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Simulation and Implementation Results of a 3-Phase 4-Wire Shunt Active Power Filter

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***Abstract*—This paper presents a laboratory prototype of a 3-phase 4-wire Shunt Active Power Filter used to compensate the source currents in an electrical system. The controller, based on the well known p-q theory was implemented on a DSP and determines the reference currents to be generated by a 2-level inverter. Some experimental results are presented and compared with computer simulations obtained with EMTDC/PSCAD V4.2. Other simulation results that demonstrate some of the improvements that will be made to the implemented prototype are also presented.**

***Index Terms*— Power Quality, Shunt Active Filter, p-q Theory, Computer Simulations, PSCAD, Switching Techniques.**

I. Introduction

THE widespread usage of non-linear loads like variable speed drives, switched power supplies, UPSs, rectifiers, and other industrial loads are known to deteriorate the power quality of the electrical systems. Problems such as harmonics, low power factor and imbalance can have dire consequences to the power distribution systems and the consumers [1].

The utilization of switching semiconductors in equipments, which are responsible for introducing harmonic content on the electrical systems, can also be used to mitigate this and other power quality problems. In 1976 Gyugi and Strycula introduced the concept of Active Power Filters [2]. This type of filters, contrarily to the passive ones, like LC filters or capacitor banks, has the capability to dynamically adapt to the conditions of the system in terms of harmonics and reactive power compensation, and additionally can also compensate imbalance.

This paper deals with a laboratory prototype of a Shunt Active Filter for three-phase four-wire systems, which is capable of compensating current harmonics, reactive power and current imbalance. Some tests with the laboratory prototype are presented, and the acquired results are also compared with a simulation model developed with PSCAD. Improvements in the Shunt Active Filter are suggested and tested in the simulation model.

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II. Control Theory

The p-q Theory was introduced in 1983 by *Akagi et al.* [3] for three-phase three-wire systems, with a brief mention to systems with neutral wire. Later, *Watanabe et al.* extended it to three-phase four-wire systems. Initially the *α-β-0* transformation (T), shown in (1), is applied both to the load currents i_a, i_b, and i_c, and also to the system's voltages v_a, v_b and v_c.

$$T = \sqrt{2/3} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = T \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = T \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

Then the instantaneous real power, p, the instantaneous imaginary power, q, and the instantaneous zero-sequence power, p_0, are calculated in the new reference frame.

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3}$$

Knowing that the source should only supply the average value of the instantaneous real power, it is necessary to calculate the power components that should be supplied by the Shunt Active Filter. These components are p_x and q_x. p_x contains the alternating part of the real power, $\tilde{p}$, the negative of the mean value of the instantaneous zero-sequence power, $\overline{p}_0$, and the negative value of p_{reg}. q_x consists in the instantaneous imaginary power, q.

$$p_x = \tilde{p} - \overline{p}_0 - p_{reg} \tag{4}$$

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

p_{reg} is the component to be drawn from the source in order to maintain the dc link capacitor voltage V_{dc} constant and is calculated by the following expression:

$$p_{reg} = \left(V_{ref}^{\ 2} - V_{dc}^{\ 2} \right) \cdot K_p \tag{6}$$

Now it is possible to determine the reference currents that should be generated by the inverter in the *α-β-0* coordinates:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^{\ 2} + v_\beta^{\ 2}} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_x \\ q_x \end{bmatrix} \tag{7}$$

$$i_{c0} = i_0 = \frac{1}{\sqrt{3}} \cdot \left(i_a + i_b + i_c \right) \tag{8}$$

A. Controller Implementation on a DSP/Microcontroller

The control theory was implemented on a *Texas Instruments TMS320LF2407A* DSP. Since the performance of this DSP reduces considerably when using floating point calculations, the control theory was expanded in order to perform the calculations only using integers, which decreases the time necessary to determine the reference currents. This expansion also reduced drastically the number of algebraic divisions, which would take a considerable amount of processing time.

Instead of using digital Butterworth filters to determine the average values of p and p_0, sliding average arrays were applied to determine these values, which are much simpler to implement and require less processor resources, but require more memory space.

Figure 1 presents a simplified block diagram of the implemented controller used to determine the reference currents. Because of the expansion used to simplify the calculations, no direct conversion is made to the *α-β-0* coordinates, but to auxiliary variables (e_{aux} and i_{aux}). However, the variables p, q and p_0 are still calculated according to the p-q theory developed by *Akagi*.

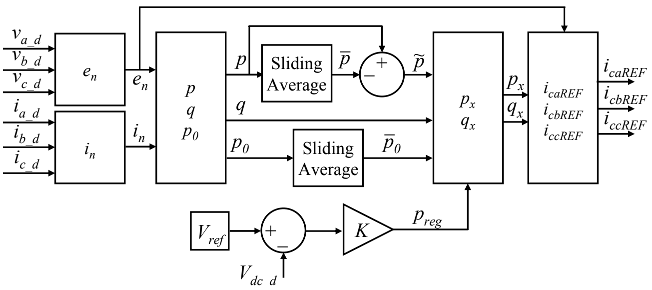

Fig. 1. Block diagram of the digital controller.

III. Hardware Description

The Shunt Active Filter prototype presented in this work uses a standard 2-level inverter implemented with Mitsubishi PM25RSB120 IGBTs modules. In order to minimize the noise injected by the inverter on the electrical system, it is used an inductance to interface each of the inverter legs with the phases and neutral of the electrical system, and a first order RC high-pass filter between each phase and the neutral wire. Figure 2 illustrates the implemented inverter with its inductances and RC filters.

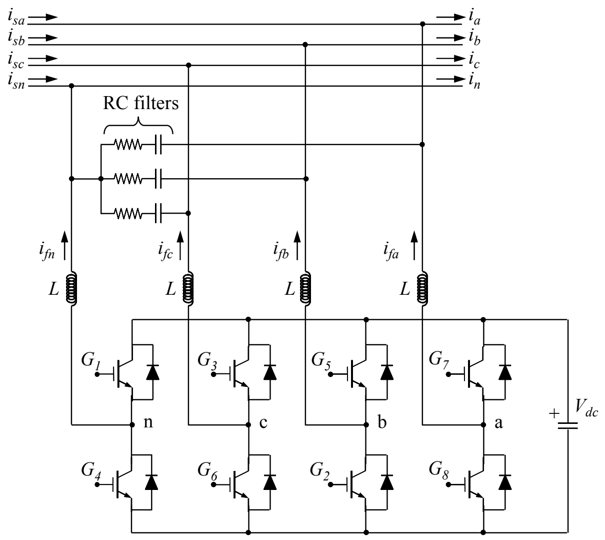

Fig. 2. Implemented Shunt Active Filter inverter.

The modulation technique used to drive the IGBTs was the *Periodic Sampling*, which is a very simple technique but that does not work with a fixed switching frequency [5]. It only establishes an upper frequency limit, which is defined by the clock input of a Flip-Flop (Figure 3).

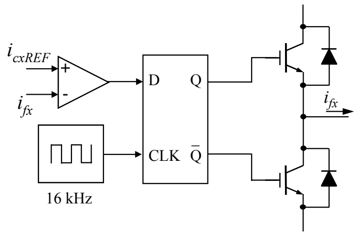

Fig. 3. Periodic Sampling method.

The implemented laboratory prototype can be seen in Figure 4, where it is possible to identify the inverter, the voltage and current sensors, the signal conditioning circuits and the DSP.

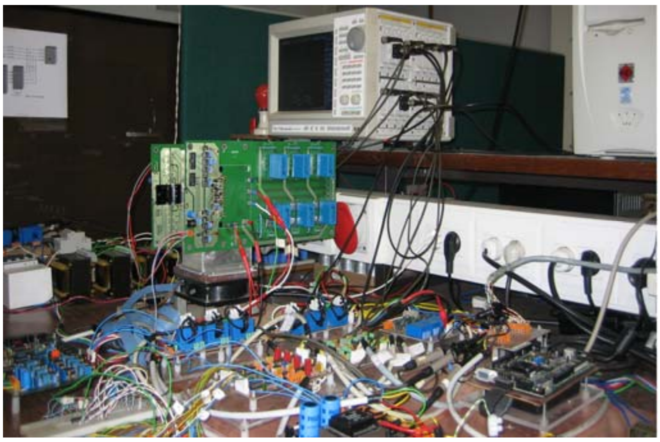

Fig. 4. Implemented laboratory prototype.

Table I indicates some of the parameters used in the experimental setup.

TABLE I
PARAMETERS OF THE SHUNT ACTIVE FILTER

Digital sampling frequency	32 kHz
dc-link capacitor (*C*)	740 µF
Output inductance (*L*)	5 mH / 0.9 Ω
RC filter	7.4 µF / 3 Ω
Reference dc voltage (V_{dc})	220 V
Maximum switching frequency	16 kHz

IV. TEST ELECTRICAL SYSTEM

The prototype was evaluated on a 3-phase, 4-wire, 75 V (phase to neutral), 50 Hz electrical system with 2 different loads, which is shown in Figure 5. The Shunt Active Filter was tested in 2 distinct situations. The first scenario was planned to test its capability to compensate a high level of imbalance and a low power factor. A RL load was connected between phase *b* and the neutral wire, which causes an imbalance of 200%, according to the IEEE Standard [6], and a power factor of 0.12 (this load is mainly inductive). In the second scenario, a 4 diodes bridge rectifier with a RL load connected between phases *a* and *c*, was added to electrical system. The THD of the currents was 30.2% in these phases. The current imbalance of the test electrical system became 84 %.

During the laboratory tests the measured voltage THD on each phase was around 3%. This voltage distortion was related to conditions of the electric grid, which feeds the test electrical system. Despite the fact that the harmonic content was slightly different on the three phases, the imbalance was less than 1%.

Figure 6 shows the voltages in the test electrical system during the tests with the laboratory prototype, and Figure 7 shows the load currents when the inductance and the rectifier are working.

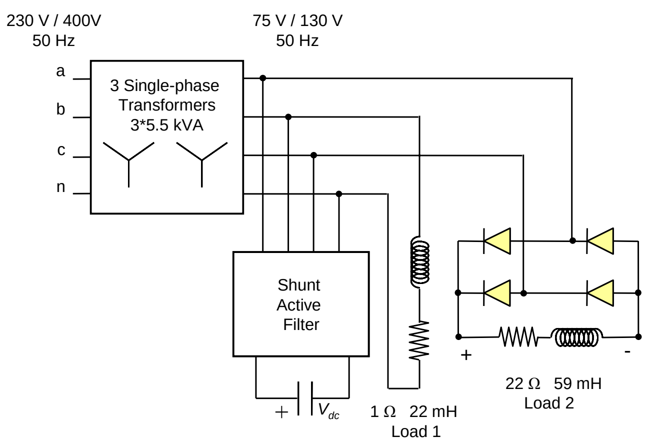

Fig. 5. Electrical system to test the Shunt Active Filter.

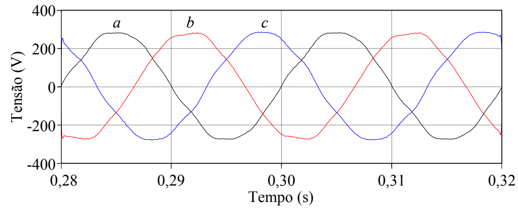

Fig. 6. Experimental voltage waveforms of the test electrical system.

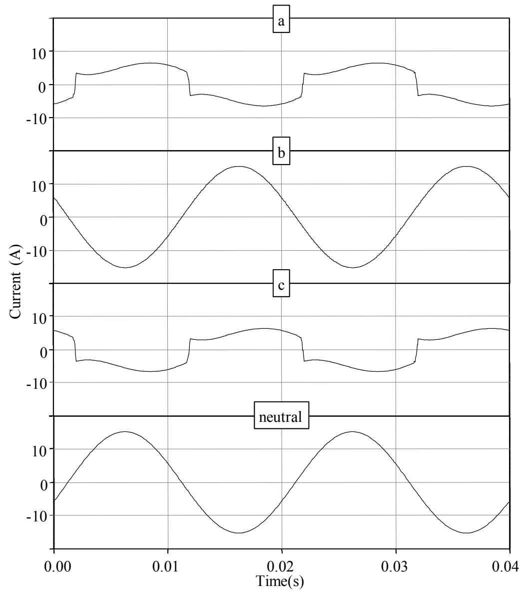

Fig. 7. Experimental load currents for the second test scenario.

A. Simulation Environment

Besides implementing the laboratory prototype, an accurate simulation model was developed, in order to try to predict the behavior of the Shunt Active Filter to help its design. The simulation model was designed with PSCAD 4.2.

Several steps were taken in order to guarantee an accurate simulation model:

- The simulated Shunt Active Filter controller used only integer 16 bit variables, in order to mimic the controller implemented in the DSP;
- ADCs, DACs and signal conditioning were simulated as mathematical functions, but this was useful because the calculations were made in the same digital scale used in the DSP, and therefore it became possible to predict overflows and other problems that could not be detected in the debugging phase of the software controller;
- Processing delays were used in order to simulate the time needed by the DSP to perform the calculations;
- Diodes, IGBTs and transformers were modeled according to the datasheets of the real components, and care was taken in order to accurately model the passive components.

Comparing Figure 8, which shows the simulated load currents for the second test scenario, with the currents from the actual implementation, presented in Figure 7, it is possible to confirm that the loads have been accurately modeled.

The simulated voltage waveforms of the electrical system were also modeled according to the conditions observed in the experimental setup. Figure 6 shows that the voltage waveforms during the tests had some harmonic content that changed the behavior of Shunt Active Filter based on the p-q theory [7, 8], therefore, the simulations were also done using distorted voltage waveforms, similar to the ones found in the actual system. The wave shapes were accurately modeled in the simulation system, through the use of a power quality analyzer that measured the voltage harmonics until the 15th order.

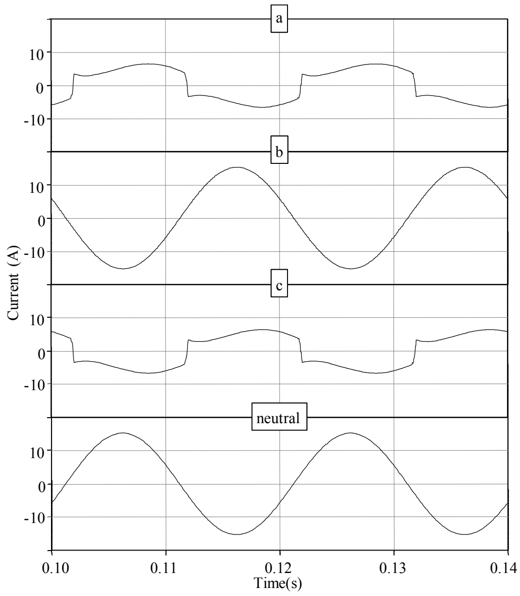

Fig. 8. Simulated load currents for the second test scenario.

V. Simulation and Implementation Results

Figure 9 shows the source currents of the electrical system when the Shunt Active Filter prototype is compensating power factor and imbalance in the first test scenario. Figure 10 shows the results in the same scenario obtained with the simulation model. In this scenario the load currents are zero in phases *a* and *c*, and its sinusoidal with a 0.12 power factor in phase *b*. It can be observed that the harmonic distortion in the source currents is moderately high in this scenario (about 10% - considering all harmonics up to the 50th order). It occurs because the source currents after compensation are too small (2.1 A RMS), since there is only a single-phase mainly inductive load in phase *b*, and then the noise produced by the active filter becomes very significant.

The second scenario, shown in Figure 11 (prototype) and in Figure 12 (simulation), demonstrates an improvement of the source current in terms of noise, since more active power is required by the loads, and the source currents are greater (4.7 A RMS). On the other hand it is possible to see that the source currents have some peaks that result from the rapid change of the load current, and on the response delay of the control system. Because of these problems the source currents THD was about 12%.

In both scenarios the power factor of the source currents increased to 0.99, both in the laboratory prototype and in the simulation model. There was also a significant reduction of the imbalance, which decreased to 2.7% on the first scenario, and to 2.0% on the second scenario.

Another important aspect of the Shunt Active Filter is the dc-link voltage behavior. Figure 13 shows this voltage at the terminals of the capacitor bank of the laboratory prototype, and Figure 14 shows the same voltage in the simulation model. These voltages were obtained when the active filter was compensating both loads (second scenario). It is possible to see that there is high-frequency noise on the dc voltage, because of a relatively high equivalent series inductance in the capacitor bank.

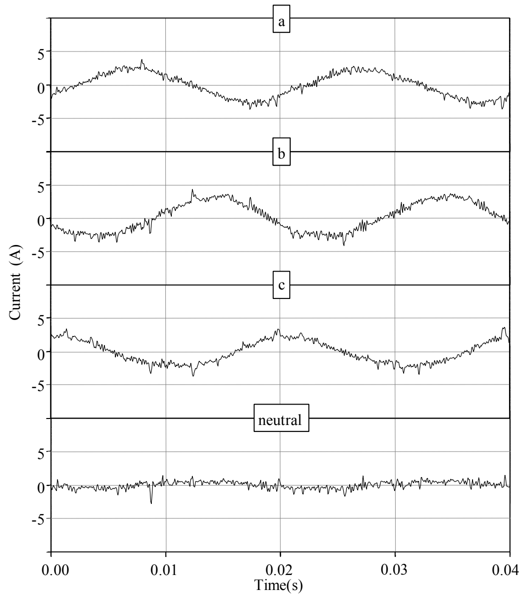

Fig. 9. Experimental results of the Shunt Active Filter prototype compensating a single-phase imbalanced, inductive load.

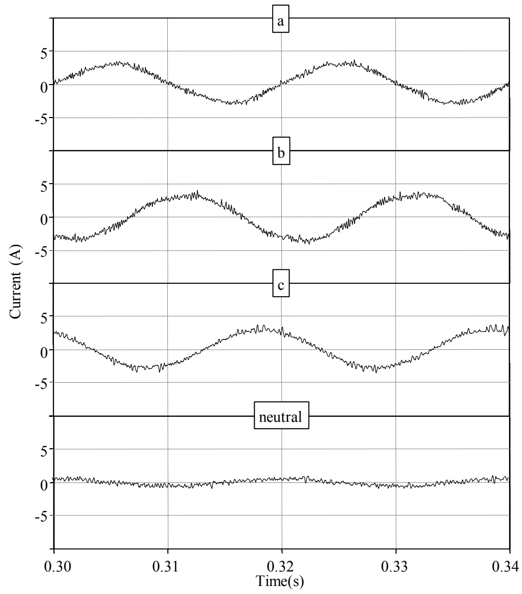

Fig. 10. Simulation results of the Shunt Active Filter compensating a single-phase imbalanced, inductive load.

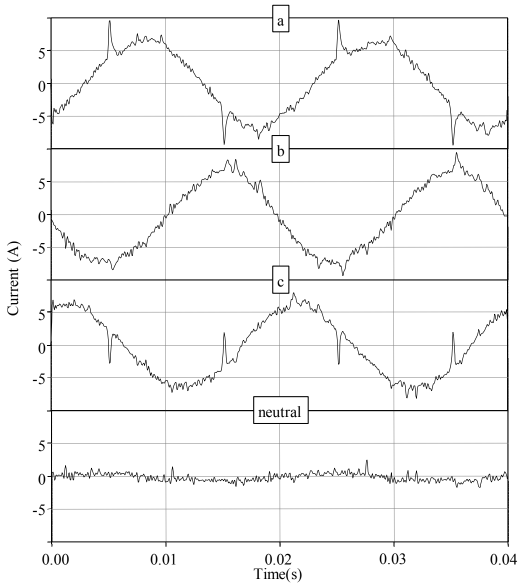

Fig. 11. Experimental results of the Shunt Active Filter prototype compensating both loads.

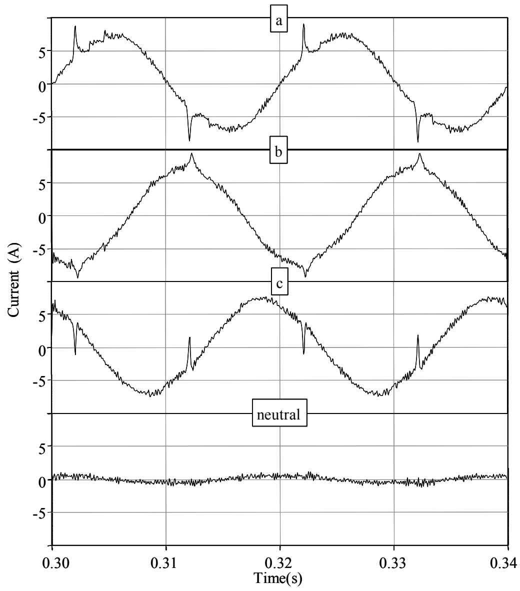

Fig. 12. Simulation results of the Shunt Active Filter compensating both loads.

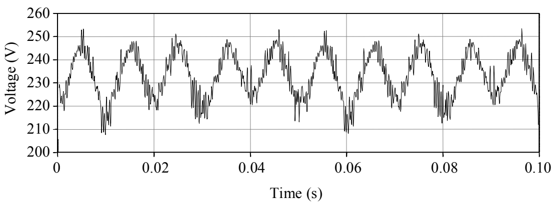

Fig. 13. Experimental results: dc-link voltage.

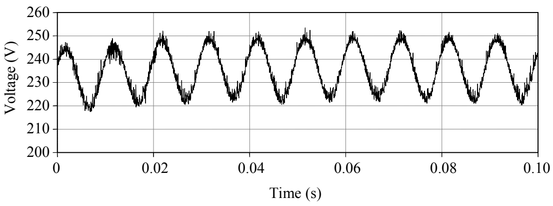

Fig. 14. Simulation results: dc-link voltage.

The differences between the DC voltages of the experimental and simulation results is because it is difficult to estimate the impedance accurately, however the results are approximate enough.

VI. Future Improvements

Because of the periodic sampling method used to determine the IGBTs drive signals, the Shunt Active Filter inverter does not operate with a fixed switching frequency. This makes it more difficult to filter the inverter output, and requires that larger inductances are used for this purpose. These inductances can become heavy and large for high power active filters. The major advantage of this switching method is the fact that it is very simple to implement, and the fact that it never presents stability problems. There is, however, the possibility of using a PWM technique without increasing the complexity of the control system. The classical PWM approach uses a PI controller, but for active filters that have to generate non-sinusoidal waveforms, this approach is not the best one, because the integrator affects the transient response [5]. A possible solution consists of using a unitary proportional gain and configuring correctly the triangular carrier waveform.

The fact that the noise is concentrated around the frequency of the carrier makes it theoretically easier to filter out the noise injected by the semiconductors with a tuned LC filter. The problem is that a real inductance also contains a resistive part, which deteriorates the performance of this filter. Therefore a second order RC filter with a 4 kHz cutoff frequency was used instead.

Another important upgrade consists of compensating the delays produced by the control system, by exploring the half wave symmetry of the reference currents, otherwise when the load currents change fast, like in Figure 8, the active filter is not capable of compensating them correctly, and a current impulse will appear as shown in Figures 11 and 12 [9, 10].

With these modifications it is possible to drastically reduce the value of the inverter output inductances, and also to decrease the value of the voltage on the dc side of the inverter. The new Shunt Active Filter has the following characteristics:

TABLE II
New parameters for the simulation model of the Shunt Active Filter

Digital sampling frequency	40 kHz
dc-link capacitor (*C*)	1500 μF
Output inductance (*L*)	1.5 mH / 0.3 Ω
RC filter	19.8 μF / 2 Ω
Reference dc voltage (V_{dc})	200 V
Fixed switching frequency	15 kHz

The performance of the simulated Shunt Active Filter with these modifications can be seen in Figures 15 and 16.

When the active filter is compensating only the inductive load (first scenario), the source currents THD is 6%, with RMS values of 2.2 A in two phases and 2.1 A for phase *b*, meaning that the imbalance is reduced from 200% to 3%.

When the second load is turned on (second scenario), the THD drops to 4.1% for phase *b* and to 3.5% for the remaining phases, with RMS values of 5.0 A in phase *a* and *b* and 5.1 A for phase *c*, leading to an unbalance that was reduced from 84% to 1.3%.

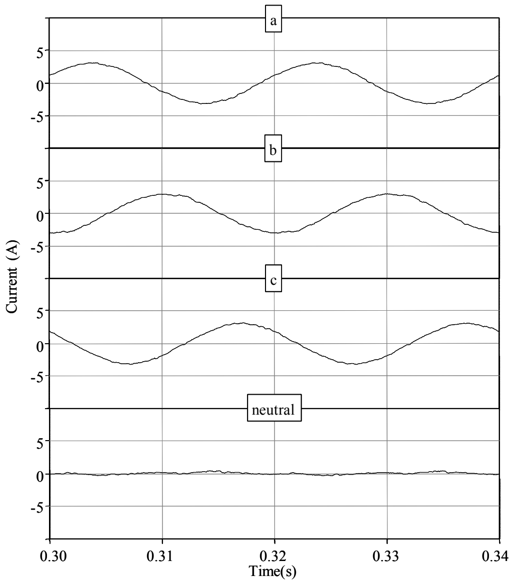

Fig. 15. Simulation results of the improved Shunt Active Filter compensating a single-phase imbalanced, inductive load.

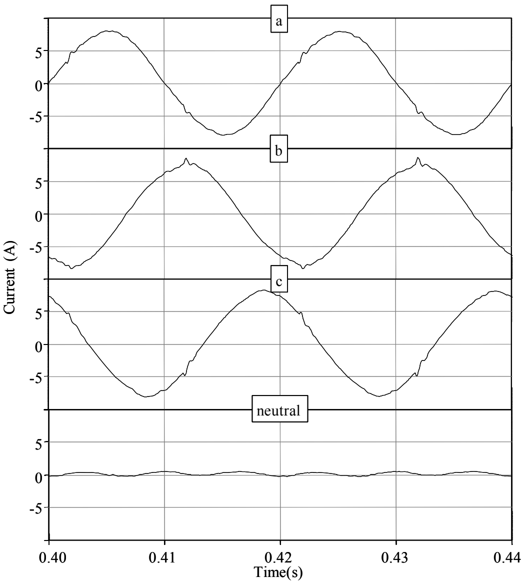

Fig. 16. Simulation results of the improved Shunt Active Filter compensating both loads.

VII. Conclusions

This work presented experimental and simulated results of a 3-phase 4-wire Shunt Active Filter prototype, with a digital control system based on the p-q theory which works with variable switching frequency.

The Shunt Active Filter was tested on 2 different operating conditions: with a linear single-phase inductive (imbalanced) load, and with linear and non-linear imbalanced loads. The performance of the active filter was satisfactory in terms of imbalanced and reactive power compensation, but showed limitations regarding the harmonic distortion.

The comparison between the experimental and the simulated results attests the accuracy of the simulation model developed for the Shunt Active Filter.

Using the simulation model, modifications of the Shunt Active Filter were proposed and tested. These modification clearly demonstrated improvements in the performance of the active filter.

VIII. References

[1] A. Bachry; Z. A. Styczynski, “An analysis of distribution system power quality problems resulting from load unbalance and harmonics”, IEEE PES - Transmission and Distribution Conference and Exposition, Volume 2, 7-12 Sept. 2003 pp. 763 – 766.

[2] Gyugyi, L. and Strycula, E.C.: “Active ac Power Filters” Proceeding of IEEE Industry Application Annual Meeting, vol. 19-C, 1976, pp. 529-535.

[3] H. Akagi, Y. Kanazawa, A. Xabae, “Generalized Theory of the Instantaneous Reactive Power in Three-phase Circuits”, IPEC‘83 – Int. Power Electronics Conference; Tokyo, Japan; 1983; pp. 1375-1386.

[4] E. H. Watanabe; R. M. Stephan; M. Aredes; New Concepts of Instantaneous Active and Reactive Powers in Electrical Systems with Generic Loads; IEEE Transactions on Power Delivery, vol. 8, no. 2, Apr. 1993; Page(s) 697 – 703.

[5] S. Buso; L. Malesani; P. Mattavelli; Comparison of Current Control Techniques for Active Filter Applications; IEEE Transactions on Industrial Electronics, vol. 45, Issue 5, Oct. 1998; Page(s):722 – 729.

[6] IEEE Standard 519-1992, “Recommended Practices and Requirements for Harmonic Control in Electric Power Systems”, 1992.

[7] J. L. Afonso, C. Couto, J. S. Martins, “Active Filters with Control Based on the p-q Theory”, IEEE Industrial Electronics Society Newsletter, vol. 47, nº 3, Sept. 2000, pp. 5-10.

[8] L. A. Pittorino; A. Horn; J. H. R. Enslin; “Power Theory Evaluation for the Control of an Active Power Filter”; Proceedings of the 4th IEEE AFRICON; vol. 2, 24-27 Sept. 1996, Page(s):676 – 681.

[9] J. L. Afonso; M. J. S. Freitas; J. S. Martins; “p-q Theory Power Components Calculations; 2003 IEEE International Symposium on Industrial Electronics”, ISIE '03, vol. 1, 9-11 Jun. 2003; pp.: 385 – 390.

[10] J. L. Afonso, “Filtro Activo Paralelo com Controlo Digital para Melhoria da Qualidade de Energia Eléctrica”, Ph.D. dissertation, Dept. Industrial Electronics, Univ. Minho, Portugal, 2000.

IX. Biographies

Ricardo Luís Guerreiro Pregitzer was born in Porto, Portugal, on April 1981. He graduated in Industrial Electronics from University of Minho, Portugal, in 2003. He is enrolled in M.Sc. at University of Minho, where he is working on the development of Active Power Filters. His main research areas of interest are Power Quality and Renewable Energies.

José Carlos da Cunha Costa was born in Braga, Portugal, on June 1978. He graduated in Industrial Electronics from University of Minho in 2004. His main research area of interest is Power Quality.

Júlio S. Martins was born in Mozambique, on September 1957. He graduated in Electrical Engineering from Oporto University in 1979 and received his Ph.D. degree from University of Minho, Portugal, in 1994. Since 1979, he works as a lecturer in the Department of Industrial Electronics of the University of Minho, occupying at the present the position of Associate Professor. His main areas of interest are Electrical Machines and Drives, Active Power Filters and Microsystems.

João Luiz Afonso was born in Rio de Janeiro, Brazil, on May 1963. He graduated in Electrical Engineering and received the M.Sc degree from the Federal University of Rio de Janeiro, in 1986 and 1991, respectively. He received the Ph.D. degree in Industrial Electronics from University of Minho, Portugal, in 2000. He joined the University of Minho in 1993, where he is an Assistant Professor in the Industrial Electronics Department. His main areas of interest are Active Power Filters, Power Quality and Renewable Energy.