Non-Linear Passivity Approach Applied to a Three Phase Active Shunt Power Filter

V. Cárdenas, M. Oliver, N. Visairo, S. Ramírez
Electrónica, CENIDET.
Interior Internado Palmira s/n Col. Palmira,
C.P. 62490.Cuernavaca, Mor. MEXICO
Fax: 52 (73) 12 24 34
e-mail: v.cardenas@ieee.org

C. Núñez
Departamento de electrónica
ITESRC
Carretra 57, Km.120, Agujita, Coahuila,
MEXICO
Fax: 52 (861) 3 36 07
e-mail: aecnunez@cenidet.edu.mx

H. Sira-Ramírez
Deparatamento de Sistemas de
Control, Escuela de Ingeniería,
Universidad de los Andes
Mérida 5101, Venezuela
(074) – 402846

Abstract-- This paper presents a three-phase shunt active power filter controlled by the non-linear passivity technique. The dissipative features in which the passivity technique is based on allow the development of a non-linear controller having a good dynamical response, robustness and stability. The control circuit is based on a DSP. Analysis and modeling are presented as well as simulation and experimental results, which verify the satisfactory of the proposed approach.

I. Introduction

ith the proliferation of active and non linear loads, including the increasing number of static power converters and arc furnaces, the performance of a power distribution installation is been considered as an essential component, because of the presence of high order harmonics produced by non linear loads. Just to mention some, harmonic elimination techniques have been widely studied and traditional solutions such as passive filters have many well-known disadvantages [1,2], therefore active power filters are becoming very important. Active power filters are connected to AC mains in order to eliminate voltage variations and harmonic components. Shunt active power filters eliminate the current harmonic components working as a current source to provide only the harmonic components that the load demands and correcting the power factor, so that only the fundamental current component is present in the AC mains. In active power filters there are many control strategies, which have been studied in order to obtain a good performance.

This paper presents a shunt active power filter approach controlled by the non-linear passivity technique. There is a good agreement between the active filter dynamics and the dissipative features in which the passivity technique is based on; this allows the development of a non-linear controller having a good dynamical response, robustness and stability. Passivity based control has shown to be an adequate alternative when applied for the dynamical control of dc-dc converters [3,4]. The paper is organized as follows: in section II the active filter model is obtained; in section III the passivity based controller is analyzed and designed; in section IV the simulation and experimental results are presented, and finally the conclusions are shown in V.

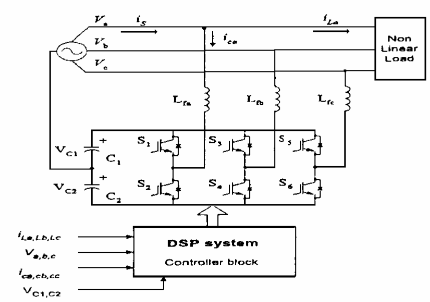


Fig. 1 Shunt active power filter topology

The control circuit is based on a digital signal processor (DSP), where the reference current signals are generated using the PQ theory [2], and the passivity control law is programmed. The active filter topology used is shown in Fig. 1: it can be modeled as a current source supplying the harmonic currents required by the non-linear load.

II. Active Filter Model

Reference Signal Generation

The reference signal required by the controller is obtained by means of the instantaneous reactive power theory. Fig. 2 shows the control system configuration programmed in the DSP, where the voltage and load currents are transformed from three-phases (i_{La}, i_{Lb}, i_{Lc}) to two-phases (i_α, i_β), including the zero sequence component.

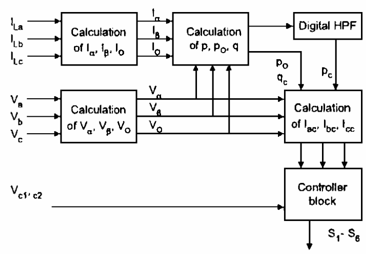


Fig. 2 Control system configuration programmed in the DSP

The transformation of the load current and the ac mains voltages are based on the following expressions:

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1) \qquad \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (2) \qquad \begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Equation (3) can be inverted to explicitly obtain the three-phase harmonic currents giving:

$$\begin{bmatrix} i_{ac} \\ i_{bc} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_0 \\ p_c \\ q_c \end{bmatrix} \quad (4)$$

here p_c is the negative ac component of p obtained by through a digital filtering, q_c is the negative of q, and p_o is the zero sequence component. The physical meaning and the reason for the naming of the instantaneous active and reactive currents are presented in [2].

III. Model of the Active Filter

The active power filter model is obtained now in order to get the passivity based control. The equivalent single-phase circuit for the operation mode is shown in Fig. 3.

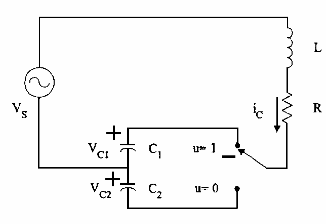


Fig. 3 Equivalent circuit for shunt active power filter modeling

For u = 1:

$$\dot{x}_1 = -\frac{R}{L}x_1 - \frac{1}{L}x_2 + \frac{V_S}{L} \qquad (5) \qquad C\dot{x}_2 = x_1 \qquad C\dot{x}_3 = 0$$

For u = 0:

$$\dot{x}_1 = -\frac{R}{L}x_1 + \frac{1}{L}x_3 + \frac{V_S}{L} \qquad (6) \qquad C\dot{x}_2 = 0 \qquad C\dot{x}_3 = -x_1$$

here $C_1 = C_2 = C \qquad x_1 = i_C \qquad x_2 = V_{C1} \qquad x_3 = V_{C2}$

By considering every possible combination, the system model is obtained in the following matrix form:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}0 & -u/L & (1-u)/L\\ u/C & 0 & 0\\ -(1-u)/C & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}-R/L & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}V_S/L\\ 0\\ 0\end{bmatrix} \qquad (7)$$

or:

$$\begin{aligned}\dot{\mathbf{X}} &= \mathbf{f(x)} + \mathbf{g(x)u} + \mathbf{b}\\ \mathbf{y} &= \mathbf{h(x)}\end{aligned} \qquad (8)$$

IV. Passivity-Based Controller Design

A system is said to be passive if the stored energy in the system is less than or equal to the total energy supplied to the system in a given period of time. In the case of the active filter, this principle is fulfilled, and consequently, this technique can be applied [4].By considering that the forces acting on a dynamical system can be divided into stabilizing forces, unstabilizing force and conservative forces, passivity-based control only modifies the unstabilizing forces. hen this passivity principle is applied to active filters, the controller obtained respects the non affecting forces and a more natural and less stressing control law is applied to the system. From equation (7), the associated exosystem for the active filter is:

$$\begin{bmatrix}\dot{x}_{1d}\\ \dot{x}_{2d}\\ \dot{x}_{3d}\end{bmatrix} = \begin{bmatrix}0 & -u/L & (1-u)/L\\ u/C & 0 & 0\\ -(1-u)/C & 0 & 0\end{bmatrix}\begin{bmatrix}x_{1d}\\ x_{2d}\\ x_{3d}\end{bmatrix} + \begin{bmatrix}-R/L & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}x_{1d}\\ x_{2d}\\ x_{3d}\end{bmatrix} + \begin{bmatrix}-R_1/L & 0 & 0\\ 0 & 1/R_{CD}C & 0\\ 0 & 0 & 1/R_{CD}C\end{bmatrix}\begin{bmatrix}x_1 - x_{1d}\\ x_2 - x_{2d}\\ x_3 - x_{3d}\end{bmatrix} + \begin{bmatrix}V_S/L\\ 0\\ 0\end{bmatrix} \qquad (9)$$

here: R_1 and R_{CD} are the virtual resistive elements associated to the exosystem; X_{1d}, X_{2d}, and X_{3d} are the corresponding reference state variables. From the exosystem, the control law based on the passivity technique is obtained:

$$u = \frac{x_{3d} - Rx_{1d} + V_S - L\dot{x}_{1d} - R_1(x_1 - x_{1d})}{x_{2d} + x_{3d}} \qquad (10)$$

There are three essential conditions to apply passivity approach: 1) The system must be stable, 2) The relative degree of the system must be equal one, and 3) The stored energy must be less than the supplied energy. The analysis to verify the above three points is shown as follows:

V. Stability analysis.

The stability analysis is carried out by using the remaining dynamic concept, this is, the internal behavior of the system considering that it is time variant. The following equations show the remaining dynamic:

$$\begin{aligned}C\dot{x}_2 &= \frac{x_1x_3 - Lx_1\dot{x}_1 - Rx_1^2 + x_1v_s}{x_2 + x_3}\\ C\dot{x}_3 &= \frac{-x_1x_2 - Lx_1\dot{x}_1 - Rx_1^2 + x_1v_s}{x_2 + x_3}\end{aligned} \qquad (11)$$

The simulation results of the remaining dynamic show that the system is stable in a limited region. This can be observed in Fig. 4.

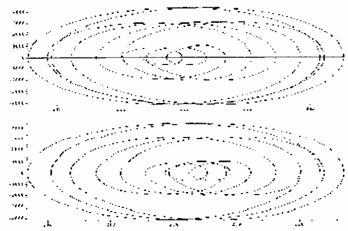


Fig. 4 Phase diagram of the remaining dynamic (top to bottom): remaining dynamic of x_2; remaining dynamic of x_3

VI. Relative degree of the system.

Relative degree equal one is an essential condition to apply the passivity control law [4]. The relative degree is equal to the number of times that the output has to be differentiated to have the value of the input u explicitly appearing in the output expression. In equation (9) it can be observed that the input u is appearing in the first derivative of X. Therefore, the relative degree of the system is equal to one and the non-linear technique can be applied.

VII. Stored energy in the system.

From Fig. 2, two elements that stored energy can be seen: the capacitor and the inductor. Also, it can be observed one dissipative element: the resistance. The general expression that must be satisfied is:

$$\underbrace{V(x(t)) - V(x(0))}_{\text{Stored energy}} \le \underbrace{\int_0^T u^T(t)\, y(t)\, dt}_{\text{Supplied energy}} \tag{12}$$

Using the storage and dissipative elements of the non-linear model, the right hand inequality (12) becomes:

$$\underbrace{-R\int_0^T x_1^{\,2}\, dt}_{\text{Dissipated energy}} + \underbrace{\int_0^T x_1 V_s\, dt}_{\text{Supplied energy}} \le \underbrace{\int_0^T x_1 V_s\, dt}_{\text{supplied energy}} \tag{13}$$

It can be observed in (13) that the stored energy is less than the supplied energy.

VIII. Simulation and Experimental Results

The following plots present the results from simulation obtained by the use of the passivity based control for the active shunt power filter. In Fig. 5 the system and exosystem currents are presented. The upper trace represents the reference current, the system current X_1 is represented by the intermediate trace and lower trace presents the difference between the two signals above (error signal). At start, this error is high because the capacitors are initially charged to the peak voltage value of the ac mains. hen the capacitors are charged to the reference voltage the current error is exclusively due to the difference between the reference and the filter currents.

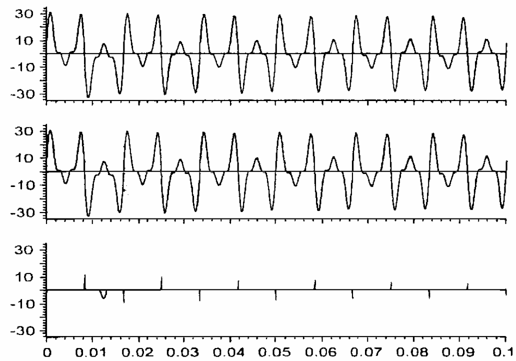


Fig. 5 Simulation results (top to bottom): reference current; active filter current; current error.

Fig. 6 presents the simulation results when the system is affected by a load transient. The signals present from top to bottom are: the load current; active filter current; ac mains current; dc bus voltage (given by the addition of the voltages in capacitors C_1 and C_2) and the control law *u* (whose instantaneous value represents the filter duty cycle).

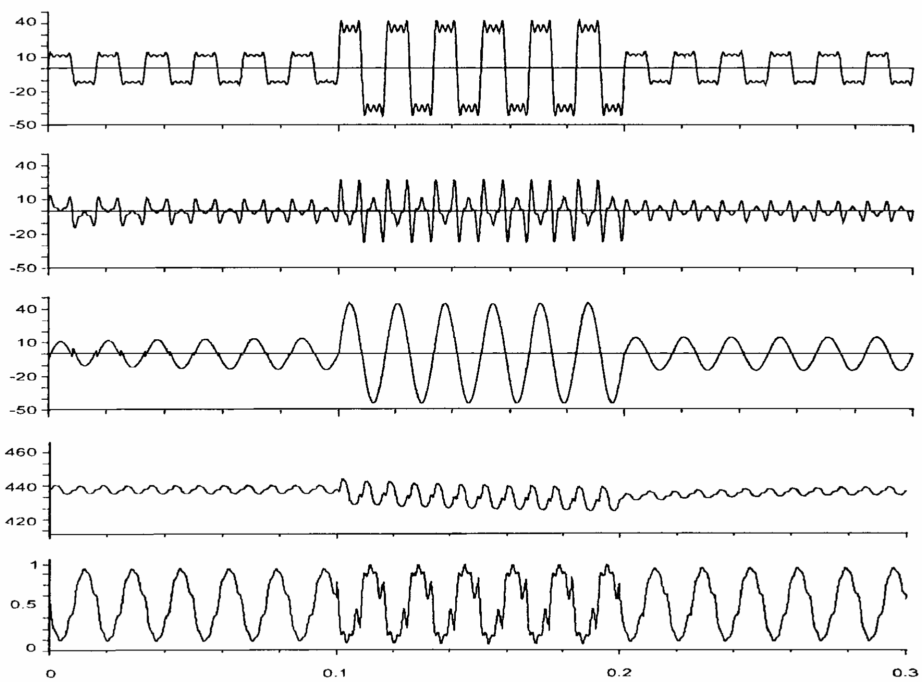
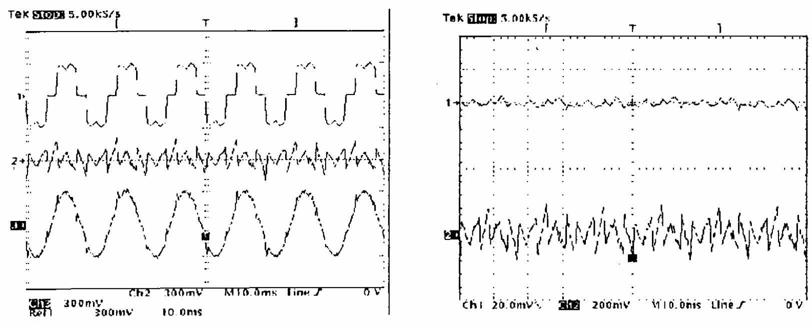


Fig. 6 Simulation of the transient response (top to bottom): load current; active filter current; ac mains current; cd bus capacitor voltage; control law *u*.

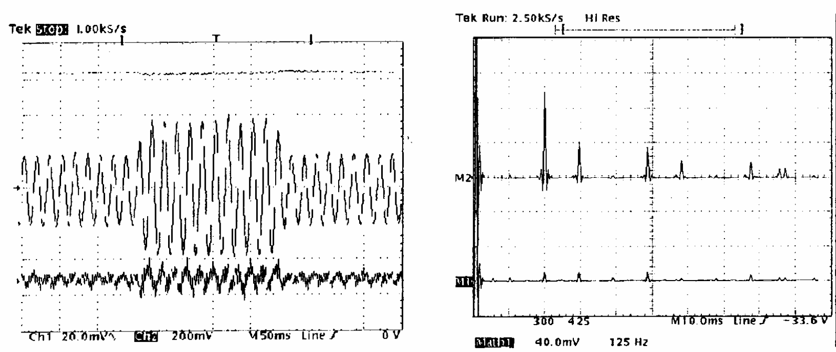
A transient in the load step can be seen in the capacitor voltage. The value of this transient is much more less than the dc bus average value. To avoid the capacitors to be discharged it is necessary to introduce a compensating factor in the reference current. There is a change in the control law *u* whenever the load current increases. This is due to the new duty cycle pattern required to provide the current harmonics demanded by the load. An experimental prototype of a three-phase, 20 kVA active filter has been used to experimentally verify the filter performance under the passivity based control law. The values for the passive elements remain the same as those from simulations and the power stage is conformed by a three phase IGBT inverter having a maximum frequency of 10 kHz. The nonlinear load is a three-phase rectifier with a resistive load in dc.The exosystem and the control law (based on passivity) with the P M duty cycle were programmed in the DSP by using equations (9) and (10). The non-lineal differential equations of the exosystem are solved in the DSP by numerical methods, particularly the third order Runge-Kutta method. Fig. 7(a) represents from top to bottom the load current, filter current and the ac mains current. It can be seen that the ac mains current has a low harmonic content compared with the load current.



(a) (b)

Fig. 7. (a) Compensation with the active filter (top to bottom, 10ms/div): load current [30 A/div]; active filter current [30 A/div]; ac mains current [30 A/div]. (b) Compensation with the active filter (top to bottom, 10ms/div): capacitor voltage [20 V/div]; active filter current [20 A/div].

Fig. 7(b) presents the dc bus capacitor voltage and the active filter current, The vertical scale for the dc bus voltage is 20 V/div. It can be appreciated that the voltage ripple presents a low magnitude. Fig. 8(a) shows the system response under a load transient. The upper trace represents the dc bus voltage, the intermediate trace presents the ac mains current and the lower trace shows the filter current. An adequate compensation can be observed even during the load transient.



(a) (b)

Fig. 8. (a) Experimental results for transient response (top to bottom, 50ms/div): capacitor voltage [100 V/div]; ac mains current [30 A/div]; active filter current [30 A/div]. (b) Current harmonic content (top to bottom, 125 Hz/div): load current [4 A/div]; ac mains current [4 A/div]

The Fig. 8(b) shows the harmonic spectrum for the load current and the ac mains current, with the active filter compensating the harmonic currents. The upper trace corresponds to the load current and bottom trace corresponds to the ac mains current. It can be appreciated that the fifth harmonic in the ac mains current is clearly lower than the fifth harmonic in the load current. The other significant harmonics have similar results. The Table I presents the current harmonic content in the ac mains before and after current harmonic compensation by the active filter. The harmonic content has been reduced by the use of the active filter and also the power factor has been incremented tending to unity

Harmonic components demanded to the AC mains by a nonlinear load with and without active filter AF (as a percent of the fundamental).

	ithout AF	ith AF
Po (kVA)	**7.80**	**7.26**
P.F.	**0.93**	**0.99**
I_3	1.32%	1.38%
I_5	25.30%	3.45%
I_7	11.11%	2.82%
I_9	0.35%	0.31%
I_{11}	7.37%	2.55%
I_{13}	4.59%	0.53%
I_{15}	0.76%	0.27%
I_{17}	2.22%	0.40%
THD	**29.1%**	**5.37%**

TABLE I

IX. Conclusions

A three-phase shunt active power filter controlled by the passivity-based control technique and using a digital signal processor (DSP) has been presented. To validate the filter performance, experimental and simulation results were obtained. The use of passivity-based control produces a good harmonic current compensation by the active filter, and the system dynamics are adequately driven. A novel contribution of this work is the application of passivity to active filtering. Some other significant results from this work are an improvement in the power factor and in the transient response by the use of the active filter and the developed controller. Actually, research is been carried out comparing passivity-based control and other control techniques as sliding mode control and conventional control (PID) to justify the use of non-conventional control techniques to improve the active filter performance. It is important to consider that the controller must achieve an adequate harmonic current compensation in a minimum time (to properly follow the reference current signal) with a minimum commutation frequency (to reduce the losses in the filter).

X. REFERENCES.

[1] H. Akagi "Trends in Active Power Line Conditioners" IEEE Transactions on Power Electronics, Vol. 9, No. 3, May 1994. Pp. 263-268

[2] H. Akagi, Y. Kanazawa, A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components", IEEE Transactions on Industrial Applications, Vol. IA-20, p. 625, 1984.

[3] H. Sira-Ramirez, M. Ilic "A Geometric Approach to the Feedback Control of Switch Mode dc-to-dc Power Supplies", IEEE Transactions on Circuits and Systems, Vol. 35, Iss 10, Oct. 1988 Pp. 1291-1298

[4] H. Sira Ramírez, R. Ortega, R. Pérez, M. García, "Passivity based controllers for the stabilization of dc-to-dc power converters", Automática 1997, 33, 499-513.

[5] J. Dixon, J. Contardo, L. Morán "DC Link Fuzzy Control for an Active Power Filter, Sensing the Line Current Only" *IEEE Power Electronics Specialist Conference -PESC'97,* pp. 1109-1114.