AN ADAPTIVE RESONANT CONTROLLER APPLIED TO THE STATCOM

Abnery J. Ortiz, Emanuel L. van Emmerik, Mauricio Aredes, L. G. B. Rolim
Power Electronics Laboratory, Electrical Engineering Program, COPPE/Federal University of Rio de Janeiro, Brazil
{abnery, emmerik, aredes, rolim}@coe.ufrj.br

***Abstract* – A static synchronous compensator (STATCOM) is considered as an ac voltage source, where the amplitude, phase and frequency of the output voltage can be controlled. However, it can be regarded as an ac current source due to its shunt connection. Taking advantage of this characteristic, it is possible to implement two kinds of control strategies based on current and voltage control. The first strategy acts on the current that is injected by the STATCOM. On the other hand, the voltage control acts on the output voltage of the converter. Either in the current or voltage control, proportional integral (PI) controllers are utilized with sinusoidal references. But these controllers do not guarantee zero steady state errors, due to the fact that PI controllers have infinite gain at low frequencies, and do not have at the input signal's fundamental frequency. This paper proposes an adaptive resonant controller (PR controller) applied to the STATCOM that is based on the internal model principle that guarantees zero steady state error and frequency adaptation. Results of simulations utilizing both the current and voltage controls with the adaptive resonant controller are presented.**

***Keywords* – STATCOM, control of power converters, PI controllers, simulations.**

I. INTRODUCTION

Over the last years, three major classes of voltage source inverters based on current or voltage regulators have been evolved, being hysteresis, linear PI controller and dead beat regulators. These classes can be divided into *d - q* synchronous and stationary frame. In *d - q* synchronous frame controllers, zero steady state can be achieved, because it converts a sinusoidal into a dc signal. In this case, a conventional PI controller can be applied. However, PI controllers are also usually employed in case of stationary frame, which has poor response for ac compensating references, because they do not achieve zero steady state error and causes phase errors as well [1].

A synchronous frame regulator is more complex, as it requires means to transform a measured stationary frame ac current (or voltage) to rotating frame dc quantities, and to transform the resultant control action back to the stationary frame for execution. In [2] a current control based on the internal principle model of control theory is proposed. It is applied to a single phase pulse width modulation (PWM) inverter and active filter. In this case, the frequency adaptation is not studied. In [3] a review of the current control techniques for three phases voltage sources PWM converters is presented.

This paper presents an adaptive PR controller applied to the current and voltage control of the STATCOM that is based on the internal model principle that guarantees zero steady state error and frequency adaptation. A comparison is made between the performance with PR controller and with PI controller utilizing both the current and voltage controls.

II. BASIC CONCEPTS

The STATCOM is a Flexible ac Transmission System (FACTS) equipment connected in parallel with an ac three phase system in order to compensate continuously reactive power, either inductive or capacitive. This characteristic is utilized to control the active power flow in a transmission line, for voltage regulation or the electric system stability improvement [4].

A. STATCOM Operation

As mentioned above, the STATCOM is a controlled ac voltage source. However, due to its parallel connection, it might be considered as an ac current source [5].

The STATCOM operation is illustrated by Fig. 1. The STATCOM and power supply are represented by ideal voltage sources, V_i and V_S, respectively. Equivalent inductance between STATCOM and the power supply is represented by X_L. In Fig. 2, a phasorial diagram with the voltages of the STATCOM and power supply is shown.

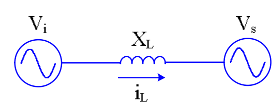

Fig. 1. Simplified equivalent of the STATCOM.

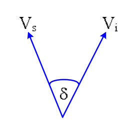

Fig. 2. Phasorial diagram of the STATCOM.

The power flow exchange between the STATCOM and the power supply is determined by:

$$P = \frac{ViVs}{X_L}\sin\delta \quad (1)$$

$$Q = \frac{Vs^2}{X_L} - \frac{ViVs}{X_L}\cos\delta \quad (2)$$

As mentioned before, there are two manners of controlling reactive power. The first one is controlling the converter output current and the second one is controlling the converter output voltage. In the following a brief description of them will be presented [7].

1) Current control - The block diagram of this strategy is presented in Fig. 3. It shows that the current control acts on the converter output current that is injected into the system. It is based on the instantaneous power theory (pq theory) through which both instantaneous real (p_{comp}) and imaginary (q_{comp}) power references are generated to get compensation currents $(i^{*}_{\alpha\beta})$, which maintain the ac bus voltage (v_{rms}) regulated or power factor compensated. The dc link voltage (v_{cc}) is regulated by means of the real power control (p_{comp}).

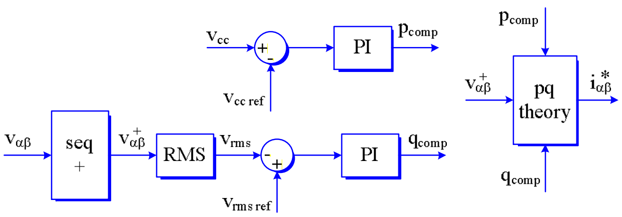

Fig. 3. Current control block diagram

2) Voltage control – Fig. 4 shows the block diagram of the voltage control. This strategy acts on the converter output voltage, which controls the current injection to the grid. This control strategy supplies the amplitude (A) and the phase (δ) of voltage references, which will be compared with a triangular carrier (SPWM). In this case, the dc link voltage (V_{cc}) is regulated by means of the phase (δ) control.

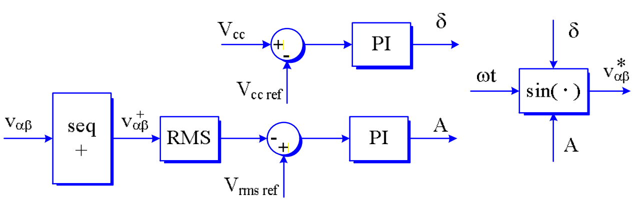

Fig. 4.. Voltage control block diagram

Fig. 5 illustrates a general scheme of the STATCOM control.

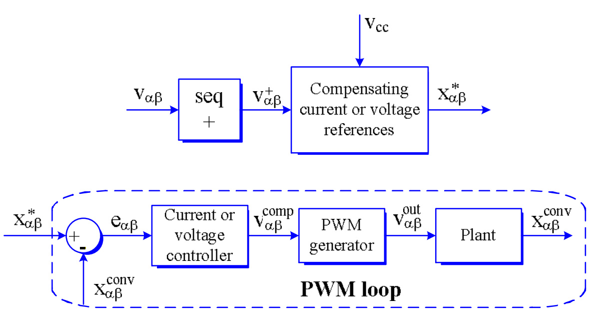

Fig. 5. Simplified control of the STATCOM block diagram.

Both the current and voltage control use conventional PI controllers (current or voltage controller block in Fig. 5), whose input is the difference between the voltage (current) reference and the measured converter output voltage (current) ($e_{\alpha\beta}$). The controller outputs are voltage references ($v^{comp}_{\alpha\beta}$), which are synthesized using PWM switching technique for the purpose of supplying a converter output voltage ($v^{out}_{\alpha\beta}$), according to the reference. The last block of the simplified STATCOM control, shown in Fig. 5, is the plant of the system which depends on the control strategy and the measurement point to feedback the PWM loop [6].

In the PWM loop, both reference and feedback signals are usually sinusoidal waves and PI controllers do not work adequately. Since these controllers have only infinite gain at low frequency and do not have at the fundamental frequency of the input signal, a zero steady state error is not obtained.

B. PI Controllers

For the control of power converters, a PI controller is the most common feedback control design. Its transfer function is given by:

$$U(s)=\left(k_p+\frac{ki}{s}\right)*E(s) \qquad (3)$$

Where k_p, k_i and E(s) are proportional and integral gains, and the error signal, respectively. When the error is a DC signal, zero steady state error can be obtained by using a PI controller. However, in many power electronic applications, references signals are often composed of sinusoidal signals. If the system is three phase, park transformation offers a useful solution, because this transformation converts a fundamental reference frequency signal into a DC signal. This way, a conventional PI controller can achieve zero steady state error. Nevertheless, the need to transform the signals from the stationary reference frame to the synchronous reference frame leads to a complex implementation [8]. To solve these problems a stationary frame adaptive control method based on the internal model from control theory is proposed.

C. Internal Model Principle

This principle states that in a feedback system, the output of the control follows faithfully its reference signal with zero steady state error, if the system fulfils the following two conditions [2]:

- The closed loop system is asymptotically stable
- The open loop transfer function of the system includes a mathematical model that can generate the input reference.

This principle explains the well known use of integrators when the aim is tracking DC signals. The Laplace transform of a step input is the same as an integrator $\left(\frac{1}{s}\right)$, which satisfies the first and the second point of the principle.

Thus, to fulfill the internal model principle, a controller with a sinusoidal transfer function is required. There are two possible sinusoidal functions, cosine function or sine function. Nevertheless, as shown in Fig. 6, the cosine function has an adequate phase margin (90º). Therefore, the feedback control system would probably be highly underdamped.

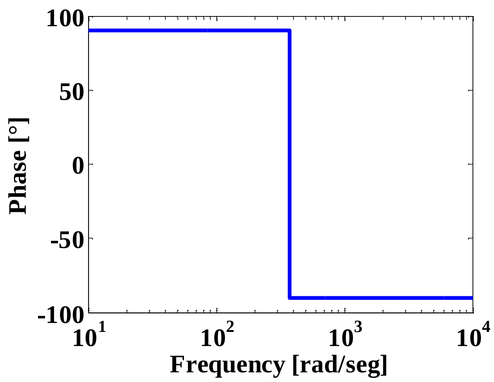

Fig. 6. Bode phase plot of the cosine function.

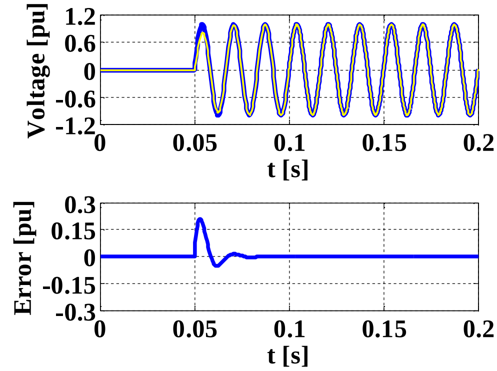

Fig. 8. Sinusoidal response of the PWM loop with the adaptive resonant controller.

III. CONTROLLER CHARACTERISTICS

Both the current and voltage control of the STATCOM are represented at stationary frame (αβ). Its simplified equivalent block diagram including the adaptive resonant controller is shown in Fig. 7.

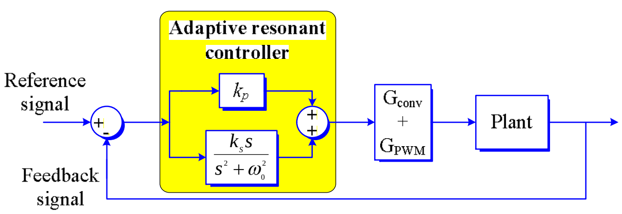

Fig. 7. Simplified block diagram of either the STATCOM current or voltage control including the adaptive resonant controller.

This controller consists of a proportional term (k_p) and a resonant term, which has two poles at the frequency of the input signal. The controller equation is given in (4):

$$C(s) = k_p + \frac{k_s s}{s^2 + \omega_0^2} \quad (4)$$

According to [12], the converter and its switching technique can be modeled utilizing the simplified average model, whose transfer function can be approximated by a unitary gain $(G_{conv} + G_{PWM} = 1)$. Moreover, for simplicity the plant has been represented by a first order transfer function.

Fig. 8 shows simulation results of the simplified PWM loop with a PR controller (kp = 2 ks = 900) and a first order transfer function (R = 1 Ω L = 0.4 mH). The PR controller parameters were calculated according to [15].

The block diagram of the resonant term is depicted in Fig. 9.

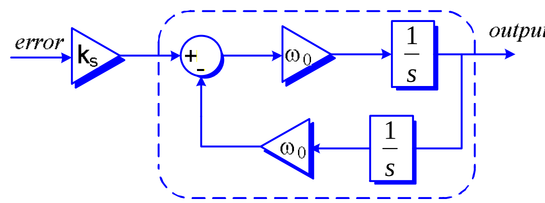

Fig. 9. Block diagram representation of the resonant term.

As shown in Fig. 10, the resonant term has an infinite gain at the resonant angular frequency $\omega = \omega_0$, for this reason this structure is known as a generalized integrator.

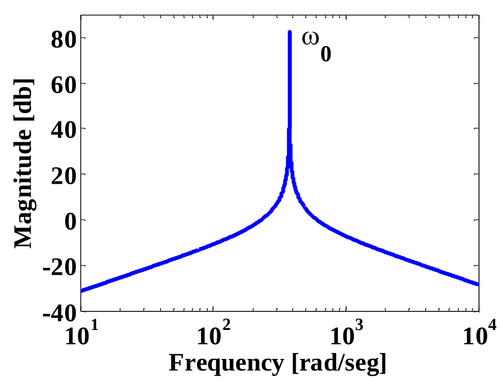

Fig. 10. Bode magnitude plot of the cosine function.

However, the frequency of the reference input signal could suffer variations, which result in a poor performance of the controller. Fig. 11 shows the effect of a frequency step change of 2Hz (from 60Hz to 62Hz) at t = 0.4 s on the performance of the proposed controller. The sinusoidal reference signal is introduced at t = 0.1 s. It is clearly shown that the controller response gets worse; oscillations due to the frequency step are presented in the error signal. To solve this problem, an adaptive resonant controller with a feedback from the synchronizing circuit is proposed and tested in simulations.

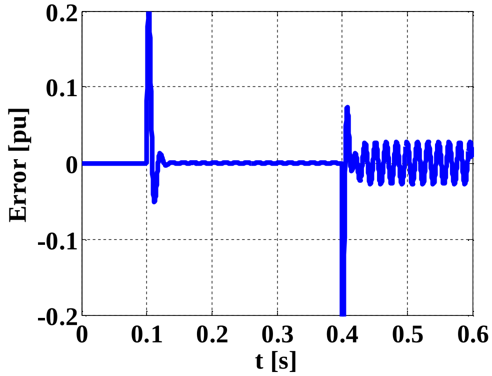

Fig. 11. Error signal with a frequency step of 2 Hz in the reference signal.

IV. SIMULATIONS RESULTS

The performance of both the current and voltage control with PR controllers are investigated, utilizing PSCAD for simulations in the time domain. The power converter was simulated in the following conditions: dc voltage V_{cc} = 500 V, grid voltage V_g = 220 V (rms) with a low THD. The RC filter (C = 68 μF and R = 1 Ω) has its resonance frequency at 1 KHz, based on the fact that the switching frequency was settled at 10 kHz. According to [15], the resonant controller parameters for fundamental frequency compensation are as follows: kp = 0.4 and ks = 10. Both the STATCOM current and voltage control to regulate the PCC voltage have been simulated.

A. Current Control Performance

The current control was implemented with resonant controllers in the PWM loop, which receive the fundamental frequency feedback signal tracked by the synchronism circuit. In this case a simple algorithm was used (SOGI – FLL [14]).

Fig. 12 shows the main electrical and control signals involved in the STATCOM operation. In this case the converter synthesizes an output voltage (v_{stat}), which has a phase difference of 90° with the output current (i_{stat}). This current is controlled by the reference current (i_{ref}) that is generated by the master control. The figure shows that zero steady state error (e_i) is achieved. It means that the current generated by the master control is perfectly in phase with the output current converter, thus phase and amplitude error are eliminated. The error signal contains only high frequency components due to the IGBT switching, other frequencies are completely attenuated.

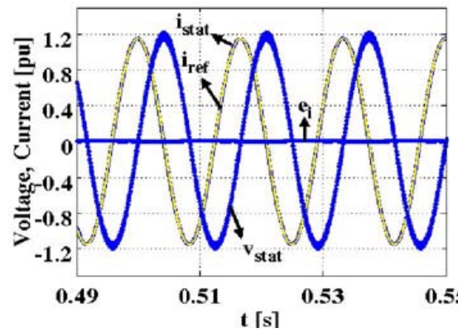

Fig. 12. Control and electrical signals concerning to the STATCOM current control with PR controllers.

Fig. 13 shows the same set of variables that were presented in Fig. 12, this case using PI controllers, instead of PR controllers. It is clearly shown that the steady state error is not eliminated. In fact, the error signal amplitude reaches 10% of the reference current fundamental component.

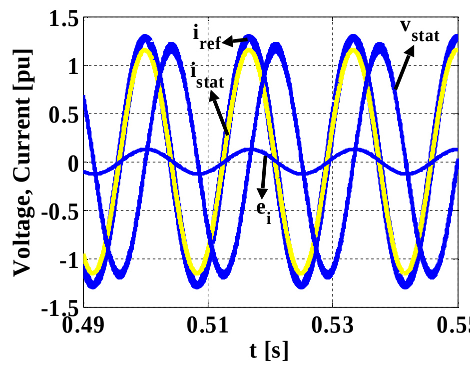

Fig. 13. Control and electrical signals concerning to the STATCOM current control with PI controllers.

Fig. 14 shows the moment when the STATCOM is connected to the bus to control the PCC voltage. The equipment is connected to the grid at 0.1 s and subjected to regulate the PCC voltage in 1 p.u. during 0.5 s. After that, a negative voltage step of 0.1 p.u. is applied to the reference of the PCC voltage control during 0.4 s. Finally, a voltage step of 0.2 p.u. is applied during 0.4 s. The response time and overshoot, which are about 100 ms and 5%, respectively, reflect the behavior of the PI controller of the voltage control loop.

Fig. 15 presents the dynamic response of the DC link voltage to the three voltage steps in the reference voltage regulated by the STATCOM. A wind up integrator in the DC link voltage control was implemented to get a better dynamic.

B. Voltage Control Performance

Simulation results with the voltage control applied to STATCOM are shown in this section. Similar as in the current control, PR controllers are used in the PWM loop. These ones receive the fundamental frequency tracked by the synchronism circuit.

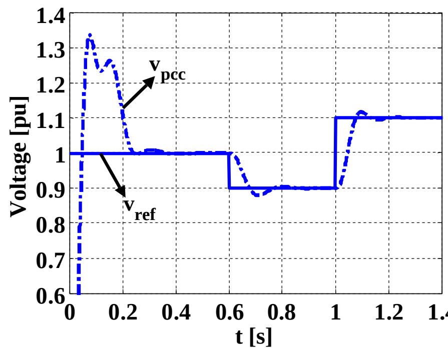

Fig. 14. PCC voltage regulated by the STATCOM under current control mode.

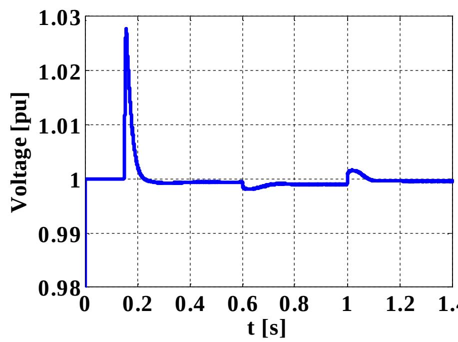

Fig. 15. DC link voltage under current control mode.

Simulation results of the STATCOM voltage control can be observed in Fig. 16. It shows that the converter output voltage (vstat) has a phase difference of 90º with the STATCOM current (istat). The converter output voltage is controlled by the reference voltage (vref) that is generated by the master control.

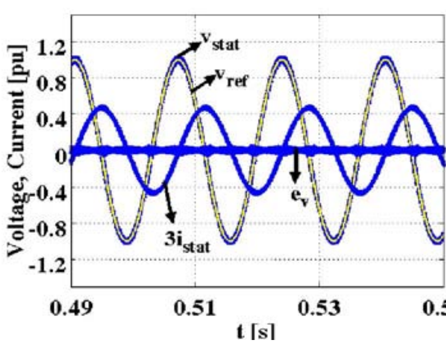

Fig. 16 Control and electrical signals concerning to the STATCOM voltage control with PR controllers.

The objective of the PR controllers in the PWM loop is clearly reached. It means, there are no amplitude and phase differences between both the reference and feedback signals. Thus, zero steady state error has been obtained, due to the fact that the internal model principle has been fulfilled.

On the contrary, Fig. 17 presents the same signals as shown above when PI controllers are used. The error signal between the reference and feedback signal has an oscillatory behavior; its amplitude is about 20% of the reference voltage's fundamental component. This occurs when the internal model principle is not met.

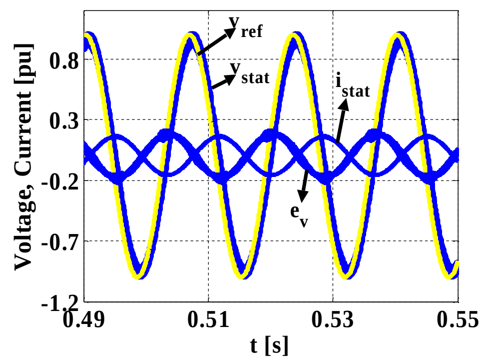

Fig. 17 Control and electrical signals concerning to the STATCOM voltage control with PI controllers.

The same voltage references were applied to the master control of the STATCOM under voltage control mode; so that both the current and voltage control dynamics can be compared. In Fig. 18, for the steady state, it is possible to conclude that parameters like settling time, overshoot and response time were similar to the ones obtained in the current control case. Nevertheless, the transient state presents a notorious difference due to the presence of a non minimum phase zero introduced by the bus voltage control. The non minimum phase zero might turn the voltage control implementation more difficult than the current control.

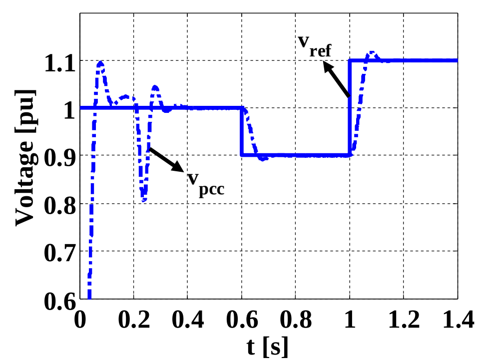

Fig. 18 PCC voltage regulated by the STATCOM under voltage control mode.

Fig. 19 shows the DC link voltage regulation during the three voltage steps. The voltage returns to its reference value throughout the three PCC voltage references.

The results obtained from both the STATCOM current and voltage control indicate that the voltage regulation loop has a good dynamic response during steady state, however great differences were appreciated in the voltage control, during the transient state because of the presence of a non minimum phase zero. Though, with the current control, stability problems associated with the master control were not observed.

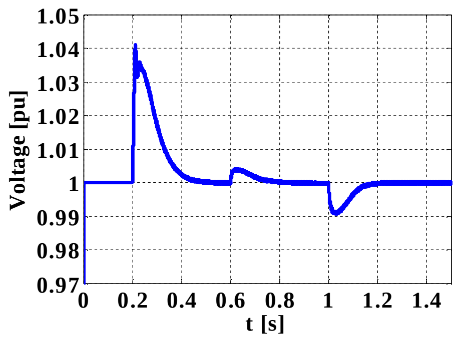

Fig. 19 DC link voltage under voltage control mode.

V. CONCLUSIONS

An adaptive resonant controller applied to both the STATCOM current and voltage control have been presented in this paper. Simulation results of a simplified PWM loop were shown in order to present the principle. Furthermore, complete simulations of a 25 kVA STATCOM operating under both current and voltage control with PR controllers in the PWM loop were illustrated. It is clearly shown that neither amplitude nor phase errors between the reference and feedback signals were observed, thus zero steady state error has been obtained, thanks to the use of PR controllers. The frequency adaptation of the PR controller was done by means of a very simple and low cost use of the synchronism circuit; and it allows the use of lower integral gains. Finally, it was observed that the PR controller only influences the PWM loop dynamic and does not interfere in the overall control.

VI. REFERENCES

[1] D. N. Zmood and D. G. Holmes, "Stationary Frame Current Regulation of PWM Inverters With Zero Steady State Error", IEEE Transactions On Power Electronics, Vol.18, No. 3, May 2003.

[2] Shoji Fukuda, Senior and Takehito Yoda, "A Novel Current-Tracking Method for Active Filters Based on a Sinusoidal Internal Model", IEEE Transactions On Industry Applications, Vol. 37, No. 3, May/June 2001.

[3] M. Kazmierkowski and L. Malesani, "Current Control Techniques for Three Phases Voltage Source PWM Converters: A Survey", IEEE Transactions On Industrial Electronics, Vol. 45, No. 5, May/June 1998.

[4] N. G. Hingorani, L. Gyugyi, "Understanding FACTS – Concepts and Technology of Flexible AC Transmission Systems", IEEE Press, New York, 1999.

[5] Antonio Carlos Borré, Amaury Simões Xavier, Flávio Gonçalves da Cruz Ribeiro, Mauricio Aredes, "Comparative Analysis between the indirect and direct control current injection in a D-STATCOM" (in Portuguese), Eletrônica de Potência (Florianópolis), v. 11, p. 103-110, 2006.

[6] Abnery J. Ortiz, Mauricio Aredes, E. Bueno and P. Rodríguez, "Comparative study of the current and voltage controllers applied to the STATCOM", in IECON, Taiwan, 2007 (accepted).

[7] Amaury Simões Xavier, Antonio Carlos Borré, Fernando José Giffoni, Edisio Alves de Aguiar Junior, Flávio G. C. Ribeiro, Maurício Aredes, "Direct And Indirect Current Control Injection in a D-STATCOM Using Space Vector Modulation", in: VII International Conference on Industrial Applications, 2006, Recife - PE. VII INDUSCON, 2006. v. 01.

[8] Se-Kyo Chung, "A Phase Tracking System for Three Phase Utility Interface Inverters", IEEE Transactions On Power Electronics, Vol.15, No. 3, May 2000.

[9] GC Goodwin, SF Graebe, ME Salgado, "Control System Design", 2001.

[10] Timothy CY Wang and Xiaoming Yuan, "Design of Multiple-Reference-Frame PI Controller For Power Converters", in 35rh Annual IEEE Power Electronics Specialists Conference, Aachen, Germany, 2004.

[11] Xiaoming Yuan, Senior Member, IEEE, Willi Merk, Herbert Stemmler, and Jost Allmeling, "Stationary-Frame Generalized Integrators for Current Control of Active Power Filters With Zero Steady-State Error for Current Harmonics of Concern Under Unbalanced and Distorted Operating Conditions", Ieee Transactions On Industry Applications, Vol. 38, No. 2, March/April 2002.

[12] E. Bueno, "Optimización del Comportamiento de un Convertidor de Tres Niveles NPC Conectado a la Red Eléctrica" Tesis, *Universidad de Alcalá*, Mayo 2005.

[13] E. H. Watanabe, M. Aredes, R. M. Stephan, "New Concepts of Instantaneous Active and Reactive Powers in Electrical Systems with Generic Loads", IEEE Transactions On Power Delivery, Vol. 08, No. 2, Pp. 697-703, April 1993.

[14] P. Rodriguez, A. Luna, M. Ciobotaru, R. Teodorescu and F. Blaabjerg, "Advanced Grid Synchronization System for Power Converters Under Unbalanced and Distorted Operating Conditions", in Proc. IEEE Int Symp. Ind. Electron. (ISIE'06), 2006.

[15] Paolo Mattavelli, "A Closed – Loop Selective Harmonic Compensation for Active Filters", in Proc. IEEE Transaction on industry applications, vol 37, No. 1, January/February 2001.