UTILIZATION OF A UNIFIED POWER QUALITY CONDITIONER IN A SINGLE PHASE HIGH FREQUENCY AC DISTRIBUTION SYSTEM

Jeferson M. Corrêa*, Sudipta Chakraborty*, Felix A. Farret+ and Marcelo G. Simões*

Colorado School of Mines*
Golden, CO, U.S.A.
jcorrea, schakrab, msimoes@mines.edu

The Federal Unverity of Santa Maria+
Santa Maria, RS, Brazil
ffarret@ct.ufsm.br

Abstract – **This paper presents a High Frequency AC-based Microgrid as an interesting step towards integration of renewable energy sources in a distributed generation system. The successful implementation of a HFAC Microgrid depends on the best management of the sources and the common bus, which can be accomplished using a Unified Power Quality Conditioner (UQPC), which can compensate for current and voltage harmonics and also for reactive power. Its controller is based on the instantaneous p-q theory and the results obtained so far show that this conditioner can be effectively used to improve the system utilization.**

KEYWORDS

Microgrid, high frequency link, active filters, unified power quality conditioner.

I. INTRODUCTION

To guarantee the supply of the actual and increasing energy demand, with reduced cost, lower losses and reliability, Distributed Generation (DG) has been considered as a promising alternative for the coordinated and flexible expansion of the actual energy distribution system [1]. A DG system consists of an application of small size generators, typically from 1 kW to 10 MW, scattered through the system, used to provide the electrical energy closer to the consumers. Present DG power sources include: hydro, wind, photovoltaic, fuel cells, gas turbines, batteries, ultra-capacitors, super-inductors and flywheels. These small modular generation technologies interconnected to distribution systems can form a new type of power system, the so-called *Microgrid* [2]. The Microgrid concept assumes a cluster of loads and micro-sources operating as a single controllable system that can provide both power and heat to its local area.

However, to obtain the maximum utilization of such system, an intelligent integration of all sources and loads is necessary. One way to accomplish such goal is using a High Frequency AC (HFAC) link, which consists of a common bus that operates at a high frequency, for example 20 kHz. The utilization of a HFAC bus presents some advantages that will be addressed in this paper. Considering the optimum HFAC bus utilization, it is extremely important to compensate for reactive power, load current harmonics, resulted from non-linear loads, and voltage distortions, this ones resulting from the source and/or converter non-linearities. A Unified Power Quality Conditioner (UPQC), which integrates shunt and series active filters, is an electronic solution that can accomplish all these functions [3].

The UPQC controller uses instantaneous values of load and source currents and source voltage to obtain the actual active and reactive power components. The definition of these components is based on the instantaneous power theory (or p-q theory) [4]. The main advantage of using the p-q theory is that it is not necessary to calculate the root mean square (RMS) values or to use FFT, which require a large computational time and affect the control system dynamics. After obtaining these power components, the controller calculates the compensating reference current and voltage, which are then synthesized using voltage-source PWM converters. It is also important to highlight that the PWM converters do not need any active voltage source, but only one capacitor across the DC common bus.

In Section II we introduce the HFAC Microgrid in some details and discuss some of its advantages. Section III presents a description of the UPQC and its controller. This section also presents the PWM converters and their controllers. Section IV shows some simulation results justifying our claims and in Section V we conclude our paper with some pertinent remarks.

II. THE HFAC-BASED MICROGRID

Fig. 1 shows the proposed HFAC Microgrid, including the UPQC. The system represents a configuration with some static power sources (fuel cell and photovoltaic cells), energy storage devices (battery) and some loads (linear, non-linear and active). The HFAC-based Microgrid may have several interconnected energy sources and loads and the integration of all sources may cause some distortion in the source voltage, v_S, making it not perfectly sinusoidal. Also, the loads to be connected across the bus cannot be predicted and a significant contribution of non-linear loads may exist, increasing the harmonic content of the source current, i_s. In addition, it is known that the electrical motors, mainly induction machines, consume more than 60% of the total electrical energy. The reactive power required by induction machines may increase the utility size, make the custom voltage unstable, cause resonance problem and enlarge the power losses and stresses in power systems. The UPQC is integrated in the system so as to guarantee that the voltage at the Point of Common Coupling (PCC), v_L, is harmonic-free. It also acts on the total load current, i_L, to compensate for current harmonics and reactive power, in a way that the total source current, i_S, is also harmonic-free and in phase with the fundamental source voltage, resulting in a unitary displacement factor.

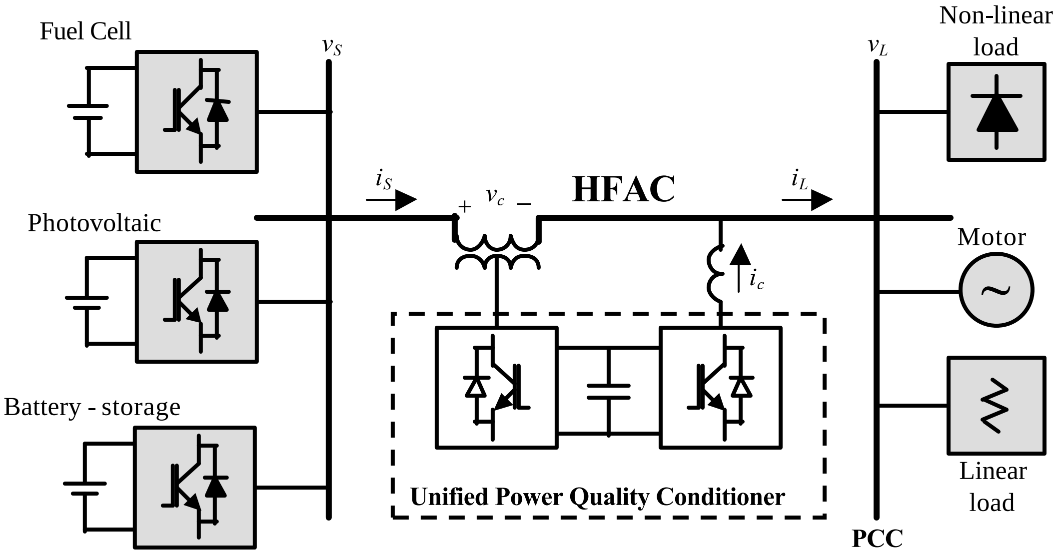

Fig. 1 – HFAC-based Microgrid concept

To generate the high frequency voltage, each source may use a power electronic converter, which can be a series resonant converter [5]. In this way, zero-voltage or zero-current switching schemes can be utilized, reducing the overall losses. An HFAC-based Microgrid system will have the following advantages [6]:

?? At higher frequencies, power quality is improved because the harmonics are of higher orders and easily filtered out.

?? · Acoustic noise is minimized due to the fact that the human ear cannot sense sounds above 20 kHz.

?? · Fluorescent lighting will experience dramatic improvement. The ballast inductance is reduced proportionally to the frequency with the corresponding reduction in the size and weight

?? · High frequency induction motors can be used for compressors, high-pressure pumps and turbines. AC frequency changers based on matrix converters can be used to soft-start high frequency induction motors.

?? · Harmonic ripple current in electric machines will decrease, improving efficiency.

?? · High frequency power transformers and other passive circuit components become smaller.

?? · The size of harmonic filters for batteries will decrease.

?? · Auxiliary power supply units are easily available by tapping the AC link. They would be smaller with better efficiency.

?? · Storage units are easily connected to an HFAC-based Microgrid improving reliability. Batteries have been the traditional energy storage source, but flywheel or ultra-capacitor are also viable alternate devices.

III. THE UNIFIED POWER QUALITY CONDITIONER

The UPQC is used to compensate for current and voltage harmonics and, also, to compensate for the reactive power in the fundamental frequency. The compensating reference current and voltage can be calculated using the p-q theory, which was first proposed for multi-phase systems [4] and it needs to be adapted for single-phase systems [7,8]. Liu *et al* [8] proposed a method in which the p-q theory is applied for single-phase systems, aiming at the application of a hybrid active filter. In their method, it is necessary to obtain an instantaneous ?/2 phase lag of the current and voltage waveforms to define a pseudo two-phase system. In this way, the system has only a 90^o delay and the phase lags are easy to obtain. For high frequency application, as we are considering in this paper, this time delay is only a small fraction of time, which do not affect significantly the system dynamic. However, as presented in [8], the reference compensating current is calculated to eliminate the current harmonics only. For the HFAC system, besides harmonic mitigation, we are also interested in reactive power compensation, in order to optimize the HFAC bus utilization, and also in voltage harmonic compensation. As normally utilized in three-phase systems, it is possible to define what quantities should be compensated [9,10], based on the p-q power components, making the compensator more flexible.

Fig. 2 presents the UPQC, which consists of the integration of a series active filter and a shunt active filter [11]. The p-q theory is used to obtain the reference compensating current (for the shunt active filter) and reference compensating voltage (for the series active filter) that should be applied to the system to compensate for the undesired power components.

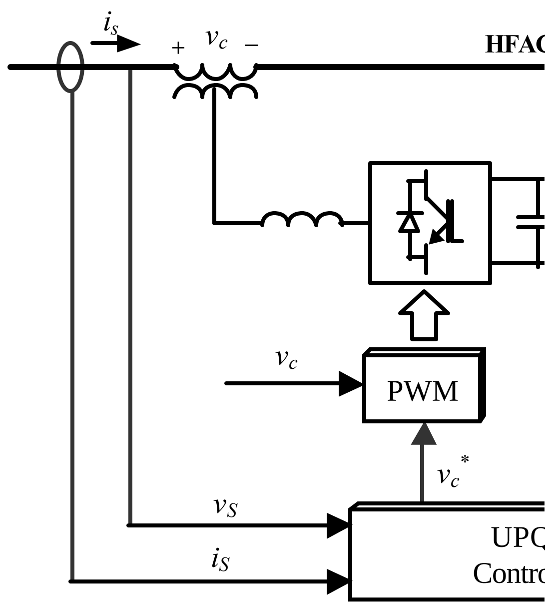

Fig. 2. Basic configuration of the Universal Power Quality Conditioner (UPQC)

To obtain a pseudo two-phase system, the voltage and current waveforms must be delayed by 90°. Doing this, the system can be analyzed in ??? coordinates, and be used directly to obtain the instantaneous active and reactive power components [8]. First, the actual voltage and current are considered to be ?-quantities. The values in ?-phase are assumed to be 90° lagging in respect to ?-phase. Then, the instantaneous active and reactive power can be calculated as [10]:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \quad (1)$$

In Liu *et al* [8], the method to obtain the compensating reference current is based on the calculation of the fundamental components in ??? coordinates, which needs an intermediary calculation. However, as presented by Watanabe *et al* [9] for three-phase system, the compensating current in ??? coordinates can be obtained directly from the system variables, based on the power components to be compensated. This is the approach used in this paper, except that it is adapted to single-phase systems. Then, the compensating reference currents, in ??? coordinates, can be defined by the inversion of Equation (1), using the power components to be compensated [10]:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{v_m^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ q \end{bmatrix} \quad (2)$$

where

$$v_m^2 = v_\alpha^2 + v_\beta^2 \quad (3)$$

In Equation (2) it was considered the compensation of the current harmonics and instantaneous reactive power. After calculating the compensating reference current, in ??? coordinates, the resulting compensating current must be converted to a?b?c coordinates. This component is defined only by the ?-component, which is the one in phase with the load current [8]. In this way, the reference current for the UPQC is related as:

$$i_c^* = i_{c\alpha}^* \quad (4)$$

The calculated current (i_c^*) is used as the reference for the shunt PWM inverter, which supplies the actual compensating current i_c, as shown in Fig. 3. The shunt active filter uses a current controlled-voltage source inverter, with bipolar PWM switching [12]. The shunt converter also controls the capacitor voltage. This is accomplished by an additional current component that is added to the reference current. This additional current is obtained taking into account the power losses in the capacitor circuit [11]. The output of the PI compensator is limited and then compared to a saw-tooth waveform. The resulting logic signal is used to drive the PWM switches. The output filter (L_f and R_f-C_f) attenuates the harmonics originated from the converter switching.

Similarly to the current compensation, to compensate for voltage distortions, the series compensator can be also designed based on the p?q theory. From the same Equation (1), we have, isolating the fundamental voltage components in ??? coordinates [11]:

$$\begin{bmatrix} v_{f\alpha} \\ v_{f\beta} \end{bmatrix} = \frac{1}{i_m^2} \begin{bmatrix} i_\alpha & i_\beta \\ i_\beta & -i_\alpha \end{bmatrix} \begin{bmatrix} \overline{p} \\ \overline{q} \end{bmatrix} \tag{5}$$

where

$$i_m^2 = i_\alpha^2 + i_\beta^2 \tag{6}$$

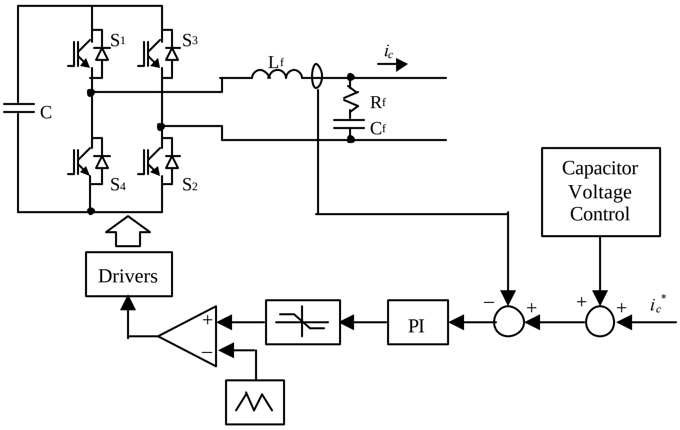

Fig. 3 – Shunt active filter – PWM converter and controller

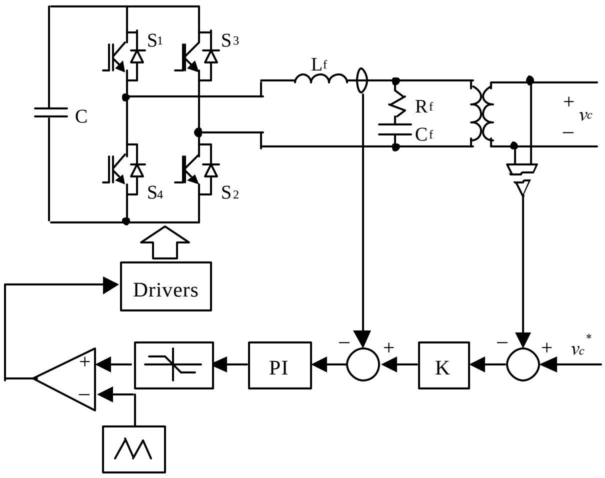

Fig. 4 – Series active filter – PWM converter and controller

The fundamental voltage, in a?b?c?coordinates, is defined by the ?-component only, which is the one in phase with the supply voltage. The compensating reference voltage is, then defined by:

$$v_c^* = v_s - v_f = v_s - v_{f\alpha} \tag{7}$$

This voltage is used as the reference for the series PWM inverter, which supplies the actual compensating voltage v_c, as shown in Fig. 4. The series active filter uses a voltage controlled-voltage source inverter, also with bipolar PWM switching. The controller uses an external voltage control loop and an internal current control loop. The voltage error is multiplied by a gain K and the resulting signal is compared to the converter output current. The PI controller uses the difference between these two signals to adjust the PWM duty cycle accordingly.

IV. SIMULATION RESULTS

Using the software PSIM?, several simulations were implemented to evaluate the proposed HFAC-based Microgrid. The following simulations correspond to a high frequency voltage with a 10%-third harmonic content, as shown in Figure 5, with amplitude of 400 V and frequency of 1.0 kHz. The voltage source supplies the parallel association of a non-linear load (composed of a series connection of a diode, a 5 ? –resistance and a 0.05 mH–inductance) and a linear load (a 10 ? –resistance). Figure 6 shows the load current, without compensation, for this test. From Figures 5 and 6 it can be seen that both, voltage and current present a high harmonic content. The shunt active filter of the UPQC is controlled to mitigate both current harmonics and reactive power. In this way, it is expected that the integrated source current becomes sinusoidal and also, in phase with the fundamental integrated source voltage. The compensating current and the resulting source current are shown in Figure 7 and 8, respectively. It can be seen that the source current is similar to a sine wave. The shunt active filter has supplied the current harmonics and the instantaneous reactive current.

Figure 9 presents the compensating voltage and Figure 10 presents the resulting source voltage, after compensation. It can also be seen that the resulting voltage is almost a perfect sine wave. The series active filter of the UPQC has compensated the voltage distortions.

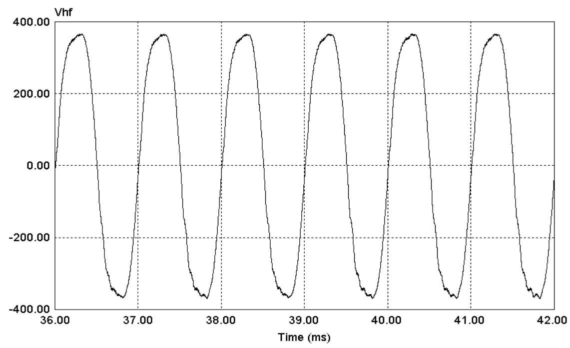

Fig. 5 – HFAC bus voltage without compensation

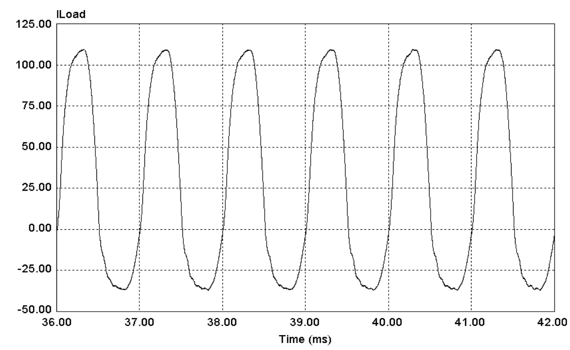

Fig. 6 – HFAC load current without compensation

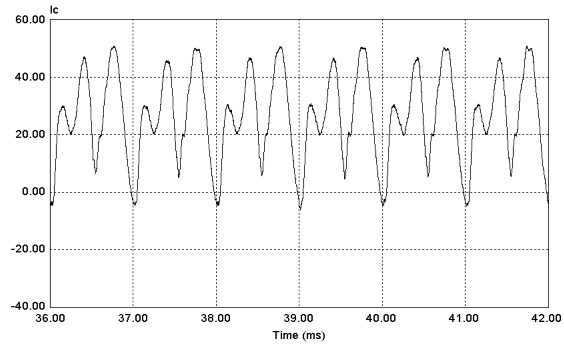

Fig. 7 – Compensating current

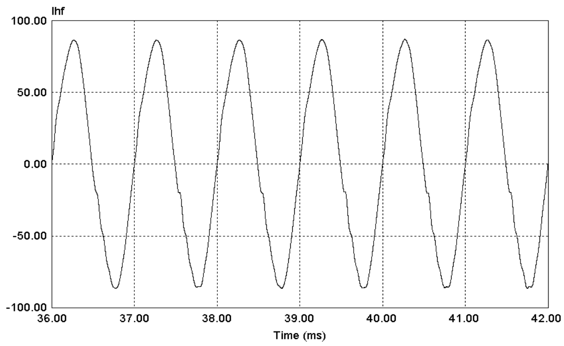

Fig. 8 – HFAC source current after compensation

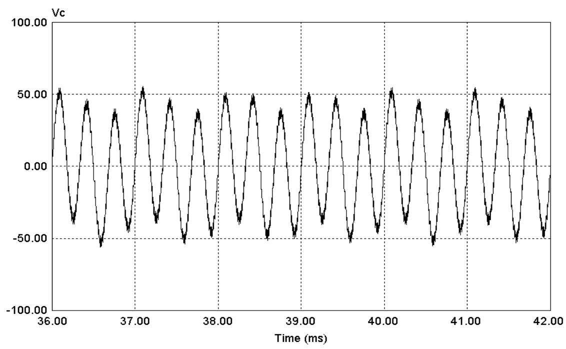

Fig. 9 – Compensating voltage

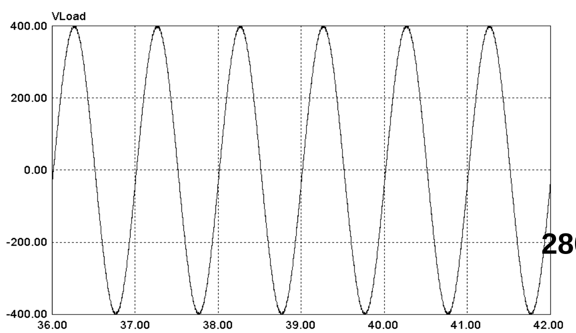

Fig. 10 – HFAC load voltage after compensation

V. CONCLUSION

HFAC-based Microgrid has been presented as a novel step towards integration of renewable energy sources in a distributed generation system. The successful implementation of HFAC-based Microgrid with adequate control based on the p-q theory can guarantee a better utilization of the sources and the common bus. This paper presents results related to the application of the p-q theory to a single-phase Unified Power Quality Conditioner (UPQC) for HFAC-based Microgrid systems. After have been calculated the instantaneous real and imaginary powers, the compensating reference current and compensating reference voltage are calculated using the power components to be compensated. These references are, then, used as inputs to the shunt and series active filters, respectively, which use PWM inverters to synthesize the desired waveforms.

The simulation results show that using the single-phase p-q theory method, the source current becomes approximately sinusoidal and in phase with the fundamental source voltage. In addition, it has been shown that is possible to compensate also for voltage distortions, resulting in a sinusoidal load voltage. This is an important aspect when considering sensitive loads connected to systems, which can be adversely affected by poor voltage waveforms.

ACKNOWLEDGEMENT

This work has been supported In part by the Brazilian Agency CAPES and by National Science Foundation The authors recognize and appreciate the strong support from the Federal University of Santa Maria for allowing exchange of technical information with NUDEMI and NUPEDEE, and from the Colorado School of Mines, Engineering Division (USA).

REFERENCES

[1] Borbely, A. and Kreider, J. F.); "*Distributed Generation: The Power Paradigm for the New Millennium*"; CRC Press.
[2] Lasseter, R. H.; "MicroGrids"; PES Winter Meeting , 2002, vol.1, pp. 305-308.
[3] Fujita, H. and Akagi, H.; "*The Unified Power Quality Conditioner: The Integration of Series- and Shunt-Active Filters*"; IEEE Trans. on Power Electronics, Vol. 12, No. 2; March/1998; pp. 315 – 322.
[4] Akagi, H.; Kanazawa, Y; and Nabae, A.; "*Generalized Theory of the Instantaneous Reactive Power in Three-*

Phase Circuits"; Int. Power Electronics Conf. - IPEC'83; Tokyo, Japan; 1983; pp. 1375 – 1386.

[5] Sood, P. K. and Lipo, T. A.; "*Power conversion distribution system using a high-frequency ac link*"; IEEE Trans. on Industry Applications, Vol. 24, No. 2; Mar/Apr 1998; pp. 288 – 300.

[6] Simões, M. G.; Chakraborty, S.; Farret, F. A. and Corrêa, J. M., "*Intelligent Based Hierarchical Control of Power Electronics for Distributed Generation Systems*"; Workshop in Power Electronics for Fuel Cells, National Fuel Cell Research Center, Irvine, CA; August 8-9, 2002.

[7] Haque, M. T. and Ise, T.; "*Implementation of Single-Phase pq Theory*"; Power Conversion Conference, PCC - Osaka 2002; pp. 761 – 765.

[8] Liu, J.; Yang, J.; and Wang, Z.; "*A New Approach for Single-Phase Harmonic Current Detecting and its Application in a Hybrid Active Power Filter*"; The 25th Annual Conference of the IEEE Industrial Electronics Society – IECON'99; Vol. 2; 1999; pp. 849 – 854.

[9] Watanabe, E. H.; Stephan, R. M. and Aredes, M.; "*New Concepts of Instantaneous Active and Reactive Powers in Electrical Systems with Generic Loads*"; IEEE Trans. on Power Delivery; Vol. 8; No. 2; April 1993; pp. 697 – 703.

[10] Afonso, J.; Couto, C, and Martins, J.; "*Active Filters Based on the p-q Theory*"; IEEE Industrial Electronics Society Newsletter; Vol. 47; No. 3; September; 2000; pp. 05 – 10.

[11] Aredes, A.; Heumann, K. and Watanabe, E. H.; "*An Universal Active Power Line Conditioner*"; IEEE Trans. on Power Delivery, Vol. 12, No. 2; April 1998; pp. 545 – 551.

[12] Mohan, N.; Undeland, T. M. and Robbins, W. P.; "*Power Electronics: Converters, Applications and Design*"; John Wiley & Sons, Inc.; 1995; 802 p.