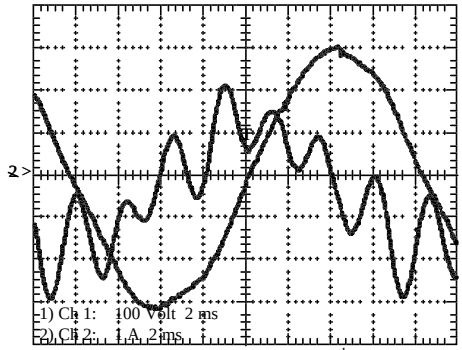

Fig. 13 – Phase voltage and line current of the7th order filter (100V/div, 100A/div, 2mS/div).

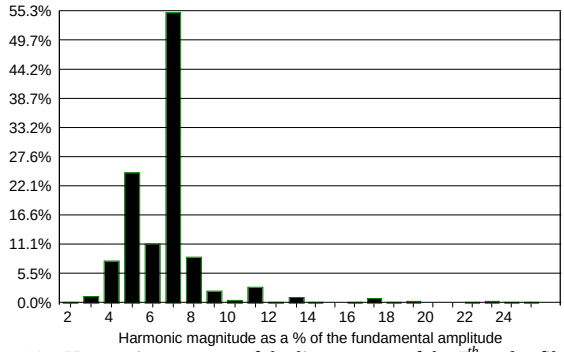

Fig. 14 – Harmonic spectrum of the line current of the 7th order filter.

Table 2 –Electrical data concerning one-phase of the 5th order filter.

Voltage V RMS	Current A RMS	Power kW	Voltage THD	Current THD	Power Factor	Power Factor Displacement Degrees	Instantaneous Power kVA	Reactive Power kVAr
213	403	1.74	2.73%	119.82%	.0269	-89.8	64	64.5

Harmonic order	Freq	Voltage RMS	Voltage %	Voltage Phase Degrees	Current RMS * 100	Current %	Current Phase Degrees
Fundamental	60 Hz	212 V	100.00%	0.0	2.53 A	100.00%	0.0
Harmonic 3	180 Hz	1.02 V	0.48%	-128	49.4 mA	1.95%	-8.27
Harmonic 5	300 Hz	3.75 V	1.77%	-109	2.99 A	118.20%	-52.1
Harmonic 7	420 Hz	1.06 V	0.50%	162	65 mA	2.57%	66.1
Harmonic 11	659 Hz	524 mV	0.25%	-156	29.7 mA	1.17%	106
Harmonic 13	779 Hz	565 mV	0.27%	-118	9.56 mA	0.38%	-14.3
Harmonic 15	899 Hz	263 mV	0.12%	86.9	4.3 mA	0.17%	12

Table 3 –Electrical data concerning one-phase of the 7th order filter.

Voltage V RMS	Current A RMS	Power W	Voltage THD	Current THD	Power Factor	Power Factor Displacement Degrees	Instantaneous Power VA	Reactive Power VAr
210	132	259	3.06%	62.32%	.0099	-90.6	27 600	27 600

Harmonic order	Freq	Voltage RMS	Voltage %	Voltage Phase Degrees	Current RMS * 100	Current %	Current Phase Degrees
Fundamental	60 Hz	210 V	100.00%	0.0	1.03 A	100.00%	0.0
Harmonic 3	180 Hz	749 mV	0.36%	-123	13.6 mA	1.33%	-6.57
Harmonic 5	300 Hz	5.22 V	2.49%	-110	239 mA	23.34%	163
Harmonic 7	420 Hz	1.36 V	0.65%	168	572 mA	55.81%	-64.6
Harmonic 11	659 Hz	700 mV	0.33%	-162	36 mA	3.51%	119
Harmonic 13	779 Hz	575 mV	0.27%	-99.5	17.6 mA	1.72%	92 m
Harmonic 15	899 Hz	157 mV	0.07%	106	1.83 mA	0.18%	25.8

Table 4 –Electrical data concerning one-phase of the 11th order filter.

Voltage V RMS	Current A RMS	Power W	Voltage THD	Current THD	Power Factor	Power Factor Displacement Degrees	Instantaneous Power VA	Reactive Power VAr
217	93.6	164	3.10%	47.03%	.008	-90.2	20 300	20 300

Harmonic order	Freq	Voltage RMS	Voltage %	Voltage Phase Degrees	Current RMS * 100	Current %	Current Phase Degrees
Fundamental	60 Hz	216 V	100.00%	0.0	877 mA	100.00%	0.0
Harmonic 3	180 Hz	623 mV	0.29%	66	8.69 mA	0.99%	133
Harmonic 5	300 Hz	5.55 V	2.57%	-107	140 mA	15.96%	166
Harmonic 7	419 Hz	1.34 V	0.62%	150	52.3 mA	5.96%	-122
Harmonic 11	659 Hz	845 mV	0.39%	-122	364 mA	41.46%	-12.9
Harmonic 13	779 Hz	300 mV	0.14%	-78.1	77.3 mA	8.81%	-875 m
Harmonic 15	899 Hz	130 mV	0.06%	130	4.33 mA	0.49%	37.3

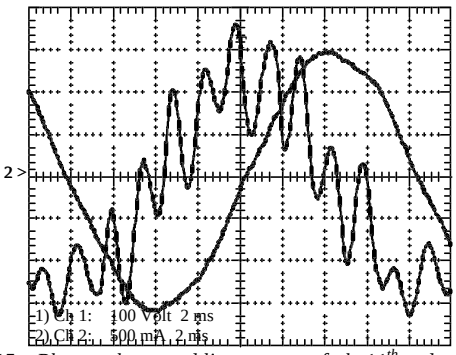

Fig.15 – Phase voltage and line current oft the11th order filter (100V/div, 50A/div, 2mS/div).

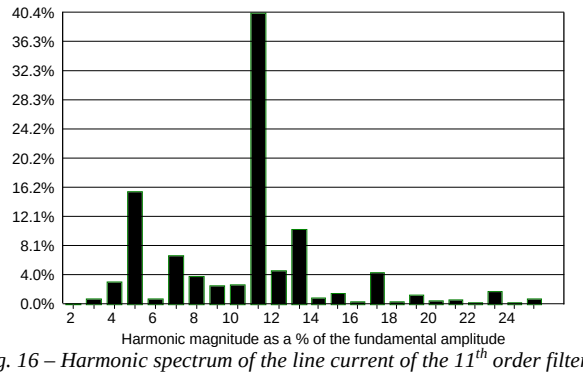

Fig. 16 – Harmonic spectrum of the line current of the 11th order filter.

Table 5 –Electrical data concerning one phase of the high-pass (13th and higher order) filter.

Voltage V RMS	Current A RMS	Power W	Voltage THD	Current THD	Power Factor	Power Factor Displacement Degrees	Instantaneous Power VA	Reactive Power VAr
215	294	2 320	3.06%	20.22%	.0367	-88.5	63 200	63 200

Harmonic order	Freq	Voltage RMS	Voltage %	Voltage Phase Degrees	Current RMS * 100	Current %	Current Phase Degrees
Fundamental	60 Hz	214 V	100.00%	0.0	2.88 A	100.00%	0.0
Harmonic 3	180 Hz	766 mV	0.36%	-108	35.7 mA	1.24%	5.72
Harmonic 5	300 Hz	5.58 V	2.60%	-104	401 mA	13.95%	175
Harmonic 7	420 Hz	1.11 V	0.52%	164	106 mA	3.69%	-105
Harmonic 11	660 Hz	631 mV	0.29%	-134	233 mA	8.09%	-15.8
Harmonic 13	780 Hz	544 mV	0.25%	-82.9	199 mA	6.93%	-104
Harmonic 15	900 Hz	195 mV	0.09%	98.4	27.8 mA	0.97%	-78

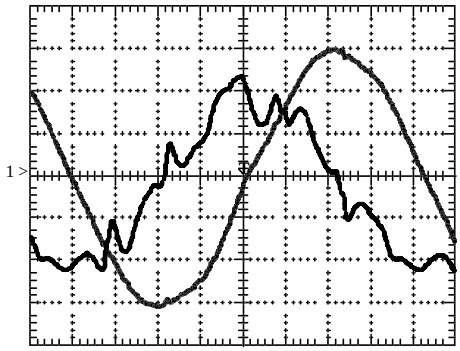

Fig. 17 – Phase voltage and line current at the high-pass (13th and higher order) filter (100V/div, 200A/div, 2mS/div).

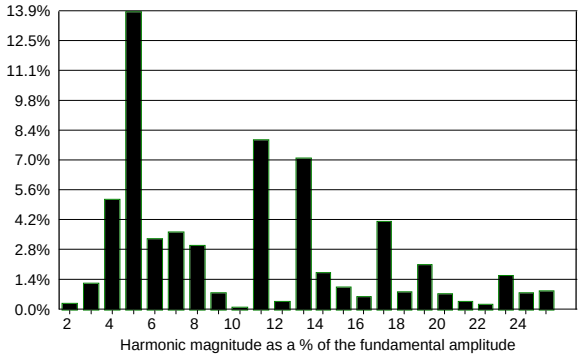

Fig. 18 – Harmonic spectrum of the line current at the high-pass (13th and higher order) filter.

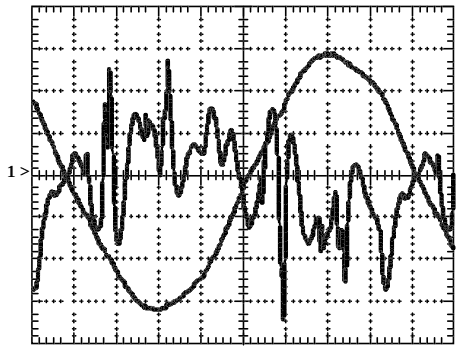

Fig. 19 – Phase voltage and line current at the bypass resistor of the high-pass (13th and higher order) filter (100V/div, 300A/div, 2mS/div).

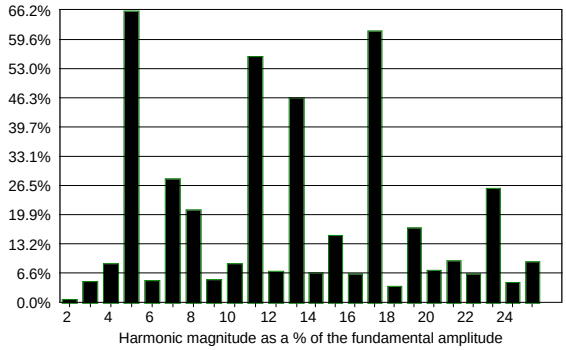

Fig. 20 – Harmonic spectrum of line current at the bypass resistor of the high-pass (13th and higher order) filter.

V. Conclusion

Even though in technical literature one can find several charming studies concerning active harmonic filtering for medium power electrical systems, in some cases passive filtering can be employed successfully, providing power factor correction both for linear and harmonic reactive power.

This solution may appear, at first glance, an old-fashioned way to deal with harmonics, resulting in bulky and voluminous filters, but it seems that, even today, it may represent a very interesting approach, cost-effective, robust and applicable to industrial plants with non-linear loads.

VI. References

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