Non-Linear Passive Control with Inductor Current Feedback for an UPS Inverter

Gustavo Alarcón	CENIDET
Víctor Cárdenas	CENIDET
Sinuhé Ramírez	CENIDET
Nancy Visairo	CENIDET
Ciro Nuñez	CENIDET
Marco Oliver	CENIDET
Hebertt Sira-Ramíez	Universidad de los Andes, Venezuela

Topic: *Control theory as applied to power electronic systems*

Corresponding Author:

Gustavo Alarcón

Centro Nacional de Investigación y Desarrollo Tecnológico, CENIDET.

Electronics Engineering Department - Power Electronics Group

Interior Internado Palmira s/n Col. Palmira, C.P. 62490.

Cuernavaca, Mor. MEXICO

Tel: 52 (73) 18 77 41

Fax: 52 (73) 12 24 34

E-mail: g.alarcon@ieee.org

ABSTRACT:

For the control design of UPS a common assumption is to consider the associated filter and the load as linear as a time invariant system. This paper presents a single – phase inverter controlled by a technique based on variable structure systems theory, the non-linear passivity technique. The aim is to achieve a non-linear control providing good dynamical response, robustness and stability to the filter and inverter.

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I. INTRODUCTION

Uninterruptible power supplies (UPS) are designed to supply clean and uninterrupted power to equipment in critical applications such as computers, medical/life support systems, industrial controls, communication systems, etc. For a typical uninterruptible power supply, an inverter system with pulse width modulation (PWM) is used to generate a pure sinusoidal AC output voltage when the utility power is not present. It is important that the inverter incorporates a high stability and reliability as well as fast dynamic response, particularly under nonlinear loads.

The control strategy to be used is one of the most significant factors affecting the whole performance of the system. The output distortion specifications are frequently the driving factor in the choice of the switching frequency and the filter size. The simplest control strategies treat the filter and load as linear time invariant systems. In this case, the spectral components generated by the inverter itself are the only harmonics present in the load. Further, as the filter attenuates the higher order harmonics, it is relatively easy to generate output waveforms with low distortion. But the generation of harmonics free voltages at the inverter does not guarantee a low distortion at the filter output when the UPS feeds non linear loads.

Many schemes have been suggested in the literature to allow real time control of the LC filter – inverter system. The dead – beat control has been implemented with considerable success [1]. Another technique that provides high quality waveforms is by the use of current regulators [2]. Typical current regulators reported in the literature include hysteresis regulators, sinusoidal PWM regulators, predictive current controllers and adjacent state regulators.

This paper presents a single – phase inverter controlled by a technique based on variable structure systems theory, the non-linear passivity technique. Analysis, modeling, simulation and preliminary experimental results are presented for this application. There is a good agreement between the inverter 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 it is applied to dynamical control in power electronic converters, such as active filters [3] and dc-dc converters [4]. In this paper, a passivity based controller for a single – phase inverter is presented. The control circuit is based on a digital signal processor (DSP), where the reference signal is generated, and the control law is programmed.

The LC filter and the inverter topology used are shown in Fig. 1.

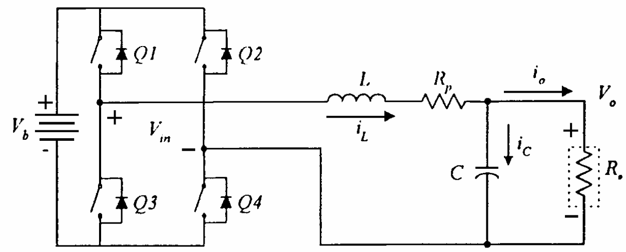


Fig. 1: Inverter topology

II. INVERTER MODEL AND PASSIVITY BASED CONTROLLER DESIGN

A system is said to be passive if the stored energy is less than or equal to the total energy supplied to the system for a given period of time. In the case of the inverter, it can be shown that this principle is fulfilled, and consequently this technique can be applied. By considering that the forces acting on a dynamical system can be divided into stabilizing forces, unstabilizing forces and conservative forces, passivity-based control only modifies the unstabilizing forces. When this passivity principle is applied to the inverter, the controller obtained respects the non affecting forces and a more natural and less stressing control law is applied to the system.

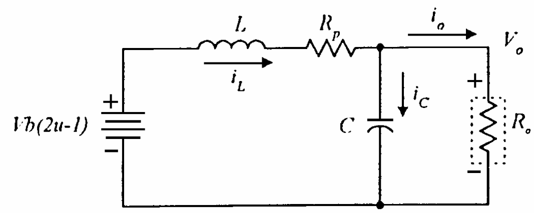


Fig. 2 Equivalent circuit for shunt active power filter modeling

The inverter model is obtained in order to design the passivity based control; the equivalent circuit for the operation mode is shown in Fig. 2. By considering every possible combination, the system model is obtained in the following matrix form:

$$\begin{bmatrix} C & 0 \\ 0 & L \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}=\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\begin{bmatrix} -\frac{1}{R_o} & 0 \\ 0 & -R_p \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\begin{bmatrix} 1 \\ 0 \end{bmatrix}V_b(2u-1) \qquad (1)$$

$$y = x_2$$

Where $x_1 = v_C = v_o$ $x_2 = i_L$

Three essential conditions must be fulfilled in order to apply the 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. From the dynamical analysis of the model it is possible to show that the inverter is non-minimum phase and passive (stored energy less than the supplied energy). This analysis will be presented in the final version of this paper.

Relative degree equal one is an essential condition to apply the passivity control law. For the inverter the output is the capacitor voltage, and the system does not have relative degree equal to one. Because of this, the capacitor voltage will be controlled through the inductor current.

Let a set of exogenous input variables $w \in R^r$ (including disturbances and/or references) which affect the plant and having an asymptotic decay of the error. This family of exogenous inputs is the family of all functions of time which are solutions of a homogenous differential equation $\dot{w} = s(w)$ with initial condition *w(0)* ranging on some neighborhood *W* of the original of R^r.

This family of system (generator of all possible exogenous input functions) is called the exosystem. The associated exosystem for the inverter is as follows:

$$\begin{bmatrix} C & 0 \\ 0 & L \end{bmatrix}\begin{bmatrix} \dot{x}_{1d} \\ \dot{x}_{2d} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}\begin{bmatrix} x_{1d} \\ x_{2d} \end{bmatrix} + \begin{bmatrix} -\frac{1}{R_o} & 0 \\ 0 & -R_p \end{bmatrix}\begin{bmatrix} x_{1d} \\ x_{2d} \end{bmatrix} + \begin{bmatrix} -\frac{1}{R_{P1}} & 0 \\ 0 & -R_{P2} \end{bmatrix}\begin{bmatrix} x_1 - x_{1d} \\ x_2 \; x_{2d} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_b(2u-1) \tag{2}$$

Where: R_{P1} and R_{P2} are the virtual resistive elements associated to the exosystem

x_{1d}, and x_{2d} are the corresponding reference state variables

From the exosystem, the control law based on the passivity technique is as follows:

$$u = \frac{1}{2}\left[\frac{L\dot{x}_{2d} + Rx_{2d} + x_{1d}}{V_b} + 1\right] \tag{3}$$

III. Simulation and Experimental Results

The following graphs present the results from simulation obtained by the use of the passivity based control. The parameter values are: $L = 0.6mH$, $C = 36\mu F$, $V_b = 180V$, $R_p = 0.07\Omega, R_{P1} = 0.1\Omega$, $R_{P2} = 100\Omega$, $V_{ORMS} = 120$, $f = 60Hz$, and a maximum output power of 5kVA. As it can be seen from Fig. 3(a), the reference voltage is a sinusoidal signal. Fig. 3(b) shows the output signal (capacitor voltage). Fig. 3(c) presents the load current; the value of the load current is simulated with a step of 10% to 90% of full rating.

At Fig. 4 are shown the results with a nonlinear load, where the current waveform corresponds to a one phase rectifier demanding harmonic currents. Upper trace shows the load current with a transient from 10% to 90% of nominal value. Middle trace shows the output voltage and bottom trace corresponds to the control signal u. It can be appreciated that the output voltage is maintained sinusoidal, with a low distortion even in the transient, where a small disturbance is appreciated.

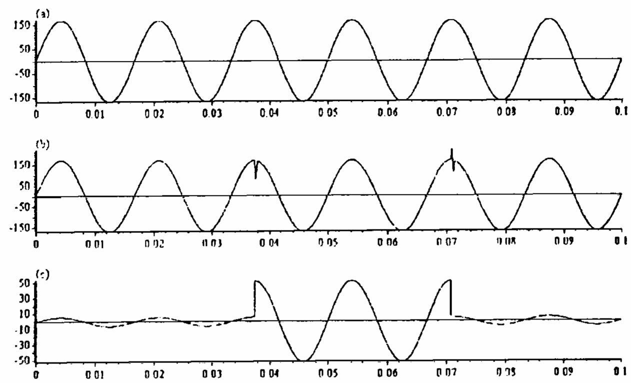


Fig. 3. Simulation results (top to bottom): (a) reference voltage; (b) output capacitor voltage x_1; (c) load current.

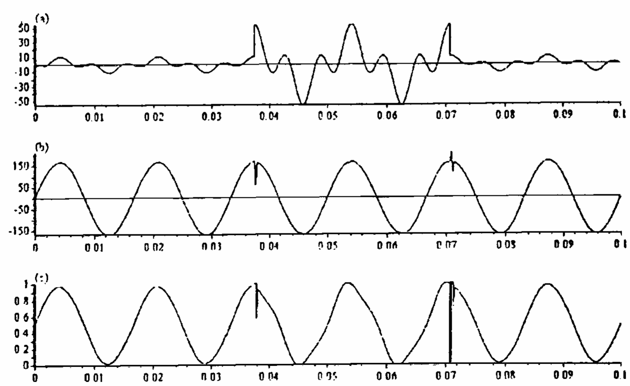
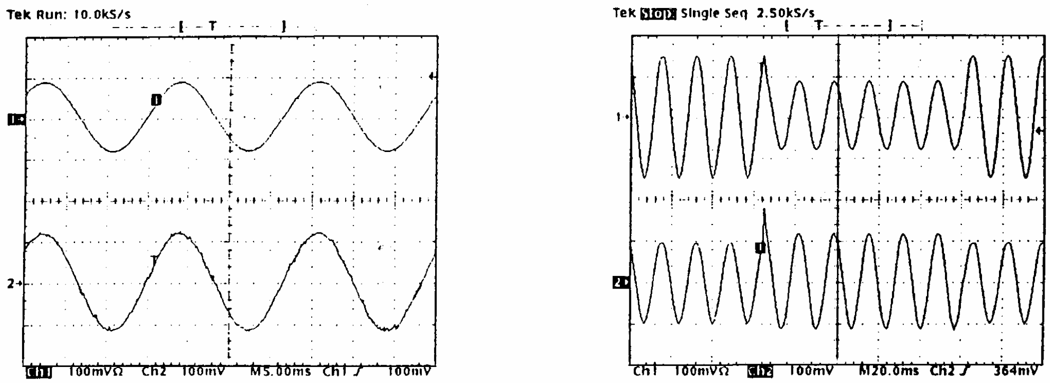


Fig. 4 Simulation results (top to bottom): (a) load current; (b) capacitor voltage x_1; (c) control u.

An experimental prototype of a 5 KVA inverter system has been used to verify the performance under the passivity based control law. The exosystem and the control law with the PWM duty cycle were programmed in a DSP.

Figure 5 (a) shows the experimental results of the output voltage and the load current in steady state. Figure 5 (b) shows the transient response of the output voltage and the load current with a load step.



(a) (b)

Fig. 5 Experimental Results (top to bottom): (a) load current [30 A/div], *output voltage* [200 v/div]; *(b) transient response: load current* [30 A/div], *output voltage* [200 v/div].

IV. CONCLUSIONS

A single phase inverter controlled by passivity based control using a digital signal processor (DSP) has been presented in this paper. A good response under non-linear load has been obtained by the use of the passivity based technique and this has been verified by comparing the simulated and experimental results. Although the passivity based technique is not new, its application to obtain a good response from the UPS inverter is novel indeed. The detailed procedure and further results will be included in the final version of this paper.

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