Robust Model Reference Adaptive Control with Adaptive Repetitive Control for UPS and AC Power Sources

E. G. Carati, H. L. Hey, J. R. Pinheiro, H. Pinheiro, H. A. Gründling

Group of Power Electronics and Control – GEPOC
Federal University of Santa Maria – UFSM
Campus Universitário – UFSM – Santa Maria – RS – Brazil
emerson@ieee.org - http://www.ufsm.br/gepoc/

Abstract – **In uninterruptible power supplies (UPS) it is desired low harmonic distortion in the output voltage. On other side, AC Power Sources require high performance controllers to generate sinusoidal, harmonic and arbitrary waveforms. In this paper a Robust Model Reference Adaptive Control law (RMRAC) with an Adaptive Repetitive Controller (ARP) are applied to control the voltage output of UPS and AC Power Sources. The RMRAC control law is used to obtain robustness in the closed-loop system, while the ARP controller is applied to compensate periodic disturbances in the output voltage waveform. In addition, an adaptive law is introduced to tune the gain of the repetitive controller when no periodic disturbances are present. Simulation and experimental results are shown to demonstrate the RMRAC-ARP controller performance under several operation conditions.**

I. INTRODUCTION

The robust stability is an important feature of a control strategy required for its applicability in practical systems. Robustness properties of adaptive control algorithms have been widely investigated in the last two decades. Rohrs *et al* [1], Egardt [2], Riedle *et al* [3] and others have demonstrated that unmodeled dynamics or even bounded disturbances can lead most of adaptive algorithms to instability. A number of modifications have been proposed to solve this problem and improve the robustness of these algorithms [4]. In the case of bounded disturbances, the basic idea of most of these modifications is to prevent the instability by eliminating the integral action of the adaptive laws. This can be achieved using dead-zone, σ-modification, and similar techniques. On other side, when unmodeled dynamics are present others modifications like normalization and projection are necessary to keep the parameters within a sphere. In particular, robust model reference adaptive control (RMRAC) is one of more attractive research topic due its input-output approach and robustness to bounded disturbances and unmodeled dynamics. However, the firsts results were based on very restrictive assumptions. Several authors have been investigating RMRAC to make these assumptions less restrictive, and majors advances can be found in works as Ioannou and Tsakalis [5], Lozano-Leal *et al* [6], Narendra and Annaswamy [7], Kreisselmeier and Anderson [8].

When unknown periodic disturbances are present in the system output repetitive control strategies have been used to minimize periodic tracking errors. In [9], Hara *et al* introduces a repetitive control (RP) in which the controlled variables follow periodic reference commands. A high accuracy asymptotic tracking response is achieved by implementing a model that generates the periodic signals into the closed-loop system. On other hand, repetitive control with robust model reference adaptive control have been successfully applied to systems as UPS and AC Power Sources, where usually the plant is time variant with unknown dynamics and periodic disturbances [10, 11]. However, in the absence of these disturbances, the RP controller becomes unnecessary. Furthermore, due to integral action of the RP controller over past errors it is desired to avoid its contribution in the control law when are present non-periodic disturbances or transients.

This paper proposes a new robust model reference adaptive control with adaptive repetitive control (ARP), where the repetitive controller gain is tuned dynamically to minimize or reject the repetitive control action when no periodic disturbances are present. The adaptive repetitive control is implemented using a gradient projection type algorithm. In addition, the RMRAC scheme uses a least squares algorithm with σ-modification and normalization [5]. A conservative upper bound for repetitive gain the can be used to guarantee the controller stability without significance performance loss. In order to verify the control strategy performance, the RMRAC-ARP controller is applied to an AC power source. Simulation and experimental results were obtained under several operating conditions, including non-linear loads, periodic and non-periodic disturbances and unmodeled dynamics. A microprocessor-based prototype is being used to demonstrate the algorithm effectiveness in realistic conditions.

In summary, the main contributions of this paper are the inclusion of an adaptive algorithm for the repetitive gain and the use of the resulting RMRAC-ARP scheme to control a real-time application.

This paper is organized as follows: In Section II the PWM inverter system is presented. The plant model and control objective is given in Section III. The RMRAC-ARP controller structure is shown in section IV, while in Section V the RMRAC and ARP adaptation algorithms are presented. Simulation and experimental results of the RMRAC-ARP controller application to UPS and AC power sources are shown in Section VI. Section VII concludes this paper.

II. PWM INVERTER SYSTEM

An UPS or an AC Power Source is composed basically by a conventional single-phase full-bridge PWM inverter as shown in Fig.1, where the inverter is the actuator, while the LC filter and resistive load R are considered as the plant of the system.

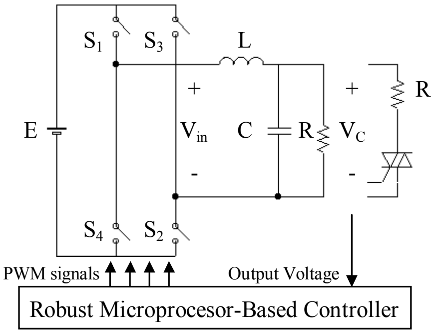

Fig. 1: PWM inverter system

The state space equations of the plant are

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\,\boldsymbol{x} + \boldsymbol{B}\,u\,, \tag{2.1}$$

or

$$\begin{bmatrix} \dot{v}_c \\ \ddot{v}_c \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_p^2 & -2\zeta_p\omega_p \end{bmatrix} \cdot \begin{bmatrix} v_c \\ \dot{v}_c \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_p^2 \end{bmatrix} v_{in}\,, \tag{2.2}$$

where $\boldsymbol{x} = \begin{bmatrix} v_c & \dot{v}_c \end{bmatrix}^T$, $\omega_p = 1/\sqrt{LC}$, $\zeta_p = (1/(2R))\sqrt{L/C}$.

The power switches are turned on and off once during each interval T, such that V_{in} is a voltage pulse of magnitude (E, 0, -E) and width ΔT centered in the interval T. A sampled-data equation of the system at time $t_{k+1} = (k+1) \cdot T$ is

$$\boldsymbol{x}(t_{k+1}) = e^{AT}\boldsymbol{x}(t_k) + \int_{(T-\Delta T)/2}^{(T+\Delta T)/2} e^{A(T-\tau)}\,\boldsymbol{B}\,E\,d\tau \tag{2.3}$$

From (2.3) a difference equation can be obtained as

$$y(t_{k+1}) + a_1 y(t_k) + a_2 y(t_{k-1}) = b_1 u(t_k) + b_2 u(t_{k-1}) \tag{2.4}$$

where $y(t_k) = \begin{bmatrix} 1/E & 0 \end{bmatrix} \cdot \boldsymbol{x}(t_k)$ is the normalized output voltage and $u(t_k) \triangleq \Delta T(t_k)/T$ is the normalized input voltage.

III. Plant Model and Control Objective

Consider the following representation for a single input single output (SISO) system:

$$y = G(z)u = \left[G_0(z)\left[1 + \mu\,\Delta_m(z)\right] + \mu\,\Delta_a(z)\right]u\,, \tag{3.1}$$

and

$$G_0(z) = k_p \frac{Z_0(z)}{R_0(z)}\,, \tag{3.2}$$

where $G(z)$ is the process transfer function, $G_0(z)$ is the transfer function of the modeled part of $G(z)$, $\mu\,\Delta_a(z)$ and $\mu\,\Delta_m(z)$ are additive and multiplicative unmodeled dynamics, respectively. $Z_0(z)$ and $R_0(z)$ are monic polynomials with degree *m* and *n*, respectively.

The following assumptions are made concerning the modeled part of the plant:

S1 - $Z_0(z)$ is a Hurwitz monic polynomial of degree $m(\leq n\text{-}1)$.

S2 - $R_0(z)$ is a monic polynomial of degree *n*.

S3 - The sign of k_p and the values of *m* and *n* are known. Without loss of generality, it can be assumed $k_p > 0$.

In AC power sources several unmodeled dynamics appear, as parasitic capacitances, inductances and resistances, dead-times and switching dynamics. Moreover, the system output is frequently connected to several kinds of loads as reactive loads and nonlinear loads. Regarding the unmodeled part of the plant, it is assumed that:

S4 - $\Delta_a(z)$ is a strictly proper stable transfer function.

S5 - $\Delta_m(z)$ is a stable transfer function..

S6 - An upper bound ($1 > p_0 > 0$) on the stability margin (p > 0), for which the poles of $\Delta_a(z/p)$ and $\Delta_m(z/p))$ are stable is known.

Let y_m be the output of the reference model described as

$$y_m = W_m(z)\,r = \frac{K_m}{D_m(z)}\,r\,, \tag{3.3}$$

where $D_m(z)$ is a Hurwitz polynomial of degree $n^* = n - m$ and e $r(t)$ is a uniformly bounded reference input. The control objective is design an adaptive controller so that for some $\mu^* > 0$ and any $\mu \in [0, \mu^*)$ the resulting closed-loop plant is stable and the plant output y tracks the reference model output y_m as closely as possible for all possible perturbations $\Delta_a(z)$ and $\Delta_m(z)$ that satisfy **S4** - **S6**. The structure of robust model reference adaptive control with repetitive adaptive controller that attends the control objective is presented in next section.

IV – RMRAC-ARP Control Structure

The plant input u and the plant output y are used to generate a $(2n-1)$ dimensional auxiliary vector $\boldsymbol{\omega}^T = \left[\boldsymbol{\omega}_1^T, \boldsymbol{\omega}_2^T, y\right]$ as follows

$$\boldsymbol{\omega}_1 = (z\,\boldsymbol{I} - \boldsymbol{F})^{-1}\,\boldsymbol{q}\,u, \quad \boldsymbol{\omega}_2 = (z\,\boldsymbol{I} - F)^{-1}\,\boldsymbol{q}\,y \tag{4.1}$$

where $\boldsymbol{F}$ is a stable matrix and $(\boldsymbol{F}, \boldsymbol{q})$ is a controllable pair.

Considering the plant input u, the plant output y, and the auxiliary states vector, described in (4.1), the plant input u for the RMRAC with ARP controller can be calculated as

$$u = \boldsymbol{\theta}^T\boldsymbol{\omega} + c_0\,r + u_{RP} \tag{4.2}$$

where $\boldsymbol{\theta}^T = \left[\boldsymbol{\theta}_1^T, \boldsymbol{\theta}_2^T, \boldsymbol{\theta}_3\right]$ is a $(2n-1)$ dimensional control parameter vector and c_0 is a feedforward gain. The repetitive control law u_{RP} is given by

$$u_{RP}(t_k) = -c_{RP}(t_k)\,\varsigma_{RP}(t_k) \tag{4.3}$$

where $c_{RP}(t_k)$ is the adaptive gain of the repetitive controller and

$$\varsigma_{RP}(t_k) = e_1(t_{k+s_a-n_a}) + \sigma_{RP}\sum_{i=2}^{n_c} e_1(t_{k+s_a-n_a})\,. \tag{4.4}$$

In (4.4), $e_1 = y - y_m$ is the tracking error, between the plant output and reference model output, n_a is the number of samples per period of the reference, s_a is a shifting parameter, $0 << \sigma_{RP} < 1 \in \Re$, and $n_c \triangleq floor(k/n_a)$.

Lemma IV.1: In absence of modeling errors and disturbances, the tracking error and the repetitive control law converge to zero asymptotically in steady state.

Proof: When no modeling errors and no disturbances are present, the proof that the RMRAC controller leads the tracking error to zero asymptotically is presented in [12] and will be omitted here. Since the tracking error converges to zero asymptotically, or $e_1 \to 0$ when $t \to \infty$, the value of S_{RP} in (4.4) and u_{RP} in (4.3) also go to zero ($S_{RP} \to 0$ and $u_{RP} \to 0$ when $t \to \infty$).

Lemma IV.2: Combining (3.1)–(3.3) and (4.1)–(4.4) the tracking error e_1 can be expressed as

$$e_1 = \frac{W_m(z)}{c_0^*}\left(\boldsymbol{\phi}^T \boldsymbol{\omega} + c_0 r + u_{RP}\right) - W_m(z) r + \mu\eta, \qquad \eta = \Delta(z) u, \tag{4.5}$$

where $\boldsymbol{\phi} = \boldsymbol{\theta} - \boldsymbol{\theta}^*$ is the parameter adaptation error, $\boldsymbol{\theta}^{*T} = \left[\boldsymbol{\theta}_1^{*T}, \boldsymbol{\theta}_2^{*T}, \boldsymbol{\theta}_3^*\right]$ is the desired controller parameters and $\Delta(z)$ is a strictly proper transfer function.

Proof: From (4.1) and (4.2) it follows that

$$\boldsymbol{\phi}^T \boldsymbol{\omega} + c_0 r + u_{RP} = \left(1 - f_1(z) - f_2(z) G(z)\right) u \tag{4.6}$$

where

$$f_1(z) = \boldsymbol{\theta}_1^{*T} (z\mathbf{I} - \mathbf{F})^{-1} q, \qquad f_2(z) = \theta_3^* + \boldsymbol{\theta}_2^{*T} (z\mathbf{I} - \mathbf{F})^{-1} q. \tag{4.7}$$

Due to the controllability of the modeled part of the plant, from (4.6) the system output can be expressed as

$$y = \frac{W_m(z)}{c_0^*}\left[\boldsymbol{\phi}^T \boldsymbol{\omega} + c_0 r + u_{RP}\right] + \mu\eta, \quad \eta = \Delta(z) u \tag{4.8}$$

where

$$\Delta(z) = \frac{W_m(z)}{c_0^*}\Delta_m(z)\left(1 - f_1(z)\right) + \frac{W_m(z)}{c_0^*} f_2(z)\, \Delta_a(z) + \Delta_a(z). \tag{4.9}$$

Since c_0^* is unknown, it can be estimated as $\varphi^* = 1/c_0^* = k_p/k_m$. Regarding that $e_1 = y - y_m$ and from (3.3) and (4.8) the tracking error can be expressed as

$$e_1 = y - y_m = \varphi^* \Psi + \mu\eta \tag{4.10}$$

where

$$\Psi = W_m(z)\boldsymbol{\phi}^T \omega + W_m(z) c_0 r + W_m(z) u_{RP} - c_0^* W_m(z) r \tag{4.11}$$

From (4.10) and defining $\boldsymbol{\zeta} = W_m(z)\boldsymbol{\omega}$, the augmented error can be obtained

$$\varepsilon_1 = e_1 + \varphi^*\left[\theta^T \zeta - W_m(z)\theta^T \omega - W_m(z) c_0 r - W_m(z) u_{RP} + c_0^* W_m(z) r\right] = \varphi^* \boldsymbol{\phi}^T \boldsymbol{\zeta} + \mu\eta \tag{4.12}$$

Considering $\overline{c}_0 = c_0 - c_0^*$ and $\overline{\varphi} = \varphi - \varphi^*$ the augmented error can be rewritten as

$$\varepsilon_1 = e_1 + \varphi\, \xi = \varphi^* \boldsymbol{\phi}^T \boldsymbol{\zeta} + \varphi^* \overline{c}_d\, y_m + \overline{\varphi}\, \xi + \mu\eta. \tag{4.13}$$

where

$$\xi = \boldsymbol{\theta}^T \boldsymbol{\zeta} - W_m(z)\boldsymbol{\theta}^T \boldsymbol{\omega} - W_m(z) c_0 r - W_m(z) u_{RP} + c_0 y_m.$$

V. Parameter Adaptation Algorithms

A. RMRAC Controller

There are a number of well-known parameter estimation techniques, which have been successfully applied to the identification problems. In the RMRAC scheme is considered the following modified least-squares adaptation algorithm:

$$\theta(t_{k+1}) = \left(\mathbf{I} - t_s\, \sigma \mathbf{P}(t_k)\right)\theta(t_k) - \frac{t_s \varepsilon_1(t_k) \mathbf{P}(t_k) \theta(t_k)}{\overline{m}(t_k)} \tag{5.1}$$

$$\mathbf{P}(t_{k+1}) = (1 + t_s \lambda \overline{\mu}^2)\mathbf{P}(t_k) - t_s\left(\frac{\mathbf{P}(t_k)\zeta(t_k)\zeta^T(t_k)\mathbf{P}(t_k)}{\overline{m}(t_k)} + \overline{\mu}^2 \frac{\mathbf{P}^2(t_k)}{R^2}\right) \tag{5.2}$$

where $\boldsymbol{P} = \boldsymbol{P}^T$ is such that

$$0 < \boldsymbol{P}(0) \le \lambda R^2 \boldsymbol{I}, \quad \mu^2 \le k_\mu \overline{\mu}^2, \tag{5.3}$$

In (5.1) and (5.2) the normalization signal $\overline{m}(t_k)$ is given by

$$\begin{gathered} \overline{m}(t_k) = 1 + \alpha_1 \left[m(t_k)\right]^2, \\ m(t_{k+1}) = (1 - t_s \delta_0) m(t_k) + t_s \delta_1 \left(\left|u(t_k)\right| + \left|y(t_k)\right| + 1\right), \\ m(t_0) > \frac{\delta_1}{\delta_0}, \quad \delta_1 \ge 1, \end{gathered} \tag{5.4}$$

where α_1, δ_0, δ_1, λ, $\overline{\mu}$ and R^2 are positive constants and δ_0 satisfies $\delta_0 + \delta_2 \le \min[p_0, q_0]$, $q_0 \in \Re^+$ is such that the poles of $W_m(z/q_0)$ and the eigenvalues of $\boldsymbol{F} + q_0 \boldsymbol{I}$ are stable and δ_2 is a positive constant. $p_0 > 0$ is defined in **S6** and σ in (4.1) is given by

$$\boldsymbol{\sigma} = \begin{cases} 0 & \text{if} \quad \|\boldsymbol{\theta}\| < M_0 \\ \sigma_0 \left(\|\boldsymbol{\theta}\|/M_0 - 1\right) & \text{if} \quad M_0 \le \|\boldsymbol{\theta}\| \le 2M_0 \\ \sigma_0 & \text{if} \quad \|\boldsymbol{\theta}\| > 2M_0 \end{cases} \tag{5.5}$$

where $M_0 > \left\|\boldsymbol{\theta}^*\right\|$ and $\sigma_0 > 2\overline{\mu}^2/R^2 \in \Re^+$ are design parameters. This recursive least-squares (RLS) technique has the advantages of fast convergence.

Lemma V.1: The parameter adaptation algorithm in (5.1)-(5.5) and (4.13) subject to assumptions **S1-S6** has the following properties: a) $V = \phi^T P^{-1} \phi \le \overline{V}$ and b) $\|\phi\|^2 \le K_\phi \,\underline{\Delta}\, \lambda R^2 \overline{V}$.

Proof: The proof of this lemma, which guarantees the identifier robustness, follows the lines of the proof of the *lemma 4.2* in [6] and it will be omitted here.

B. ARP Controller

In the design of a parameter adaptation algorithm for the repetitive controller gain should be considered that the adaptation needs to be slow compared with other plant dynamics. Moreover, the algorithm should prevent elevated values on the repetitive gain c_{RP} when the tracking error is high. Then, the following gradient projection type algorithm has been developed for adaptation of c_{RP}:

$$c_{RP}(t_k) = \begin{cases} \upsilon(t_k) & if \quad \upsilon(t_k) \le \bar{c}_{RP} \\ \bar{c}_{RP} & if \quad \upsilon(t_k) > \bar{c}_{RP} \end{cases} \qquad (5.6)$$

with

$$\upsilon(t_k) = \left(1 - \lambda_{RP}\, t_s\right) c_{RP}(t_{k-1}) + t_s\, \alpha_{RP}\, S_{Sa}(t_k)\,, \qquad (5.7)$$

where $\bar{c}_{RP}$ is a design parameter defined *a priori* for a specified stability margin and λ_{RP}, α_{RP} $\in \Re^{+}$ are positive constants. In (5.7), $S_{Sa}(t_k)$ is given as

$$S_{Sa}(t_k) = \sum_{i=1}^{n_a} \left| S_{RP}(t_{k-i}) \right|^3 . \qquad (5.8)$$

VI. Simulation and Experimental Results

A. Simulation Results

The system specifications used in obtaining simulation and experimental results are given in Table I.

TABLE I - PWM inverter parameters

Filter inductance	L = 1.2 mH
Filter capacitance	C = 75μF
DC input voltage	E = 200V
Reference voltage	V_{ref}=110V_{rms} (155V_p)
Load	R = 24Ω
Sampling time	t_s = (1/6000)s

In order to demonstrate the new ARP parameter adaptation algorithm, a transient from linear load to non-linear load is considered. Fig. 2 and Fig. 3 show the RMRAC parameters ($\boldsymbol{\theta}$) and the ARP gain (c_{RP}), respectively. It can be noted that in absence of periodic disturbances, the repetitive gain approaches asymptotically to zero. Moreover, in Fig. 4 presents a transient due to a reference change from sinusoidal to harmonic, where it is seen the good tracking capability of proposed approach. In Fig. 5 is shown the response of the repetitive controller with RMRAC controller for non-periodic disturbances. The dotted line shows the output voltage when the repetitive controller gain is constant, while the solid line is the output voltage when the repetitive adaptive controller is used. It is seen that in this case the ARP action improves the system performance.

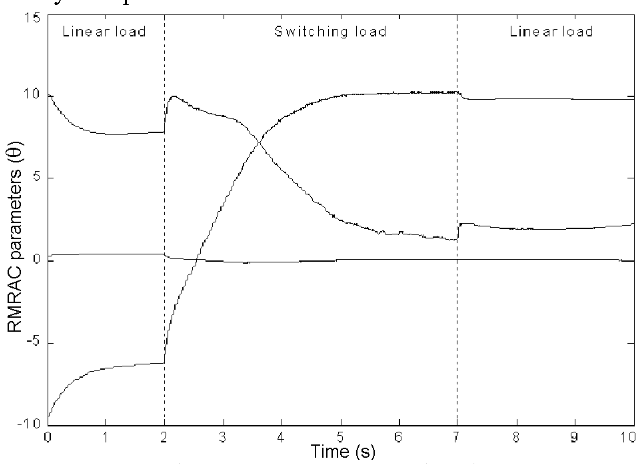

Fig. 2: RMRAC parameters adaptation.

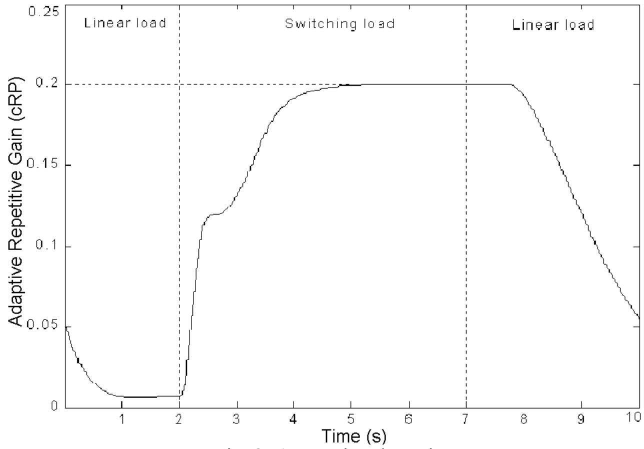

Fig. 3: ARP gain adaptation.

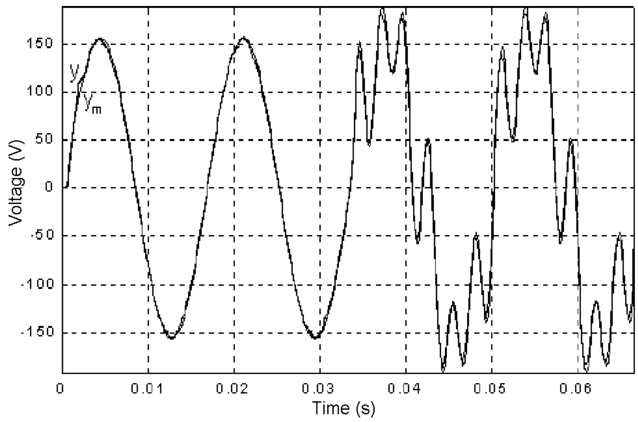

Fig. 4: Sinusoidal and harmonic waveform generation.

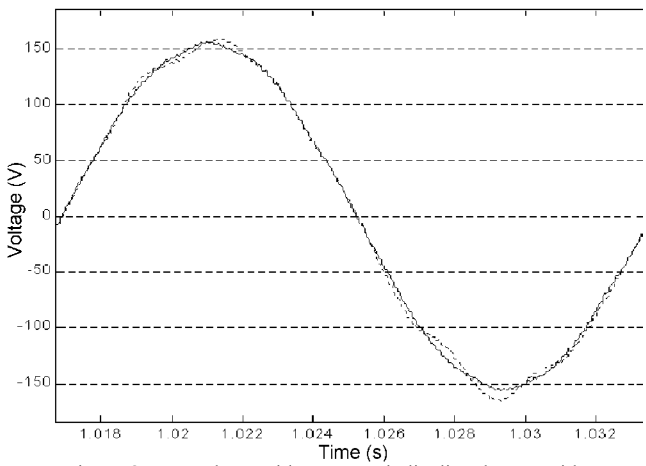

Fig. 5: Output voltage with a non-periodic disturbance: without adaptation (dotted line) and with adaptation (solid line) in the repetitive controller.

B. Experimental Results

A single-phase PWM inverter prototype has been built in the laboratory to verify the performance and demonstrate the feasibility of the proposed RMRAC-ARP control scheme. Results were obtained using a microcomputer platform with 6 kHz sampling rate.

Fig. 6 and Fig. 7 present the results of the proposed controller when generating sinusoidal waveforms, which are usually required in UPS systems. Fig. 6 shows the output voltage and load current with a 110V_{RMS} sinusoidal reference under linear load (resistive). The Total Harmonic Distortion (THD) of the output voltage is low, 2.1%. To verify the dynamic response of the proposed controller under nonlinear loads, a single-phase full-bridge rectifier with a capacitive filter ($C_f = 330\mu F$) and a resistive load ($R = 24\Omega$) has been used. Fig. 7 presents the system response to this nonlinear load with 110 V_{RMS} at 60 Hz sinusoidal reference. It can be seen the output voltage has good quality, presenting THD = 3.5%, even under this high non-linear load. The RMRAC controller associated with the adaptive repetitive controller assures a good transient response and a small tracking error in the output voltage.

Finally, to verify the performance of the AC power source in generation of waveforms with harmonics, the following reference is synthesized: $r(t) = 140\,(\sin 120\pi t + 0.2 \sin 240\pi t + 0.2 \sin 600\pi t)$. Fig. 8 shows the output voltage and the load current to a linear load of 24Ω for this reference. Fig. 9 presents the spectral analysis of the output voltage shown in Fig. 8. Fig. 10 shows the system response with the same load and to the following reference: $r(t) = 140\,(\sin 120\pi t + 0.2 \sin 300\pi t + 0.2 \sin 720\pi t)$. Fig. 11 presents the spectral analysis of the output voltage shown in Fig. 10. The good controller scheme performance it is shown in Fig. 12, where the same harmonic reference and the non-linear load are used. As can be seen by the spectral analysis in Fig. 13, the tracking capability of the proposed controller assure to follows harmonic reference even in presence of non-linear loads.

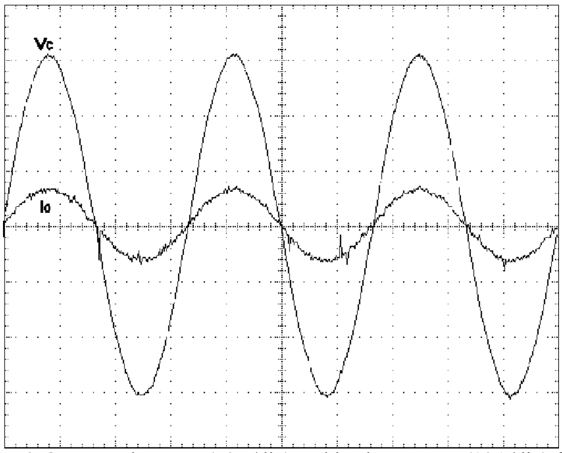

Fig. 6: Output voltage Vc (50V/div) and load current Io (10A/div) for linear load with sinusoidal reference

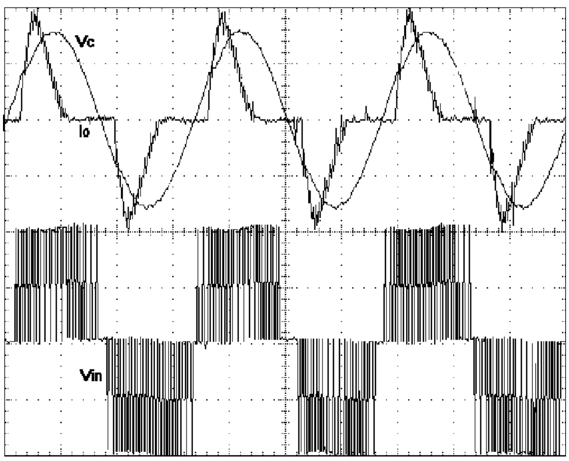

Fig. 7: Output voltage Vc (100V/div), load current Io (10A/div) and filter input voltage Vin (100V/div) to non-linear load and sinusoidal reference.

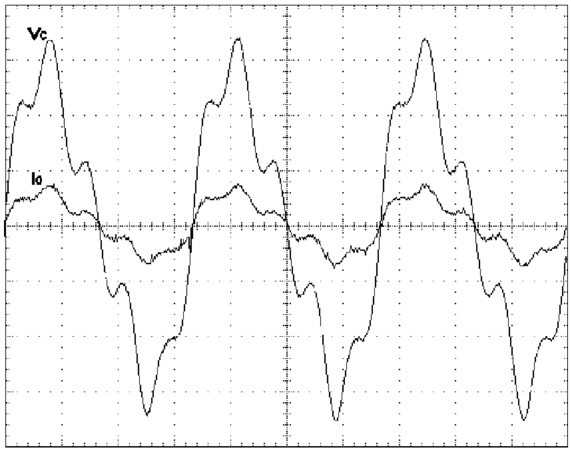

Fig. 8: Output voltage Vc (50V/div) and load current Io (10A/div) for linear load with the 2th and 5th harmonics in the reference

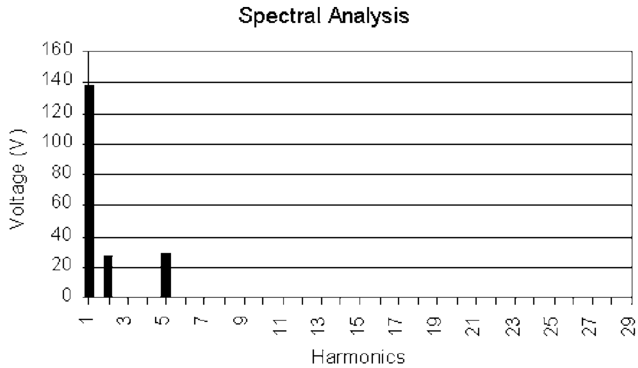

Fig. 9: Spectral analysis of the output voltage Vc to linear load with the presence of the 2th and 5th harmonics in the reference

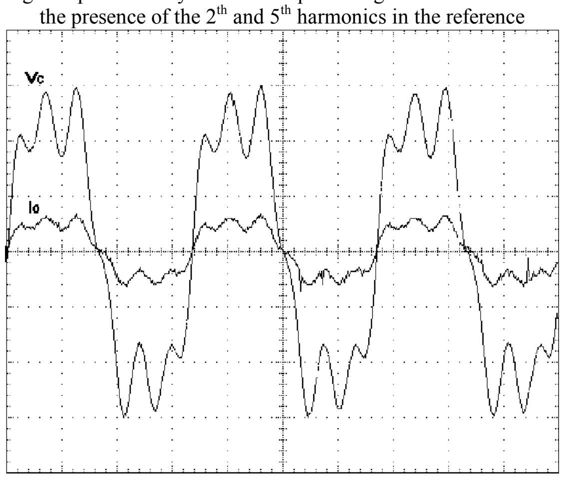

Fig. 10: Output voltage Vc (50V/div) and load current Io (10A/div) for a linear load with the 3th and 6th harmonics in the reference

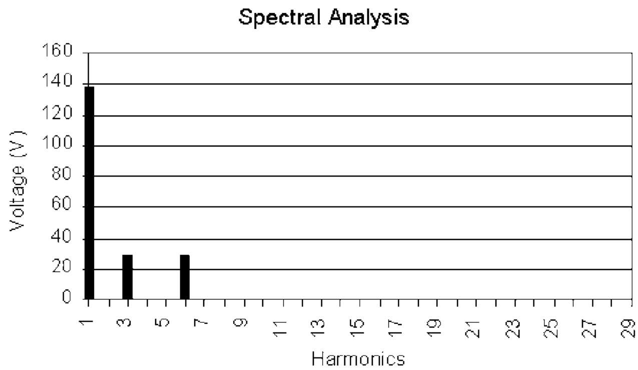

Fig. 11: Spectral analysis of the output voltage Vc to linear load with the presence of the 3th and 6h harmonics in the reference

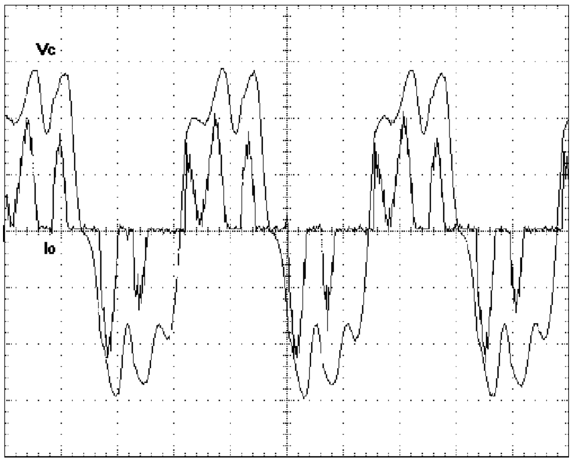

Fig. 12: Output voltage Vc (50V/div) and load current Io (10A/div) for non-linear load with the 3th and 6th harmonics in the reference

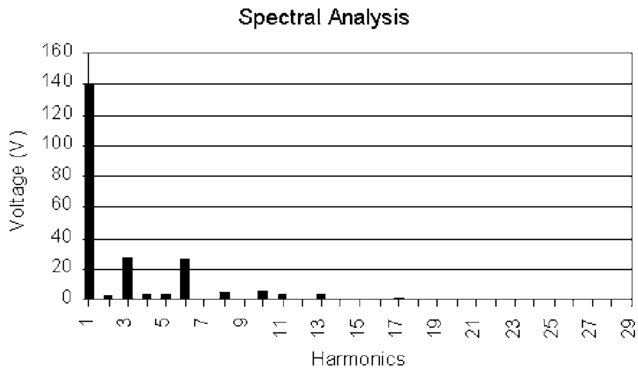

Fig. 13: Spectral analysis of the output voltage Vc to a nonlinear load with the presence of the 3th and 6th harmonics in the reference

The RMRAC parameters have been tuned off-line for implementation of the proposed scheme in a DSP320F241 with 6 kHz switching frequency. Fig. 14 shows the output voltage under linear load and for the following reference: $r(t) = 155\ (0.6 \sin 120\pi t + 0.2 \sin 600\pi t + 0.2 \sin 840\pi t)$.

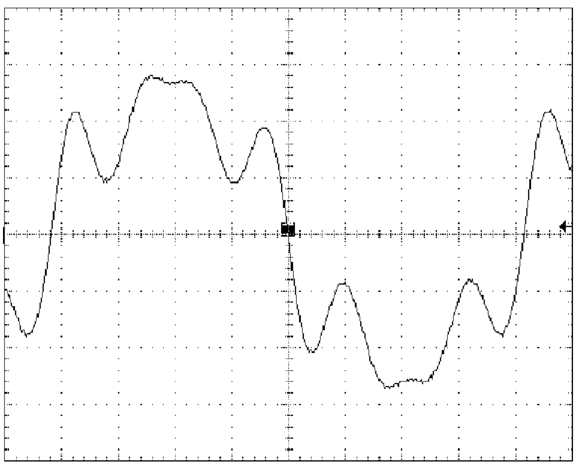

Fig. 14: Output voltage (50V/div) to harmonic waveform including 5th and 7th harmonics for a linear load.

VII. Conclusions

The main contributions of this paper are the inclusion of an adaptive algorithm for the repetitive gain and the use of the resulting RMRAC-ARP scheme to control UPS and AC Power Sources. This paper proposes a new robust model reference adaptive control with adaptive repetitive control (ARP), where the repetitive controller gain is tuned dynamically to minimize or reject the repetitive control action when no periodic disturbances are present. The adaptive repetitive control is implemented using a gradient projection type algorithm. In order to verify the control strategy performance, the RMRAC-ARP controller is applied to an AC power source. Simulation and experimental results were obtained under several operating conditions, including non-linear loads, periodic and non-periodic disturbances and unmodeled dynamics. Moreover, this scheme can be designed for a reduced-order plant, without *a priori* knowledge of the exact plant model of the PWM inverter system. The proposed system is particularly attractive for high power systems, where low switching frequencies are required. A microprocessor-based prototype is being used to demonstrate the algorithm effectiveness in realistic conditions.

References

[1] C. E. Rohrs, l. Valavani, M. Athans, G. Stein, *Robustness of Continuous-Time Adaptive Control Algorithms in the Presence of Unmodeled Dynamics*, **IEEE Transactions on Automatic Control**, Vol. 30, n. 9, pp. 881-890, 1985;

[2] B. Egardt, *Stability of Adaptive Controllers*, **Springer-Verlag, New York**, 1982;

[3] B. D. Riedle, B. Cyr, P. V. Kokotovic, *Disturbance Instabilities in an Adaptive System*, **IEEE Transactions on Automatic Control**, Vol. 29, n. 9, pp. 822-824, 1984;

[4] P. A. Ioannou, A. Datta, *Robust Adaptive Control: A Unified Approach*, **Proceedings of the IEEE**, Vol. 79, n. 12, pp. 1736-1768, 1991;

[5] P. A. Ioannou, K. Tsakalis, *A Robust Direct Adaptive Controller*, **IEEE Transactions on Automatic Control**, Vol. 31, n. 11, pp. 1033-1043, 1986;

[6] R. Lozano-leal, J. Collado, S. Mondié, *Model Reference Robust Adaptive Control Without A Priori Knowledge Gain*, **IEEE Transactions on Automatic Control**, Vol. 35, pp. 71-78, 1990;

[7] K. S. Narendra, A. M. Annaswamy, *Robust Adaptive Control in the Presence of Bounded Disturbances*, **IEEE Transactions on Automatic Control**, Vol. 31, n. 4, pp. 306-315, 1986;

[8] G. Kreisselmeir, B. D. O. Anderson, *Robust Model Reference Adaptive Control*, **IEEE Transactions on Automatic Control**, Vol. 31, pp. 127-133, 1986;

[9] S. Hara, Y. Yamamoto, T. Omata, M. Nakano, *Repetitive Control System: A New Type Servo System for Periodic Exogenous Signals*, **IEEE Transactions on Automatic Control**, Vol. 33, n. 7, pp. 659-667, 1988;

[10] H. A. Gründling, E. G. Carati, J. R. Pinheiro, *A Robust Model Reference Adaptive Controller for UPS Applications*, **IEEE Industrial Electronics Conference**, pp. 901-905, 1997;

[11] E. G. Carati, V. F. Montagner, H. A. Gründling, *A Single-Phase AC Power Source Using Robust Model Reference Adaptive Control*, **IEEE Industrial Electronics Conference**, pp. 1428-1432, 2000;

[12] P. A. Ioannou, K. Tsakalis, *A Robust Discrete-Time Adaptive Controller*, **IEEE Conference on Decision and Control**, pp. 838-843, 1986.