NONLINEAR BACKSTEPPING CONTROL OF SHUNT ACTIVE POWER FILTER

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Abstract: *This paper presents a new adaptive control technique for shunt active power filter (SAPF) based on adaptive backsepping technique. By using the nonlinear model of the shunt active power filter and backstepping method, the Lyapunov functions are constructed in order to enable the system to have uniformly asymptotic stability. An adaptive backstepping controller is designed to adopt the gradual correcting algorithm. The controller takes system nonlinearities into account in the control design. The simulation is completed by using MATLAB software. The simulation results show that the designed feedback controller makes the closed loop system stable and has better tracking performance.*

Key words: *Nonlinear Control, Adaptive Backstepping Design, Shunt Active Power Filter.*

1. Introduction

In recent years, the widespread applications of nonlinear loads increased the harmonic-related problems in utility and industrial power systems. Consequently, SAPF have been investigated and expected to be a viable solution [1, 2].

More recently various nonlinear control methodologies have been applied to the control of active power filter in order to design the controller directly by considering the nonlinear active filter dynamics.

Feedback linearization and input output linearization have been thoroughly studied over the last ten years by which means the original nonlinear model may be transformed into linear model through proper coordinate transformation [3-4] or based on the principle of average power balance [5-6]. Thus almost all of the well developed linear control techniques might be applied. These methods have been proven to be effective to the control of active filters. However, as it is based on the exact cancellation of the nonlinear items of the system model, when there are parameter uncertainties or unknown parameters, the desired results may not be obtained easily.

Backstepping control is a newly developed technique for the control of uncertain nonlinear systems, particularly those systems that do not satisfy matching conditions [7-10]. The most appealing point of it is to use the virtual control variable to make the original high-order system simple, thus the final control outputs can be derived step by step through suitable Lyapunov functions. An adaptive robust nonlinear controller can be straightforwardly derived using this control method.

As SAPF possesses well defined nonlinear model characteristics, they have become good candidate for the application of newly developed nonlinear control techniques. If the knowledge of such nonlinearities can be included in the design of nonlinear controller, an enhanced dynamic behavior of the active filter can be accomplished.

This paper presents a new adaptive control technique to three phase shunt active power filter. This technique is based on adaptive backstepping design applied to the uncertain nonlinear model of SAPF which provides an efficient control design processes for both regulation and tracking problems of uncertain parameters of R and L.

This paper is organized as follows: firstly the SAPF model in the d-q reference frame is presented in section II. In section III adaptive backstepping control methodology is developed. Finally section IV gives the simulation results and the conclusions are drawn in section V.

2. Mathematical Modelling of SAPF

The SAPF shown in Fig. 1 can be modeled in the d-q reference frame with the aim of reducing control complexity if compared with modeling in the stationary a-b-c reference frame.

The dynamic model as described in [11-12] is obtained as follows:

$$\frac{di_d}{dt} = -\frac{R_c}{L_c}i_d + wi_q - \frac{v_{dc}}{L_c}d_{nd} + \frac{v_d}{L_c} \qquad (1)$$

$$\frac{di_q}{dt} = -\frac{R_c}{L_c} i_q - wi_d - \frac{v_{dc}}{L_c} d_{nq} + \frac{v_q}{L_c} \qquad (2)$$

$$\frac{dv_{dc}}{dt} = d_d \frac{i_d}{C} + d_q \frac{i_q}{C} \qquad (3)$$

Where

i_d, i_q : The three phase inverter currents in the d-q reference frame.

v_{dc} : The DC voltage.

R_c, L_c : The resistance and inductance of the filter.

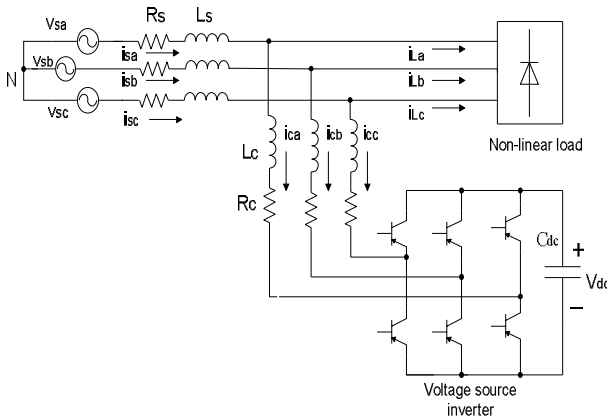d_d, d_q : The three phase switching state functions in the d-q reference frame.

Fig. 1 SAPF with a voltage source inverter

The model represented by (1), (2) and (3) is nonlinear because of the existence of multiplication terms between the state variables {i_d, i_q, v_{dc}} and the inputs {d_d, d_q}.

Furthermore the principle of operation of active filter requires that the three state variables have to be controlled independently. Therefore each of the currents {i_d, i_q} has to follow a varying reference frame extracted from nonlinear load current. In addition, the DC voltage level has to be regulated at a set point in order to maintain the compensation performance of the active filter during dynamic variations.

3. Control Design

The objective of this paper is to obtain d_d and d_q to achieve high performance current tracking and DC voltage regulation. This will be achieved when the active filter injects the load current in opposite phase.

$$i_{dref} = -i_{ldh} + i_{do} \qquad (4)$$

$$i_{qref} = -i_{lq} \qquad (5)$$

The proposed control strategy adopted in this paper is called adaptive backstepping. This recently developed nonlinear control technique has been gaining popularity among control system engineers. This control technique can be effectively used to linearize a nonlinear system in

the presence of uncertainties. Unlike in other feedback linearization methods, the

advantage of adaptive backstepping is its flexibility where by useful nonlinearities can be kept intact during stabilization. The essence of adaptive backstepping is the identification of a virtual control state and forces it to become a stabilizing function. Thus it generates a corresponding error variable. For second order systems this error variable can be stabilized by proper selection of control input via lyapunov stability theory.

In this work the virtual controls are known because the reference currents which stabilize the operation of active filter are shown in (4) and (5). The pertinent control objective is to regulate the DC voltage. The DC voltage error variable and its derivative can be given as:

$$e = v_{dcref} - v_{dc}$$

$$\overset{*}{e} = \overset{*}{v}_{dcref} - \overset{*}{v}_{dc} = \overset{*}{v}_{dcref} - \frac{dv_{dc}}{dt} = \overset{*}{v}_{dcref} - \frac{1}{C}\left[i_d d_d + i_q d_q \right]$$

$$\overset{*}{e} = -\frac{1}{C}\left[i_d d_d + i_q d_q \right]$$

(6)

The d-q current error variables can be defined as:

$$e_d = i_{dref} - i_d$$

$$\overset{*}{e}_d = \overset{*}{i}_{dref} - \overset{*}{i}_d = \overset{*}{i}_{dref} - \frac{di_d}{dt} = \overset{*}{i}_{dref} - \left[-\frac{R_c}{L_c} i_d + wi_q - \frac{v_{dc}}{L_c} d_d + \frac{v_d}{L_c} \right]$$

$$\overset{*}{e}_d = \overset{*}{i}_{dref} + \frac{R_c}{L_c} i_d - wi_q + \frac{v_{dc}}{L_c} d_d - \frac{v_d}{L_c} \qquad (7)$$

, and $e_q = i_{qref} - i_q$

$$\overset{*}{e}_q = \overset{*}{i}_{qref} - \overset{*}{i}_q = \overset{*}{i}_{qref} - \left[-\frac{R_c}{L_c} i_q - wi_d - \frac{v_{dc}}{L_c} d_q + \frac{v_q}{L_c} \right]$$

$$\overset{*}{e}_q = \overset{*}{i}_{qref} + \frac{R_c}{L_c} i_q + wi_d + \frac{v_{dc}}{L_c} d_q - \frac{v_q}{L_c} \qquad (8)$$

As the active filter inductance and resistances have to be measured adaptively. Therefore let these estimates be $\hat{L}_c$ and $\hat{R}_c$. One can define the following lyapunov function including the current and dc voltage error variables:

$$V = \frac{1}{2}\left(e^2 + e_d^2 + e_q^2 + \frac{1}{\gamma_1} \widetilde{R}_c^2 + \frac{1}{\gamma_2} \widetilde{L}_c^2 \right)$$

Where $\widetilde{L}_c = \hat{L}_c - L_c$, $\widetilde{R}_c = \hat{R}_c - R_c$, γ_1 and γ_2 are adaptive gains.

By differentiating the lyapunov function and using the error dynamics one can get:

$$\overset{*}{V} = \overset{*}{e}\,e + e_d\,\overset{*}{e_d} + e_q\,\overset{*}{e_q} + \frac{1}{\gamma_1}\tilde{R}_c\,\overset{*}{\tilde{R}_c} + \frac{1}{\gamma_2}\tilde{L}_c\,\overset{*}{\tilde{L}_c}$$

$$\overset{*}{V} = -ke^2 - k_1 e_d^{\ 2} - k_2 e_q^{\ 2}$$

$$+ e\left[-\frac{1}{C}\left(e_d\,\frac{i_d d_d}{e_d} + e_q\,\frac{i_q d_q}{e_q} \right) + ke \right]$$

$$+ e_d\left[\overset{*}{i_{dref}} + \frac{R_c}{L_c}i_d - wi_q + \frac{v_{dc}}{L_c}d_d - \frac{v_d}{L_c} + k_1 e_d \right]$$

$$+ e_q\left[\overset{*}{i_{qref}} + \frac{R_c}{L_c}i_q + wi_d + \frac{v_{dc}}{L_c}d_q - \frac{v_q}{L_c} + k_2 e_q \right]$$

$$+ \frac{1}{\gamma_1}\tilde{R}_c\,\overset{*}{\tilde{R}_c} + \frac{1}{\gamma_2}\tilde{L}_c\,\overset{*}{\tilde{L}_c} \tag{9}$$

Where k, k_1 and k_2 are closed loop feedback constants. The input switching functions can be derived from (9):

$$d_d = \frac{L_c}{v_{dc}}\left[-\overset{*}{i_{dref}} - \frac{R_c}{L_c}i_d + wi_q + \frac{v_d}{L_c} - k_1 e_d - \frac{k}{e_d}e^2 \right]$$

$$+ \frac{1}{C}\frac{L_c}{v_{dc}}\frac{e}{e_d}i_d d_d$$

$$d_q = \frac{L_c}{v_{dc}}\left[-\overset{*}{i_{qref}} - \frac{R_c}{L_c}i_q - wi_d + \frac{v_q}{L_c} - k_2 e_q \right]$$

$$+ \frac{1}{C}\frac{L_c}{v_{dc}}\frac{e}{e_q}i_q d_q$$

Substituting for the estimated values for L and R:

$$d_d = -\frac{\hat{L}_c}{v_{dc}}\overset{*}{i_{dref}} - \frac{\hat{R}_c}{v_{dc}}i_d + \frac{\hat{L}_c}{v_{dc}}wi_q + \frac{v_d}{v_{dc}} - \frac{\hat{L}_c}{v_{dc}}k_1 e_d$$

$$- \frac{\hat{L}_c}{v_{dc}}\frac{k}{e_d}e^2 + \frac{1}{C}\frac{\hat{L}_c}{v_{dc}}\frac{e}{e_d}i_d d_d$$

$$d_q = -\frac{\hat{L}_c}{v_{dc}}\overset{*}{i_{qref}} - \frac{\hat{R}_c}{v_{dc}}i_q - \frac{\hat{L}_c}{v_{dc}}wi_d + \frac{v_q}{v_{dc}} - \frac{\hat{L}_c}{v_{dc}}k_2 e_q$$

$$+ \frac{1}{C}\frac{\hat{L}_c}{v_{dc}}\frac{e}{e_q}i_q d_q$$

Substituting in the general lypunov equation (9) with further simplification:

$$\overset{*}{V} = -ke^2 - k_1 e_d^{\ 2} - k_2 e_q^{\ 2}$$

$$+ e_d\left[\begin{array}{l} \overset{*}{i_{dref}}(1 - \frac{\hat{L}_c}{L_c}) + \frac{i_d}{L_c}(R_c - \hat{R}_c) + wi_q(\frac{\hat{L}_c}{L_c} - 1) \\[2mm] + k_1 e_d(1 - \frac{\hat{L}_c}{L_c}) + k\frac{e^2}{e_d}(1 - \frac{\hat{L}_c}{L_c}) \end{array} \right]$$

$$+ e_q\left[\begin{array}{l} \overset{*}{i_{qref}}(1 - \frac{\hat{L}_c}{L_c}) + \frac{i_q}{L_c}(R_c - \hat{R}_c) + wi_d(1 - \frac{\hat{L}_c}{L_c}) \\[2mm] + k_2 e_q(1 - \frac{\hat{L}_c}{L_c}) \end{array} \right] \tag{10}$$

$$+ \frac{i_d d_d e}{C}(\frac{\hat{L}_c}{L_c} - 1) + \frac{i_q d_q e}{C}(\frac{\hat{L}_c}{L_c} - 1) + \frac{1}{\gamma_1}\tilde{R}_c\,\overset{*}{\tilde{R}_c} + \frac{1}{\gamma_2}\tilde{L}_c\,\overset{*}{\tilde{L}_c}$$

Equation (10) can be simplified and arranged in the following form:

$$\overset{*}{V} = -ke^2 - k_1 e_d^{\ 2} - k_2 e_q^{\ 2}$$

$$+ \frac{\tilde{L}_c}{L_c}\left[\begin{array}{l} e_d(-\overset{*}{i_{dref}} + wi_q - k_1 e_d - k\frac{e^2}{e_d}) + \frac{i_d d_d e}{C} \\[2mm] + e_q(-\overset{*}{i_{qref}} - wi_d - k_2 e_q) + \frac{i_q d_q e}{C} + \frac{L_c}{\gamma_2}\overset{*}{\tilde{L}_c} \end{array} \right] \tag{11}$$

$$+ \frac{\tilde{R}}{L_c}\left[-e_d i_d - i_q e_q + \frac{L_c}{\gamma_1}\overset{*}{\tilde{R}_c} \right]$$

From (11) the following update laws for the estimated adaptive values can be derived as:

$$\overset{*}{\tilde{L}} = \frac{\gamma_2}{L_c}\left[\begin{array}{l} e_d(\overset{*}{i_{dref}} - wi_q + k_1 e_d + k\frac{e^2}{e_d}) - \frac{i_d d_d e}{C} \\[2mm] e_q(\overset{*}{i_{qref}} + wi_d + k_2 e_q) - \frac{i_q d_q e}{C} \end{array} \right]$$

$$\overset{*}{\tilde{R}} = \frac{\gamma_1}{L_c}\left[e_d i_d + i_q e_q \right]$$

Based on the algorithm mentioned earlier the block diagram of the proposed ABNC is shown in Fig. 2.

$$\overset{*}{V} = -ke^2 - k_1 e_d^{\ 2} - k_2 e_q^{\ 2} \tag{12}$$

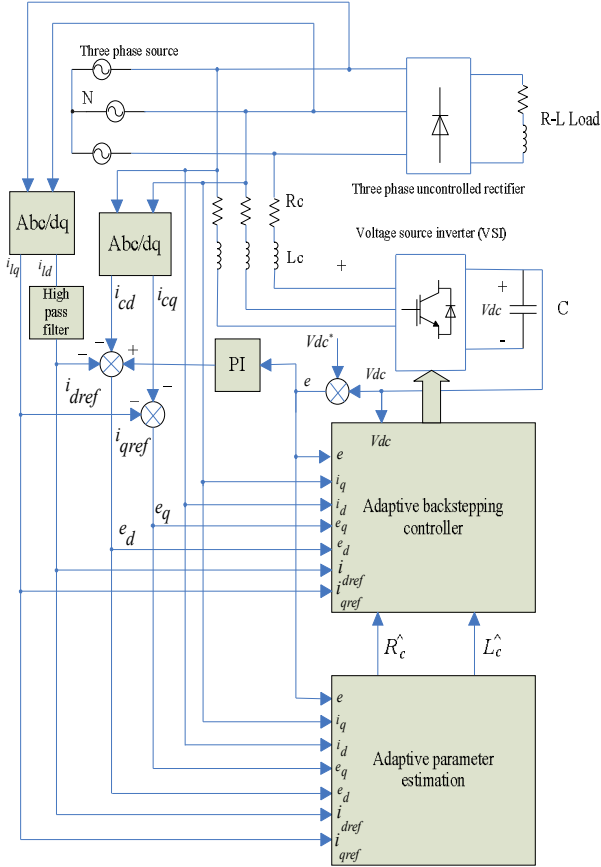In (12) as long as k, k_1 and $k_2 > 0$ the system has global asymptotic stability.

Fig. 2 The block diagram of the proposed ABNC based shunt active filter.

4. Simulation Results

In order to verify the effectiveness of the proposed controller, a computer simulation model is developed using Matlab/Simulink software. In Fig. 3 the designed feedback controller based on backstepping method enables the system to have better regulation and tracking performance. The simulation results show that the filter DC voltage has fast transient response and no steady state error. The source current after compensation exhibits better THD content (5%) than before compensation (19.5%) and good tracking.
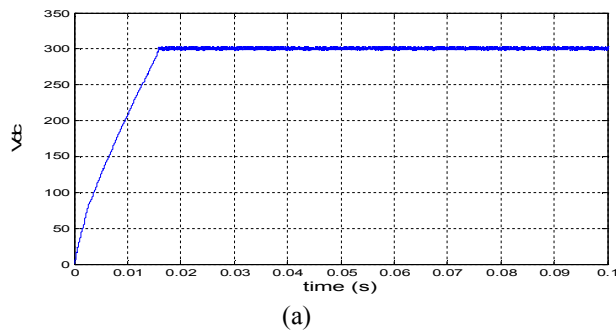

(a)
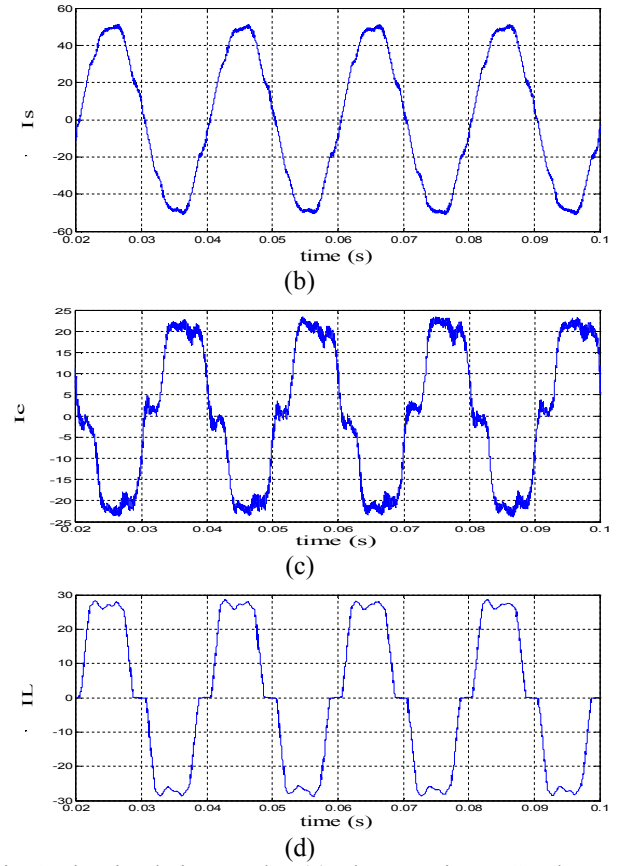
Fig. 3 The simulation results. (a) The capacitor DC voltage. (b) The source current after compensation. (c) The filter current. (d) The nonlinear load current

Fig. 4 shows the dynamic response of the active filter when the nonlinear load resistance was subjected to 100% step decrease at t=0.1s. The distortion content of the source current is not affected by the step change as well as the transient response of the DC voltage where the active filter exhibits robust performance.
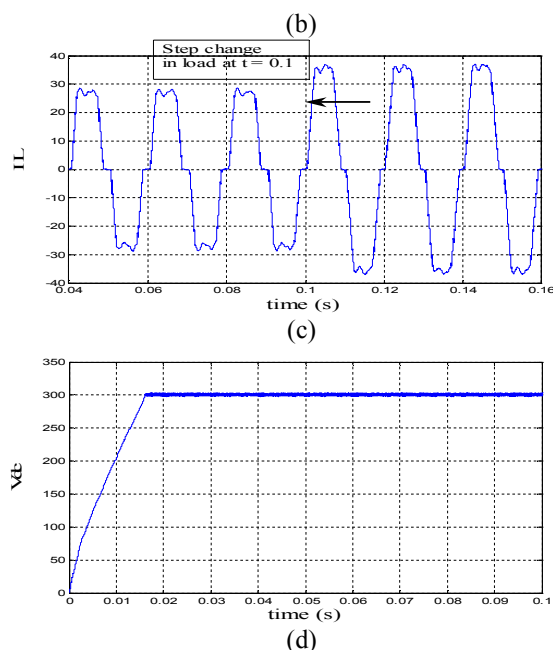

(a)

(b)

(c)

(d)
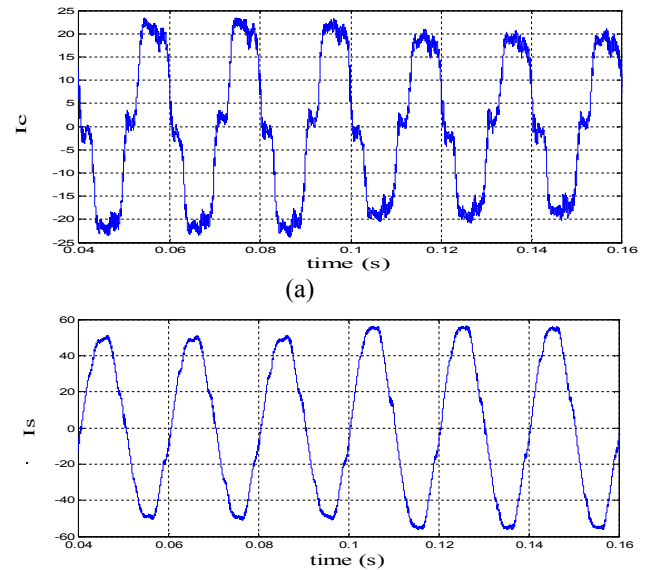
Fig. 4 The dynamic response for step increase 100% in the nonlinear load.
(a) The filter current. (b) The source current. (c) The nonlinear load current. (d) The DC voltage.

The parameters of the supply: V_s = 120 V (line-line), R_s= 1 Ω, L_s= 0.01 mH. The active filter parameters: L_c= 2 mH, R_c = 1 Ω and C_{dc}= 0.1 mF.

5. Conclusions

Successful application of adaptive backstepping control for DC voltage regulation and current tracking of the active filter has been illustrated in this paper. It has been shown that the SAPF belongs to class of nonlinear systems for which adaptive backstepping technique can be effectively used. The virtual controls of the active filter have been known and stabilizing control laws are developed subsequently using lyapunov stability theory. The detailed derivation for the control laws has been provided. The method is applied widely in nonlinear control. The simulation results verify the designed feedback controller makes the system stable and the system has better tracking and regulation performance.

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