A 3-phase 4-wire Shunt Active Filter with Selectable Harmonic Compensation and an Auto-Calibration Harmonic Algorithm

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Abstract **− This paper presents the development of two prototypes units of a three-phase four-wire shunt active filter, one for an input voltage of 220 V and the other for 380 V. Both use the same hardware; the differences are in monitoring and control embedded in the microcontroller and can correct up to the 31st harmonic. Besides, the user can choose the harmonic(s) to be compensated. To correct unforeseen errors observed in the current sampling to be synthesized at the filter's input, a harmonic auto-calibration algorithm was created to correct the amplitude and angle of each harmonic of the sampled current. A current saturation algorithm was also implemented for each leg through the analysis of the phase sequences of each harmonic, preventing the current from exceeding the established and safe value. The two prototypes have been installed and in use at the BREE industrial plant, and they have been fixing harmonics for almost a year (BREE is a company that manufactures equipment and provides engineering services for reactive compensation, power quality, and energy efficiency and is a partner in this project).**

Index Terms **— Harmonic Extraction, Independent Component Analysis, Shunt APF, Power Quality, Fourier Transform FFT.**

I. INTRODUCTION

Current harmonics, reactive power, and load unbalance are some of the issues the power system network faces at the distribution level. For generation and transmission to perform without disturbances, power system operators believe that these cases must be addressed at the distribution level itself. Passive filter, tap-changing and synchronous condenser have been used to solve the power quality issues. Nevertheless, custom power devices with sophisticated power electronics technology are widely being used to mitigate, too, such as active power filters, dynamic voltage restorer, and static compensators [1].

In the case of active power filters, the power circuit used can be with current source inverter (CSI), or voltage source inverter (VSI), which are differentiated that VSI has a DC bus, it acts as a voltage source, having a capacitor that stores energy, and the CSI has a DC bus that is a current source, and it has an inductor connected in it. The CSI has considerable power losses, making the VSI model more targeted for applications involving filters, according to [2] – [3].

Topologies used for active filters can be series and parallel (or shunt). The series topology aims to compensate for the voltage harmonic distortion. In this configuration, you must have a robust protection system due to the susceptibility to hazards caused by short circuits [4]. In shunt topology, as in this project, there is a compensation for the current harmonic distortion caused by the presence of non-linear loads. The filter injects a controlled current, added to the non-linear load current, resulting in a current with linear load behavior [5].

Another resource used to separate active filters is the number of wires, which can be three or four wires, since the distribution system loads are connected to any phase of the three-phase distribution system, which causes unbalanced loading conditions [6]. Due to this load unbalance, mainly between the phase conductors, zero sequence triple harmonics (3rd, 9lh, 15lh, ...) add up arithmetically at the neutral conductor, can be greater than the current of each of the phases, resulting in an overload of neutral conductor and distribution transformer also [7] – [8]. And when using a four-wire active filter, as in this project, there is the zero-sequence triple harmonics mitigation.

In this way, this paper aims to present the development of a three-phase four-wire shunt active filter and the results achieved in the two prototypes that are installed and operating at the BREE industrial plant, which manufactures equipment and provides engineering services for reactive compensation, power quality and energy efficiency, partner of this project. The active filters developed have an additional feature to choose which harmonic currents will be compensated. All harmonics could be compensated or just selected by the user through an

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interface, giving versatility and the possibility to adapt the equipment to the installation place.

Thus, section II has the general hardware diagram of the developed active filter. In section III, the control strategy and the firmware features embedded in the TMS320F28377 for filter operation. In section IV, the laboratory results and prototypes were installed at BREE, and finally, section V presents the discussion of results providing conclusions.

II. Converter Topology

The converter topology used is a voltage-fed inverter, that among possible topologies, the four legs inverter was chosen (Fig. 1) [9].

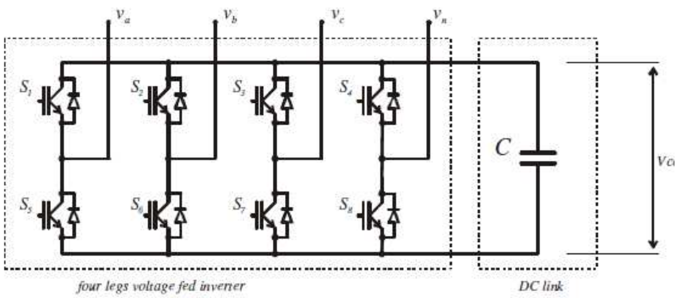


Figure 1. Voltage fed inverter with four legs [9].

There are other topologies that could be used, such as the three legs inverter. In this condition, the filter would not be able to compensate for homopolar harmonics [9]. The four legs inverter allows to control neutral currents directly, and it can reduce the capacitor value, improve its performance, even make the bus voltage control simpler.

Two prototypes were implemented and tested in BREE industrial plant (one for 127/220V and the other for 220/380V). Both devices have the same hardware and firmware developed to control them. The difference is held in the control settings and some protection limits (bus voltage, input currents, etc.).

III. Control Strategy

The developed shunt active filter is three-phase and operates with four legs. Fig. 2 shows an overall schematic of the filter's hardware. The load currents ILa, ILb, and ILc, are sampled and sent to the processor through current transformers. The phase voltages, V_{Sa}, V_{Sb}, and V_{Sc}, are also sampled, they are necessary for the filter synchronization to the grid. Through hall effect sensors, input filter currents (I_{Ca}, I_{Cb}, I_{Cc}, and I_{Cn}) are sampled. They are used in current control to ensure magnitude and phase for current injection on the PCC (Point of Common Coupling), eliminating harmonic currents from the load.

The active filter is connected to the grid through coupling inductors, which circulates currents synthesized for current controllers (it operates as a current source). To produce currents, the control strategy is composed of two parts: an identification system to generate references and current control (Fig. 2).

The reference identification system produces current levels generated at the input and simultaneously controls the bus voltage. In the case of this converter, with four legs, neutral currents, composed basically for unbalanced and homopolar currents, circulate in a dedicated leg connected to the neutral point.

The filter control was implemented in a DSP processor Texas Instruments TMS320F28377D. The selection of the harmonic currents that will be injected at the input of the active filter is based on a Texas Instruments library, which is used to carry out an FFT algorithm that allows segregation and harmonics filtering to be compensated.

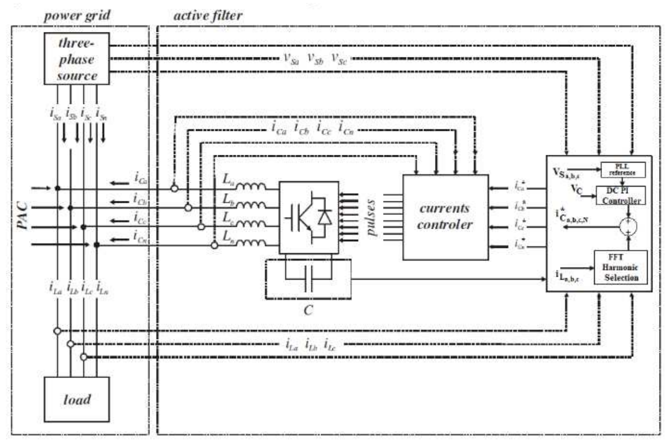


Figure 2. Topology used and general schematic of active filter hardware and control.

The FFT library requires a synchronism obtained through a PLL algorithm to determine the sampling start instant of the load current signals.

With the FFT algorithm running, the control filters out the harmonics that will not be compensated and recomposes the current signal to be added to the output of the PI controller of the voltage bus, forming the current reference. To process all data and segregate harmonic to be compensated, the FFT algorithm needs 2 cycles of grid to acquire, segregate and recompose signals for three-phase and neutral currents. This is a delay imposed by the algorithm on the control response.

The control strategy implemented in the active filter is a PI controller for each phase and neutral. This control method does not balance the currents between the phases because the magnitude and angle of the current reference in each phase is composed by the harmonics without interfering in the fundamental frequency.

In this way, the output signals of the control block generate the PWM pulses for the phase and neutral currents. The signals are applied to the IGBT transistors of the power converter through firing drivers. The PI controllers minimize the error between the current reference and the synthesized current on the inductors (L_a to L_N).

A. Mathematical Analysis

The mathematical analysis considered the attenuation of current harmonics until the 31^{st} order, four legs for the three-phase active filter, the delay interval caused by the FFT algorithm, and saturation inherent to the maximum value of current that will flow in the neutral.

The DC bus voltage of the active filter must be at least equal to the peak voltage of the grid so that the filter can deliver or receive energy at any time during the grid period. A slack margin in the filter's DC voltage is added to operate efficiently even in situations when the demand is high, such as in cases where it must inject a considerable current into the system at the peak of the network voltage. The voltage on the DC filter link is used at least 30% higher than the peak of the network voltage. Therefore, the modulation index (the relationship between the peak voltage of the network and the DC bus voltage) is always less than unity [10].

Thus, the bus voltage was defined as a compromise between the isolation parameters of capacitors and semiconductor switches used in the converter and this slack margin of the peak voltage of the network. For the prototype with 220 V input, the bus voltage V_{dc} was set at 480 V, and for the 380 V, it was set at 680 V. These values represent a modulation index of 0.64 and 0.8, respectively.

For inductors, the problem is to coordinate the inductance value with the DC bus voltage. There is a compromise between both in the sense that a higher value in the DC bus will lead to higher values in the input current, as well as a higher ripple in current.

There are methods to calculate the value of the input inductance of the active filter, one of them is the methodology presented in [10], through the parameterized curve of the inductor current, the calculated modulation index, and (1).

$$L_f \geq \frac{\overline{\Delta i}_{f_{max}} . V_{dc}}{\Delta i_{f_{max}} . 2 . f_s} \quad (1)$$

V_{dc} is the bus voltage, f_s switching frequency, $\Delta i_{f_{max}}$ filter current ripple and $\overline{\Delta i}_{f_{max}}$ maximum of parameterized filter current ripple.

In formula (2) is the minimum capacitor for a determined value of the DC voltage ripple, is [9]:

$$C_{min} = \frac{3 \cdot V_{f\_pk} \cdot I_{neg\_pk}}{4 . \omega \cdot V_{dc} \cdot \Delta V_{dc}} \quad (2)$$

V_{f_pk} represents the peak phase voltage, I_{neg_pk} peak for negative current sequence, V_{dc} and ΔV_{dc} bus voltage and its ripple, respectively.

B. FFT and Harmonic Selection

A library provided by Texas Instruments was used, which executes a program processing load currents and segregating the harmonics. During this process, implemented program eliminates unselected harmonics, and, for the final part, the library recomposes load currents without unselected harmonics. The operation must be synchronized to input voltage from the power grid, and it has predefined buffers and internal variables (Fig. 3).

To illustrate the process, Fig. 3 shows the steps starting with the synchronization of the PLL function. Observing phase A acquisition as an example, there are two buffers (BufferCFFTdata1 and data2), while one buffer is reserved to receive the input current, the other is used as input to the FFT function. For the application of the active filter, before applying the inverse FFT (IFFT), the firmware clears the slots that are not relevant for control (unselected harmonics) and runs the inverse FFT that will serve as part of the reference signal.

C. Harmonic Saturation According Phase Sequence

Considering the current capacity of the components and the thermal transfer limitations for the heat sink, a nominal value of current was found for the full equipment operation, ensuring quality in operation. Thus, it is necessary to apply saturation to the filter's output current, controlling the effective current value supported by the equipment.

The current value that circulates through the switching legs has a limit of 75 A for 220 V input voltage and 50 A for 380 V. By this way, the current that circulates through the neutral inductor has the same limit adopted for each phase.

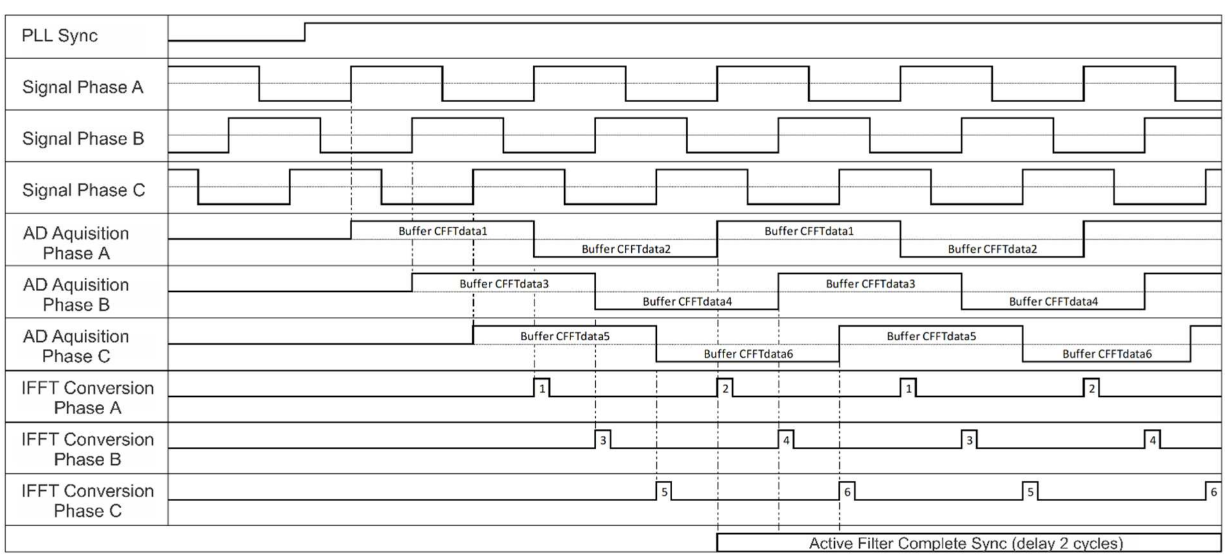


Figure 3. FFT and IFFT acquisition/processing methodology.

Furthermore, the sum of the zero-sequence current will circulate through the neutral, and, considering a balanced system, it is necessary to cause the saturation of the zero-sequence current value in each phase with 1/3 of the nominal current.

However, unbalanced phase currents that are not detected during the FFT and traditional saturation process is a problem for the system. For this reason, a saturation was developed with the purpose of getting around this problem and limiting the effective value applied on the neutral inductor current in order to address unbalanced systems.

D. Auto-Calibration

During the active filter operation, a deviation of the current values was verified when it was considered the value in RMS and the angle of the signals for each order. This difference was generated from the signal sampled by the current sensor through the delay inserted in the conditioning system and the delay inserted during the data processing.

To correct these errors, a gain multiplier and angle corrector were implemented during the self-calibration process. This process consists of to identify the gain of the multiplier and angle offset values that were set in the correction function. So, the values calculated were applied in the current control of the filter inductor.

The self-calibration function generates a signal with known order, and this signal is three-phase balanced. This signal was inserted in the output current reference to the inductor by the control. The currents are read by the sensor, sampled, and calculated by the FFT algorithm. The values of amplitude and angle of the reference signals are adjusted (increment and decrement), and when they achieve the correct values, the program records the new values in memory, which will control the active filter.

IV. DESIGN PROCEDURE

Using the maximum value of the parameterized current ripple - 0.25 for 220 V and 0.55 for 380 V (obtained through the graph according to the modulation index); the predefined value of the DC bus; the switching frequency (15.36 kHz for 220 V and 30.72 kHz for 380 V) and considering a maximum current ripple of 20% above the peak value of the current defined for the filters (75 Arms for 220V and 50 Arms for 380V), the calculated inductance value is about 170 uH for 220 V and 440 uH for 380 V.

For the DC bus capacitor, regarding the prototype with 220 V input, the minimum capacitance is set in 1,6 mF and 0.95 mF for the 380 V prototype, for a ΔVdc of 10%.

For the current saturation, the adopted value is 75 A for each phase (prototype 127 V) and 50 A for each phase (prototype 220 V). The neutral current limit is the most important because if this value is reached first, the control will have to limit the compensation in each phase.

V. RESULTS

A. Laboratories Tests

In the tests with the prototype unit (model 220V), a harmonic current with harmonic content between phases is generated (Fig. 4 - CH1 phase A), and its harmonic content is shown in Fig. 5. The compensation of the current filter (Fig. 4 - CH2) produces a total current, which can be sensed by the power grid according to channel M in Fig. 4. It is also sensed produced by the neutral leg current, through which the zero sequence currents flow (CH4 in Fig. 4). The filter busbar voltage can also be observed (Fig. 4 - CH3).

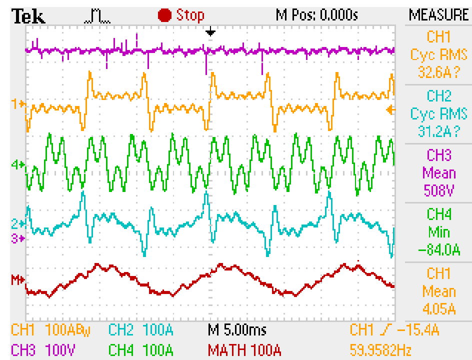


Figure 4. Harmonic currents generated and signals produce by active filter for 220 V prototype.

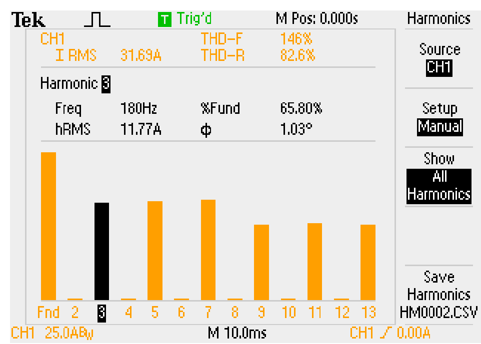


Figure 5. Harmonic current content for phase A.

Observing the 220 V unit producing a current of 60 A, the occurrence of 5th on the DC busbar voltage is observed. Fig. 6 shows the same signal sequence as Fig. 4, and an oscillation in the DC bus voltage should be observed. This oscillation (Fig. 7) reaches 46V. The capacitor bank is smaller than calculated that the oscillations should be higher than expected.

Regarding the test (Fig. 6), Fig. 8 shows the total value of the load phase current (I1), at the filter (I2) and sensed by the power grid (I3), and their respective Total Harmonic Distortion (THD).

Testing the 380 V unit, it was produced a harmonic current with diversified harmonics between phases (Fig. 9 - CH1 phase A) and its harmonic content in Fig. 10. The current filter compensation (Fig. 9 - CH2) produces a total current sensed by the power grid, according to Fig. 9 - M. The neutral leg, which the zero-sequence and unbalanced currents flow (Fig. 9

- CH4). The filter busbar voltage can be observed in Fig. 9 - CH3).

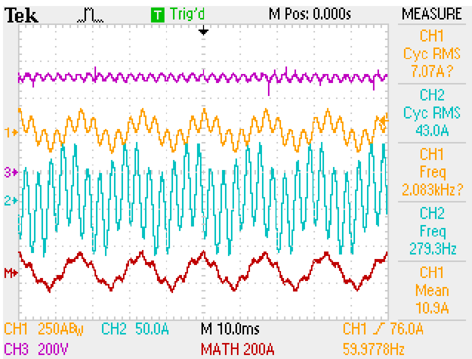


Figure 6. Harmonic currents generated and signals produce by active filter.

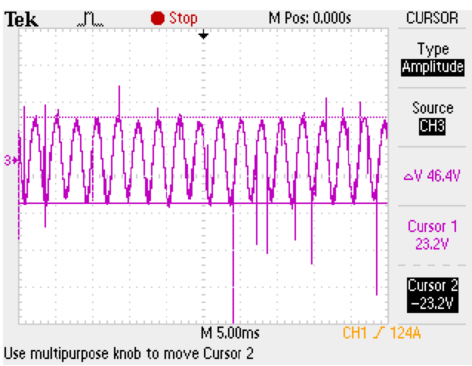


Figure 7. Oscillation voltage on busbar capacitor.

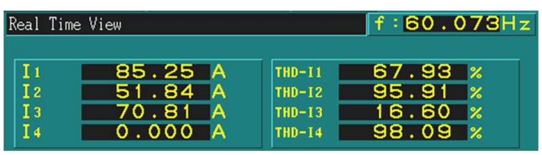


Figure 8. Value for currents and respective THDs.

After compensation, the THD results are 69,42 % for the load current and 11,90 % for the total current.

B. BREE Instalations Results

It is possible to visualize the operation of the 220 V unit at the BREE industrial plant (Fig. 11[a] and 11[b]). In Fig. 11[a], there are three-phase voltages and currents in accordance with one of three phases. In Fig. 11[b], the same currents are in evidence: Load current (yellow); Current synthesized by active filter (red); and input power utility current (blue). In Fig. 11[b], the current from the power utility is compensated.

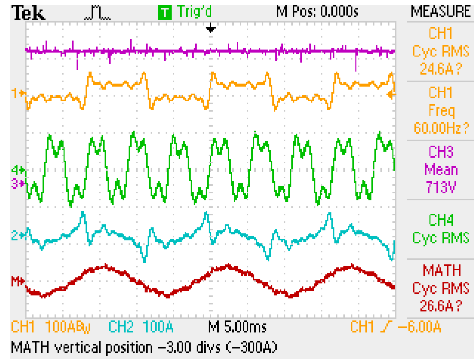


Figure 9. Harmonic currents generated and signals produce by active filter for 380 V prototype.

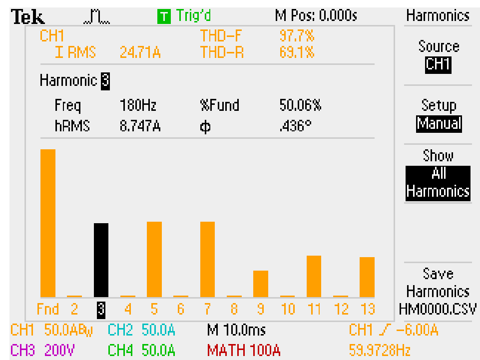
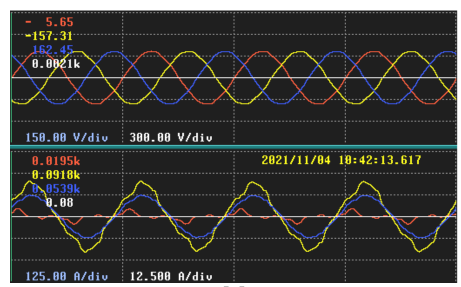
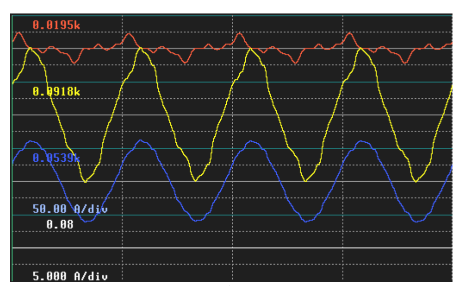


Figure 10. Harmonic current content for phase A.



[a]



[b]

Figure 11. [a] Three-phase voltages and load currents; [b] Three-phase currents for 220 V unit at the BREE industrial plant.

Analyzing the 3rd harmonic behavior, it is possible to note in Fig. 12 the harmonic current produced by the load at BREE (Fig. 12 - I2 - 12.02 A) is compensated by the filter current (Fig. 12 - I1 - 10.59 A) in one phase, as the respective phasors are offset 180 degrees.

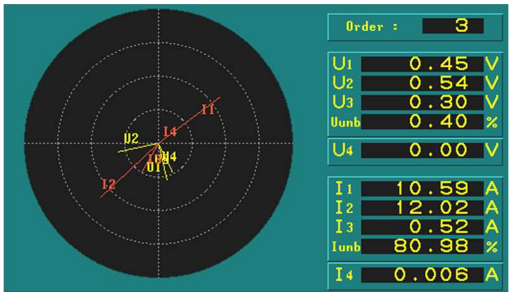


Figure 12. Third harmonic compensation.

In both units at BREE's industrial plant, measurements were collected at similar times and days. The results are shown in tables I and II, where it is demonstrated a reduction in harmonics.

Tests considered up to 11th order harmonics (TABLE I AND II) because the higher harmonics measured almost nothing or very low levels for this power plant. Observing both voltage systems, the active filter has reduced harmonic currents significantly.

TABLE I. HARMONIC CURRENTS REDUCTION (127/220 V)

Prototype 127/220V – 11 a.m. to 6 p.m.			
Harmonic	***RMS Value – no operation filter [A]***	***RMS Value – filter compensating [A]***	***Reduction in %***
3	20,80	1,80	91,38
5	9,75	3,00	69,50
7	16,5	5,77	69,46
9	7,33	2,68	63,48
11	5,71	2,6	54,50

TABLE II. HARMONIC CURRENTS REDUCTION (220/380 V)

Prototype 220/380V – 11 a.m. to 6 p.m.			
Harmonic	***RMS Value – no operation filter [A]***	***RMS Value – filter compensating [A]***	***Reduction in %***
3	7,57	3,11	58,93
5	15,81	7,23	54,29
7	5,00	2,61	47,41
9	3,00	2,06	30,39
11	-	-	-

VI. DISCUSSION AND CONCLUSIONS

A possible solution for problems related to harmonic currents in an industrial power plant was presented, mathematical analysis and design procedure were evaluated. The unit was assembled, tested in the laboratory, and a real condition.

It was possible to observe some advantages of using this method to select harmonics, and it is possible to select which harmonics to compensate or not. In a power plant has some harmonic representing resonance point, and it is possible to avoid operation on this harmonic. It is possible to concentrate all power available from the compensation system for a specific harmonic, selecting one harmonic.

The unit has many different protections and functionalities, and it was not possible to demonstrate in is this paper.

The next steps in this project are keeping tests for a long period, and it will be possible to improve the equipment and harmonic compensation, thermal dissipation, and software inside the processor.

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REFERENCES

[1] G. Pandove and M. Singh, "Robust Repetitive Control Design for a Three-Phase Four Wire Shunt Active Power Filter," *in IEEE Transactions on Industrial Informatics*, vol. 15, no. 5, pp. 2810-2818, May 2019, doi: 10.1109/TII.2018.2875035.

[2] Ortmann, M. S. "Filtro ativo trifásico com controle vetorial utilizando DSP: projeto e implementação," Master dissertation. UFSC, Florianópolis, SC, Brazil, 2008.

[3] J. G. Pinto, B. Exposto, V. Monteiro, L. F. C. Monteiro, C. Couto and J. L. Afonso, "Comparison of current-source and voltage-source Shunt Active Power Filters for harmonic compensation and reactive power control," *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, 2012, pp. 5161-5166, doi: 10.1109/IECON.2012.6389552.

[4] M. A. Chaudhari and Chandraprakash, "Three-phase Series Active Power Filter as Power Quality Conditioner," *2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2012, pp. 1-6, doi: 10.1109/PEDES.2012.6484387.

[5] P. S. Revuelta, S. P. Litrán, J. P. Thomas, "Active power line conditioners – design, simulation and implementation for improving power quality," *Elsevier*, 2016

[6] G. S. Troncha. "Uma contribuição à aplicação dos filtros ativos em sistemas elétricos de potência," Master dissertation. UFU, Uberlândia, Brazil, 2019.

[7] B. R. Khade and V. B. Virulkar, "Mitigation of harmonics in a neutral conductor for three-phase four-wire distribution system using series active power filter," *2015 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT),* 2015, pp. 1-6, doi: 10.1109/ICECCT.2015.7225998.

[8] L. F. A. Maciel, J. L. M. Morales, D. C. Gaona and J. G. M. Pimentel, "A Study of a Three-Phase Four-Wire Shunt Active Power Filter for Harmonics Mitigation," *2018 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC),* 2018, pp. 1-6, doi: 10.1109/ROPEC.2018.8661416.

[9] R. Demonti, C. G. Bianchin and J. S. Omori, "Implementation of three-phase active filter for compensation of harmonics and displacement with phases current balancing," *2008 IEEE International Symposium on Industrial Electronics,* 2008, pp. 270-275, doi: 10.1109/ISIE.2008.4676883.

[10] D. Lindeke "Projeto de um Filtro Ativo Paralelo de 1kVA Usando Técnicas de Controle Analógico e Digital" Master dissertation. Florianópolis, SC, Brazil, 2003.