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Experimental and Simulation Results of a Current-Source Three-Phase Shunt Active Power Filter using Periodic-Sampling

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***Abstract*— In this paper are presented experimental and simulation results of a Current-Source Three-Phase Shunt Active Power Filter, during its operation to compensate the currents a low power factor load and a nonlinear load. The Shunt Active Power Filter controller, described in detail along the paper, relies in the *p-q* Theory to generate the reference compensation currents and to regulate the DC-link inductor current. The regulation of the DC-link inductor current is done consuming sinusoidal currents in phase with the system voltages. The performance and the dynamic behavior of the Shunt Active Power Filter using Periodic Sampling Modulation Technique was assessed first through several computer simulations, and then through the analysis of experimental results obtained with a developed laboratory prototype. Thereby, in this paper are presented several obtained results that show the correct operation of a Current-Source Three-Phase Shunt Active Power Filter using the Periodic Sampling Modulation Technique.**

Keywords - Current-Source Inverter, Periodic Sampling, Shunt Active Power Filter; Power Quality; p-q Theory.

I. INTRODUCTION

The Power Quality is one of the most important characteristics of the modern electrical energy distribution. Consequently, the poor Power Quality can cause enormous economic losses to the industrial facilities, to the final common users, and to the electrical grid [1]. The main causes of the power quality problems are non-linear loads, due to the consumed currents with high levels of harmonic content. As consequence of the distorted consumed currents, the electrical grid voltage is also affected due to the line impedance, aggravating the power quality problems. Besides the non-linear loads, the low power factor loads also cause problems, mainly related with energy efficiency and overdimensioning of cables. Taking into account these types of loads and the associated problems of power quality, it is extremely important develops new approaches and solutions, based on Active Power Filters, that allow compensate these problems.

Aiming to solve the power quality problems associated with the currents, the Shunt Active Power Filter is the suitable solution, because it allows the dynamic compensation of current harmonics and low power factor, without causing the problems that the passive filters and capacitor banks can cause [2]. Shunt Active Power Filters can be generally classified as Voltage-Source Shunt Active Power Filters and Current-Source Shunt Active Power Filters.

Current-Source Active Filters present several advantages, such as: excellent current control, easy protection, high reliability and high efficiency also with low power loads [3]. Other advantage is that in the DC side of the inverter is placed an inductor and its lifetime is superior to the lifetime to the capacitor that is used in Voltage-Source Shunt Active Power Filters. The main disadvantages of this type of active filter are the bulky DC-link inductor, the high DC-link inductor losses, the overvoltage protection circuit that is necessary to protect the inverter, and the slow dynamics inherent to this type of inverter [4].

In this context, in this paper are presented several computer simulations and are shown experimental results of a Current-Source Shunt Active Power Filter, controlled using the *p-q* Theory and using the Periodic Sampling as modulation technique. The *p-q* Theory, which is described in detail in the paper, is both used in this Active Filter to generate the reference compensating currents and to regulate the DC link inductor current.

II. CURRENT-SOURCE ACTIVE FILTER TOPOLOGY

As referred before, aiming the goal of this paper it was developed a Current-Source Shunt Active Power Filter, based on the full-bridge topology. As shown in Fig. 1 it is constituted by a three-phase three-wire current-source inverter, by the inductor presented in the DC-link (with respective resistance to simulate a real inductor), and by the output filters based on LC passive filters (these passive filters are used to filter the high frequency switching components) generated by the inverter operation. It was also added to the model, the line impedance and a transformer in which are connected the load and the Shunt Active Power Filter.

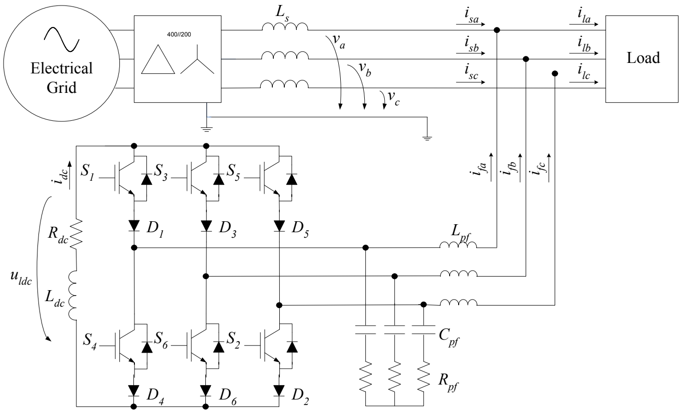

Fig. 1. Current-Source Active Filter topology.

III. DIGITAL CONTROL SYSTEM

The control of the Shunt Active Power Filters implements the p - q Theory proposed by *Akagi et al.*[5]. This power theory has been largely used in Voltage-Source Active Power Filters [6][7][8]. Nevertheless, in Currents-Source Active Power Filters the application of the p - q Theory is restricted. The DC-link current regulation is also done using the p-q Theory.

A. p-q Theory

During the simulations and the implementation of the Current-Source Active Power Filter, the p - q Theory was implemented to work as the "Sinusoidal Source Currents" algorithm [9]. To perform this task was implemented a Phase-Lock Loop Circuit (PLL) that extracts the positive sequence values of the system voltages (v_{a_pll}, v_{b_pll}, v_{c_pll}). The values of those voltages and of the system currents are converted to a α-β reference frame applying the appropriate α-β transformation (1) (2) respectively:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

The instantaneous real power, p, and the instantaneous imaginary power, q, are calculated in the new reference frame using v_α v_β i_α and i_β (3).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

Then, through a sliding average algorithm, is obtained the mean value of the instantaneous real power, ($\overline{p}$). The sliding average algorithm was implemented through an array of 640 positions. Using p and $\overline{p}$ is possible to obtain the alternating value of the instantaneous real power ($\widetilde{p}$).

The values of the p_{reg} (proportional to the DC link inductor current) and the q are then used to calculate the reference compensating powers p_x and q_x (4) (5).

$$p_x = \widetilde{p} - p_{reg} \tag{4}$$

$$q_x = q \tag{5}$$

Using p_x and q_x it is possible to determine, in the α-β reference coordinates, the reference compensating currents that should be generated by the Current-Source Shunt Active Power Filter inverter (6).

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_x \\ q_x \end{bmatrix} \tag{6}$$

The compensating reference currents $i_{c\alpha}$ and $i_{c\beta}$ are then converted to the a-b-c coordinates system and are used in the modulator to compare them with the inverter generated currents. After determine the compensation reference currents (i_{ca^*}, i_{cb^*}, i_{cc^*}), their result is compared with the Active Filter currents (i_{fa}, i_{fb}, i_{fc}), and the result is sent to a combinational logic circuit that generate the pulse patterns of the Periodic Sampling modulation technique.

In Fig. 2 is shown the block diagram of the digital control system. As presented in this figure, the DC-link inductor current is controlled by a Proportional-Integrative (PI) controller that generates a p_{reg} signal, which is proportional to the error between the reference to the DC current and the measured current. The DC link current reference is fixed at this point, so it is necessary to previously determine the amplitude of the loads currents that will be compensated, in order to adjust the value of the DC-link current reference aiming to maintain the modulation index in the linear area. Other possibility to control the current in the DC-link is based on a dynamic adjustment current reference to regulate the DC link current accordingly the load current consumption. However, now, the DC current reference is fixed, and must be adjusted accordingly with the load that the Shunt Active Power Filter will compensate.

B. Periodic Sampling Modulation Technique

The Periodic Sampling modulation technique is based on the comparison of the reference compensating currents and currents produced by the Active Filter. The results of that comparison are then sent to a combinational logic circuit that generates the pulse patterns that respect the inverter valid states [10]. The switching generator scheme implementation is based on a PAL programmable logic circuit.

The Periodic Sampling modulation technique is a non-fixed switching frequency modulation technique and is only possible define the maximum switching frequency. Although that the final currents THD is higher than Carrier-Based PWM, its dynamic response is very good.

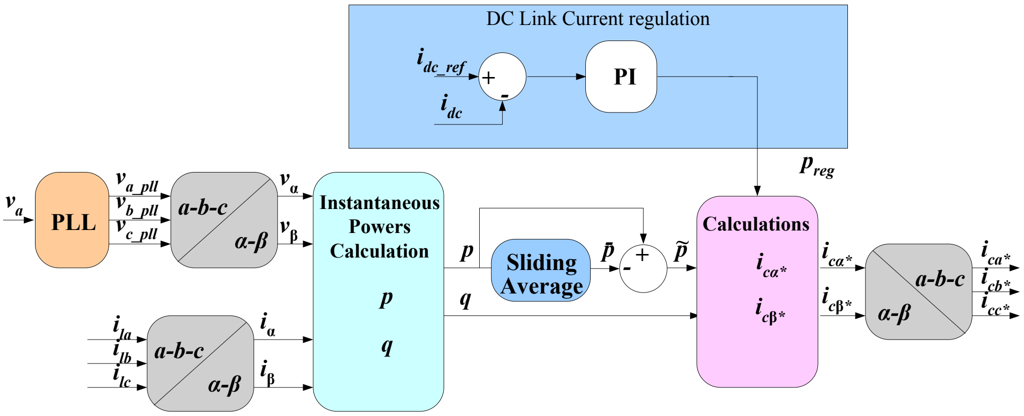

Fig. 2. Current-Source Shunt Active Power Filter control system.

IV. SIMULATION RESULTS

The simulated inverter topology of the Current-Source Active Power Filter is the same depicted in Fig. 1. The simulations were done using the software PSCAD from Manitoba HVDC Research Centre Inc. The simulations of the Active Filter were done considering real values for the simulation parameters. The Active Filter and the loads were connected to a 400//200 V 50 Hz transformer. The simulated loads are a resistive-inductive load connected in delta (in order to obtain a low power factor load), and a full-bridge rectifier (in order to obtain a nonlinear load), with resistive-inductive load. In series with the rectifier were placed three inductors with the value of 3 mH. In Table 1 are presented the values of the parameters used in the simulation model.

The Current-Source Active Power filter was simulated using Periodic Sampling as modulation technique and the sampling frequency was fixed in 16 kHz, both in simulation as in the experimental prototype.

In Fig. 3 are shown the simulation results of the Active Power Filter when compensates the consumed currents of the non-linear load. As can be seen, before the compensation (Fig. 3 a) the source currents (i_{sa}) are highly distorted. As result of the line impedances the voltage drops and consequently, as also illustrated in this figure, the system voltages (e_{sa}) are distorted too. With the operation of the Active Power Filter, which generates adequate compensating currents, the source currents (i_{sa}) acquire a sinusoidal shape with unitary power factor, as shown in Fig. 3 (b).

In Fig. 4 are shown the obtained results when the Active Power Filter is compensating the consumed currents of the low power factor load, composed by resistive-inductive elements.

Before the compensation (Fig. 4 (a)), the source current (i_{sa}), which is the consumed currents by the load, is not in phase with the line voltage (e_{sa}). Once more, after the compensation, as shown in Fig. 4 (b), the source current (i_{sa}) is in phase with the line voltage (e_{sa}), and its amplitude is lower than before. This indicates that the current reactive components are fully compensated and that the power factor is higher than before.

TABLE I. PARAMETERS VALUES OF THE SIMULATION MODEL

Parameters	Value	Loads	Parameters	Value
L_s	1.1 mH			
L_{dc}	128 mH	**R-L load**	L	146 mH
R_{dc}	0.46 Ω		R	25 Ω
C_{pf}	30 µF			
L_{pf}	5 mH	**Full Bridge Rectifier**	R_{dc}	37.5 Ω
R_{pf}	9.4 Ω		L_{dc}	146 mH
f_s	16 kHz		L_{series}	3 mH

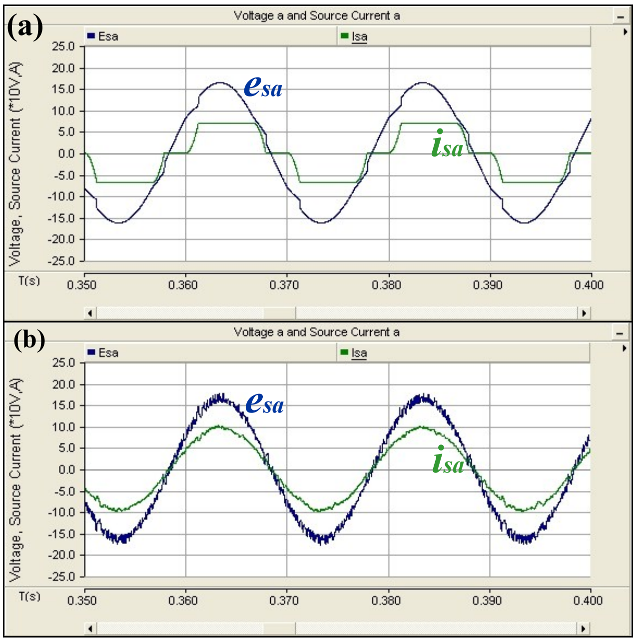

Fig. 3. Simulation results of the Current-Source Shunt Active Filter when compensating the non-linear load (full-bridge rectifier) - e_{sa} - line voltage, i_{sa} - source current: (a) Active Filter turned off; (b) Active Filter turned on.

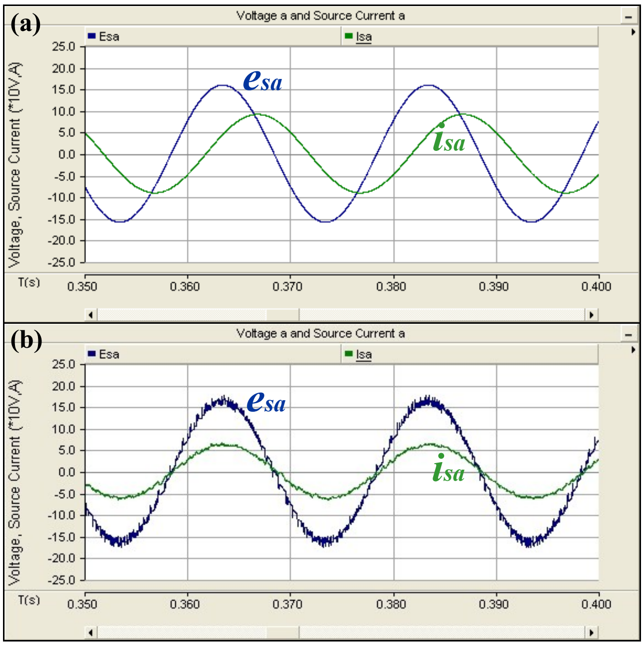

Fig. 4. Simulation results of the Current-Source Shunt Active Filter when compensating a low power factor load (resistive-inductive), e_{sa} - line voltage, i_{sa} - source current: (a) Active Filter turned off; (b) Active Filter turned on.

In both simulations, with the operation of the Active Power Filter, is possible to see that the system voltage (e_{sa}) acquires a high frequency noise. This high frequency component is due to the switching of the power semiconductor of the inverter. Although that this high frequency is undesirable, it can only be minimized though the passive filters. Nevertheless, in this case, the voltage distortion is in the point where the Active Power Filter is connected to the electrical grid, and doesn't affect significantly the electrical grid voltages.

Both of these simulation results indicate that the described control theory, which relies in the *p-q* Theory to generate the reference compensation currents and to regulate the DC-link inductor current, performs well in the detection of the undesired current components and therefore the Active Power Filter is capable of compensating them.

V. EXPERIMENTAL RESULTS

To evaluate the designed and simulated Current-Source Active Power Filter under real conditions of operation, it was developed a laboratory prototype of the Active Filter that can compensate power quality problems associated with the currents, as harmonics and power factor, with currents up to 10 A peak. The developed laboratory prototype is divided in two fundamental parts: the power hardware and the digital control system.

The power hardware is constituted by the current-source inverter topology that was depicted in Fig. 1. For this propose were used IGBTs, as controlled semiconductors, in series with diodes, and an inductor in the DC-link with nominal value $L_{dc} = 128$ mH. The Current-Source Shunt Active Filter is limited to a compensation capability of 10 peak, because of the DC-link inductor maximum admissible current.

The digital control system is composed by several parts, mainly, a Texas Instruments TMS320F2812 DSP, in were implemented the *p - q* Theory and the other control parts such as the DC link inductor current regulator. The combinational logic circuit that generates the pulse patterns was implemented using a Generic Array Logic GAL22v10. Was implemented also a signal conditioning circuit that receives the measured signals from the Hall-effect sensors (LEM LA-55P) to measure currents and LEM LV-25P to measure voltages), and adjust these signals to the range of values of the DSP ADCs input. It must be referred that were implemented some hardware and software protection schemes, to prevent the occurrence of any overvoltage in the inverter, or overcurrent. The software protection schemes consist in the inhibition of the inverter control pulses in the case that the inverter currents or voltages were higher than some pre-defined thresholds. The hardware protection schemes consisted in the general overcurrent protection schemes, such as circuit breakers. In the Dc link inductor terminals was placed a varistor to absorb any voltage spikes produced by the inverter malfunctioning. Although that this is not the ideal overvoltage protection scheme, considering the levels of power of the prototype, this protection scheme is suitable.

The developed Current-Source Shunt Active Filter laboratory prototype is shown in Fig. 5. The implemented Active Filter was tested using the same conditions and loads of the performed simulations. The parameters of the experimental results are therefore in Table 1. The wave shapes were recorded using a Yokogawa DL 708E oscilloscope.

As in the obtained computer simulations, it can be seen in Fig. 6 (a) that the full bridge rectifier consumes currents with high levels of distortion from the electrical grid. In this way, the system voltage presents also some distortion due to the line impedance and the fact that is feeding a nonlinear load. As shown in Fig. 6 (b), after the Active Power Filter is turned on it is possible to see that the source current (i_{sa}) is correctly compensated and becomes sinusoidal with unitary power factor. The system voltages (e_{sa}), as in the simulations, after the compensation acquire a high frequency component that is associated with the switching of the power semiconductors of the inverter. These results indicate that the developed Current-Source Active Power Filter is operating correctly when compensating a nonlinear load (composed by a full-bridge rectifier), contributing to mitigate the power quality problems associated with this type of load.

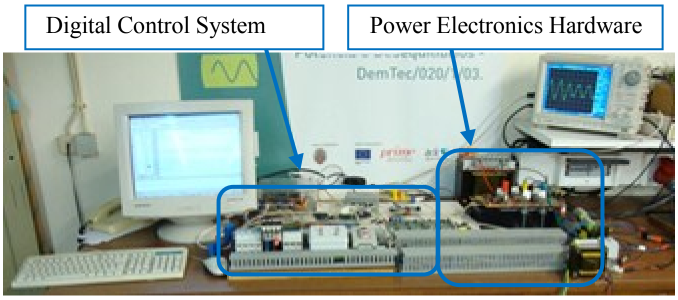

Fig. 5. Implemented Current-Source Three-Phase Shunt Active Power Filter.

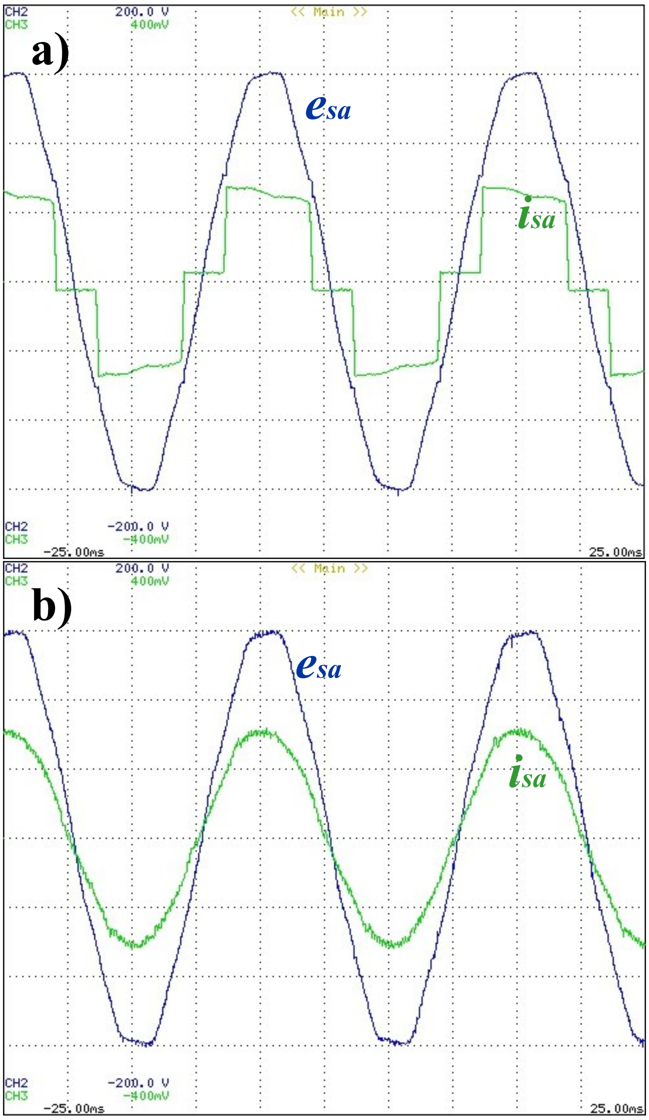

Fig. 6.Experimental results of the Current-Source Shunt Active Filter when compensating the non-linear currents (full-bridge rectifier), e_{sa} - line voltage, i_{sa} - source current: (a) Active Filter turned off; (b) Active Filter turned on.

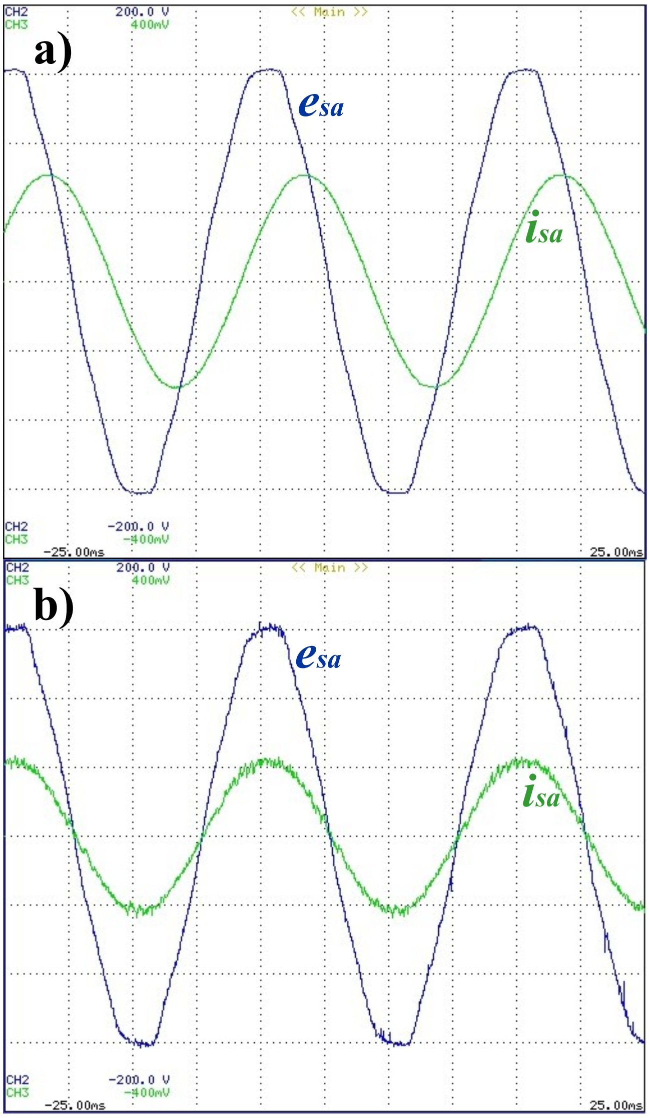

Fig. 7. Experimental results of the Current-Source Shunt Active Filter when compensating the low power factor load (resistive-inductive), e_{sa} - line voltage, i_{sa} - source current: (a) Active Filter turned off; (b) Active Filter turned on.

On the other side, in Fig. 7 are shown experimental results of the Active Power Filter when compensates a low power factor load (composed by resistive-inductive elements). As presented in Fig. 7 (a), before the compensation the source current (i_{sa}) is not in phase with the line voltage (e_{sa}), consequently, the power factor is low. After the compensation, as shown in Fig. 7 (b), the source current (i_{sa}) diminishes its amplitude and is in phase with electrical grid voltage (e_{sa}). Once more, this indicates that the developed Current-Source Active Power Filter is capable to compensate correctly low power factor loads, in this particular case composed by resistive-inductive elements. Thus, it contributes to mitigate the power quality problems associated with this type of load.

CONCLUSIONS

In this paper were presented experimental and simulation results of a Current-Source Three-Phase Shunt Active Power Filter, during its operation to compensate a low power factor load and a nonlinear load. For this purpose was developed a laboratory prototype with the necessary power electronics hardware and digital control system.

The Current-Source Three-Phase Shunt Active Power Filter controller relies on the *p-q* Theory to generate the reference compensation currents and to regulate the DC-link inductor current, as it was described in detail in the paper. To control the currents was used the Periodic Sampling Modulation Technique, and as shown through the obtained results, it allows a good performance under the two modes of operation presented.

As shown through experimental results, the developed Current-Source Three-Phase Shunt Active Power Filter performs well when compensating both a nonlinear load (full-bridge rectifier), and a low power factor load (resistive-inductive elements). The obtained experimental results are coincident with the simulation results, and therefore the performance of the Active Filter was validated. This work also shows that the *p-q* Theory can be used effectively in Current-Source Shunt Active Filters, and performs well in determining the current components that must be compensated.

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