

ADAPTIVE NONLINEAR CONTROL OF THREE PHASE SHUNT ACTIVE POWER FILTER WITH UNCERTAINTIES

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Abstract: This paper presents a new control strategy for a three phase shunt active power filter, which consists of applying an adaptive nonlinear control. This technique consists of applying an adaptive nonlinear control to the uncertain nonlinear model of shunt active power filter obtained in (dq) frame by using the power balance between the input and output sides. The designed Adaptive nonlinear controller (ANC) combines the nonlinear feedback linearization technique with linear adaptive control techniques and takes into account the uncertainties in the model parameters. We Apply an adaptive nonlinear control in order to control the line-currents, output DC link voltages and also to reduce the influence of the parameter uncertainty. Simulation results clearly show that the proposed controller has a good performance and robust to the parameter uncertainties compared with other nonlinear strategies controllers.

Key words: Shunt active power filter, feedback linearization adaptive nonlinear control, and harmonic current compensation.

1. Introduction

In recent years, the widespread applications of nonlinear loads increased the harmonic-related problems in utility and industrial power systems. Consequently, active power filters have been investigated and expected to be a viable solution [9]. The shunt active filters are known to be appropriate means to eliminate harmonic contamination created by current type nonlinear loads [4]. The shunt passive filters have been traditionally used to absorb this type of harmonics. They have, however, major drawbacks, including the dependency of their compensation characteristics on the utility grid impedance, and their susceptibility to undesirable resonance with grid and load impedances caused by wide spectrum of current harmonics generated by the load. The nonlinear loads such as phase-controlled rectifiers draw distorted currents that are characterized by sudden slope variations. Hence, the active filter and its current

control should be effective in tracking the dynamic current reference, which makes the power stage highly sensitive and the design of the control particularly critical. A number of control concepts and strategies of three-phase APF have been reported in the literature [7]-[8]. Usually, the APF control design is carried on by the three following steps [8]:

1) Measuring the network voltage and current signals, 2) deriving the compensating signals in terms of current or voltage levels, 3) Generating the gating signals for the solid-state devices using PWM, Hysteresis, sliding mode controllers, etc. In [7], the nonlinear control strategy has been applied which is very sensitive to the variation of R_c and L_c parameters, so V_{dc} link stray away from V_{dc} reference, also a control scheme based on the estimation of the reference peak source current I_{sp}^* was done.

This paper presents an adaptive nonlinear control strategy approach applied to a three-phase shunt active power filter. This control technique is based on a feedback linearization technique applied to the uncertain non linear model of the APF derived from the principle of the average power balance which provides an efficient control design processes for both regulation and tracking problems of uncertain parameters, R_c , L_c and I_L [2,3,5].

In section 2 of this paper, the nonlinear active filter model is developed and analysed. Section 3 the adaptive nonlinear control is described. Finally section 4 gives the main simulation results of the adaptive nonlinear control.

2. The active power filter mathematical model

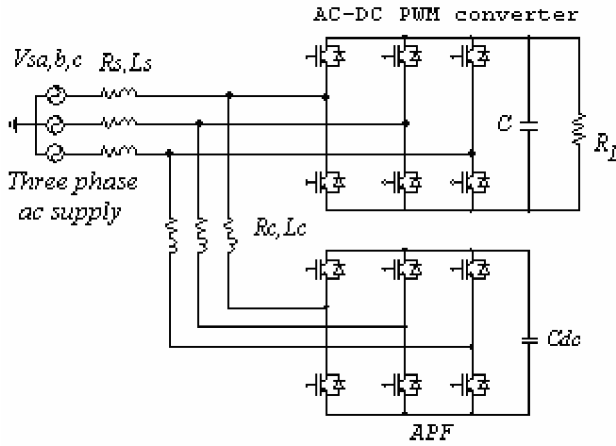


Fig.1. Three phase Active power filter topology

Figure.1 presents the topology of three-phase Active power filter under study. The principle of average power balance is used to determine the approximate model of the compensator [8]. The mathematical model is derived based on the following assumptions.

- The utility voltages are balanced and contain no harmonics.
- Only the fundamental components of currents are considered, as the harmonic components do not affect the average power balance expressions.
- All losses of the system are lumped and represented by an equivalent resistance R_c connected in series with the line inductor L_c . Ripple in the dc-link capacitor voltage is neglected.

The rms load current of single phase can be written:

$$I_C = I_{Cd} + jI_{Cq} \quad (1)$$

$$I_L = I_{Ld} + jI_{Lq} \quad (2)$$

Where I_{Ld} , I_{Cd} are the rms in phase component of the load and compensator current, respectively, and I_{Lq} , I_{Cq} are the rms quadrature component of the load and compensator current, respectively [1]. The components I_{Ld} , I_{Lq} and I_{Cd} , I_{Cq} are obtained using Park transformation,

The rms source current is then

$$I_S = I_L + I_C \text{ but } jI_{Lq} = -jI_{Cq}$$

Therefore

$$I_S = I_{Ld} + I_{Cd} \quad (3)$$

$$\text{The compensator power is: } P_{com} = n V_s I_{Cd} \quad (4)$$

$$\text{On the other hand } P_{com} = P_R + P_L + P_C \quad (5)$$

Where P_R , P_L and P_C are the Power loss in the resistor, the inductance power and The capacitor average power respectively, and V_{dc} is the instantaneous dc link voltage. The average rate of change of energy associated with ac

link and dc link is given by:

$$n V_s I_{Cd} = P_R + P_L + P_C \quad (6)$$

Then

$$n V_s I_{Cd} = n R_c \{I_{cd}^2 + I_{cq}^2\} + n \frac{d}{dt} \left\{ \frac{1}{2} L I_{cd}^2 \right\} + C_{dc} V_{dc} \frac{dV_{dc}}{dt} \quad (7)$$

The mathematical model according to the source current I_s may be written as:

$$\begin{aligned} 3(V_s I_s + 2R_c I_{Ld} I_s + L_c I_s \frac{dI_{Ld}}{dt} - R_c I_s^2 + L_c I_{Ld} \frac{dI_s}{dt} - \\ \frac{1}{2} L_c \frac{I_s^2}{dt} - R_c I_{Ld}^2 - V_s I_{Ld} - R_c I_{Cq}^2 - \frac{1}{2} L_c \frac{dI_{Ld}^2}{dt}) = \\ C_{dc} V_{dc} \frac{dV_{dc}}{dt} \end{aligned} \quad (8)$$

Let's consider x_1 and x_2 being two states variables and u is the input signal.

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} I_s \\ V_{dc} \end{bmatrix} \text{ and } u = \frac{dI_s}{dt}$$

Equation (8) can be written as:

$$\dot{x} = f(x) + g(x)u \quad (9)$$

Such that:

$$\begin{aligned} f(x) &= \begin{bmatrix} 0 \\ \frac{3}{C x_2} \{V_s (x_1 - I_{Ld}) + R_c (2 x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)\} \end{bmatrix} \\ g(x) &= \begin{bmatrix} 1 \\ \frac{3}{C x_2} L_c (I_{Ld} - x_1) \end{bmatrix} \end{aligned}$$

3. Design of the adaptive controller

Our objective is to design an adaptive nonlinear controller for use with a three phase shunt active power filter (APF) having constant but unknown R_c and L_c . We start by introducing the nonlinear feedback linearization controller for the nominal model of the APF. We can rewrite the system of equations (9) in a form that suggests an adaptive scheme for the estimation of R_c and L_c .

Equation (9) can expand as follows:

$$\dot{x} = f_n(x) + g(x)u + \delta_1 f_\delta(x) + \delta_2 g_\delta(x)u \quad (10)$$

Where:

$$\begin{aligned} f_n(x) &= \begin{bmatrix} 0 \\ \frac{3(V_s(x_1 - I_{Ld}) + R_{cn}(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2))}{C x_2} \end{bmatrix} \\ f_\delta(x) &= \begin{bmatrix} 0 \\ \frac{3(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)}{C x_2} \end{bmatrix} \end{aligned}$$

$$g(x) = \begin{bmatrix} 1 \\ \frac{3}{C x_2} L_{cn} (I_{Ld} - x_1) \end{bmatrix}$$

$$g_{\delta}(x) = \begin{bmatrix} 0 \\ \frac{3}{C x_2} (I_{Ld} - x_1) \end{bmatrix}$$

The vector δ represents the error between the nominal parameters R_{cn} , L_{cn} and the uncertain parameters R_c , L_c respectively.

$$\delta = \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix} = \begin{bmatrix} R_c - R_{cn} \\ L_c - L_{cn} \end{bmatrix} \quad (11)$$

A. Non-adaptive version of the controller

If we apply the input-output linearization, we obtain

$$y = h(x) = V_{dc}$$

$$\ddot{y} = L_f h + L_g h u \quad (12)$$

Where:

$$L_f h(x) = \frac{3(V_s(x_1 - I_{Ld}) + R_c(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2))}{C x_2}$$

$$L_g h(x) = \frac{3 L_c (I_{Ld} - x_1)}{C x_2}$$

$$\ddot{y} = \frac{3}{C x_2} \{V_s(x_1 - I_{Ld}) + R_c(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)\} + \frac{3}{C x_2} L_c (I_{Ld} - x_1) u \quad (13)$$

If we consider the linear command as $v = k(V_{dc}^* - V_{dc})$ the control law becomes:

$$\text{Or } \ddot{y} = v = k(V_{dc}^* - V_{dc}) \quad (14)$$

Then from equation (12), we deduce the input signal u as:

$$u = \frac{1}{(L_g h)} \{-(L_f h) + v\} \quad (15)$$

Then

$$u = \frac{3 \{V_s(x_1 - I_{Ld}) + R_c(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)\}}{3 L_c (x_1 - I_{Ld})} - \frac{C V_{dc} (k(V_{dc}^* - V_{dc}))}{3 L_c (x_1 - I_{Ld})} \quad (16)$$

This control law is then integrated, yielding the reference supply current peak value I_{sp}^* used afterward in the design of the non linear controller [1].

B. Adaptive version of the controller

Consider a nonlinear system of the form (9) with $L_g h(x)$ bounded away from zero. Further, let $f(x)$ and $g(x)$ have the form:

$$f(x) = \sum_{i=1}^{n1} \theta_i^{(1)} f_i(x), \text{ and } g(x) = \sum_{j=1}^{n2} \theta_j^{(2)} g_j(x).$$

Where $\theta_i^{(1)}$, $\theta_j^{(2)}$ are unknown parameters and $f_i(x)$, $g_j(x)$ are known functions [12]. At time,

Then

$$f(x) = \begin{bmatrix} 0 \\ \frac{3(V_s(x_1 - I_{Ld}))}{C x_2} \end{bmatrix} + \theta_1 \begin{bmatrix} 0 \\ \frac{3(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)}{C x_2} \end{bmatrix} \quad (17)$$

$$g(x) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \theta_2 \begin{bmatrix} 0 \\ \frac{3}{C x_2} (I_{Ld} - x_1) \end{bmatrix} \quad (18)$$

Where: $\theta_1 = R_c$ and $\theta_2 = L_c$.

Our estimates of the functions f and g are:

$$\tilde{f}(x) = \begin{bmatrix} 0 \\ \frac{3(V_s(x_1 - I_{Ld}))}{C x_2} \end{bmatrix} + \tilde{\theta}_1 \begin{bmatrix} 0 \\ \frac{3(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)}{C x_2} \end{bmatrix} \quad (19)$$

$$\tilde{g}(x) = \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \tilde{\theta}_2 \begin{bmatrix} 0 \\ \frac{3}{C x_2} (I_{Ld} - x_1) \end{bmatrix} \quad (20)$$

Here $\tilde{f}(x)$, $\tilde{g}(x)$ stand for the estimates of $f(x)$, $g(x)$ and $\tilde{\theta}_1$, $\tilde{\theta}_2$ are the estimates of the parameters θ_1 , θ_2 respectively at time t . Consequently, the linearizing control law (15) is replaced by:

$$u = \frac{1}{(L_g h)_e} \{-(L_f h)_e + v\} \quad (21)$$

With $(L_f h)_e$, $(L_g h)_e$ representing the estimates of $L_f h$, $L_g h$ respectively based on (19), (20).

$$(L_f h)_e = \frac{3(V_s(x_1 - I_{Ld}) + \tilde{\theta}_1(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2))}{C x_2} \quad (22)$$

$$(L_g h)_e = \frac{3(I_{Ld} - x_1)}{C x_2} \tilde{\theta}_2 \quad (23)$$

We define ϕ as the vector parameter error where:

$$\phi = \tilde{\theta} - \theta_n \quad (24)$$

Where θ_n stand for the nominal parameter vector

$$\theta = [\theta_1 \quad \theta_2]^T$$

Then using (21) in (12) yields,

$$\ddot{y} = v + \phi_1 W_1 + \phi_2 W_2 \quad (25)$$

$$W_1 = -\frac{3(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)}{C x_2} \quad (26)$$

$$W_2 = \frac{\lambda(x) + \alpha(x) \tilde{\theta}_1 - v}{\tilde{\theta}_2} \quad (27)$$

Such that

$$\begin{cases} \alpha(x) = \frac{3(2x_1 I_{Ld} - x_1^2 - I_{Ld}^2 - I_{Cq}^2)}{C x_2} \\ \lambda(x) = \frac{3V_s(x_1 - I_{Ld})}{C x_2} \end{cases}$$

The tracking control law is $v = k(V_{dc}^* - V_{dc})$.

And yielding the following error equation relating the tracking error e to the parameter error ϕ .

$$\dot{e} = -ke + \phi^T W \quad (28)$$

Where

$$e = y - y_m, W = \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} \text{ and } \phi = \begin{bmatrix} \tilde{\theta}_1 - \theta_{1n} \\ \tilde{\theta}_2 - \theta_{2n} \end{bmatrix}$$

The parameter adaptation laws and the control of the system can be obtained as follows:

$$\dot{\tilde{\theta}} = -\gamma e W \quad (29)$$

$$u = \frac{1}{(L_g h)_e} (-(L_f h)_e + v) \quad (30)$$

Where γ is the adaptation gain vector.

If $y(t)$ converge to $y_m(t)$, then all the error variables are bounded and converge to zero asymptotically.

We can draw the conclusion of the resulting strategy control of the objective design in figure.3.

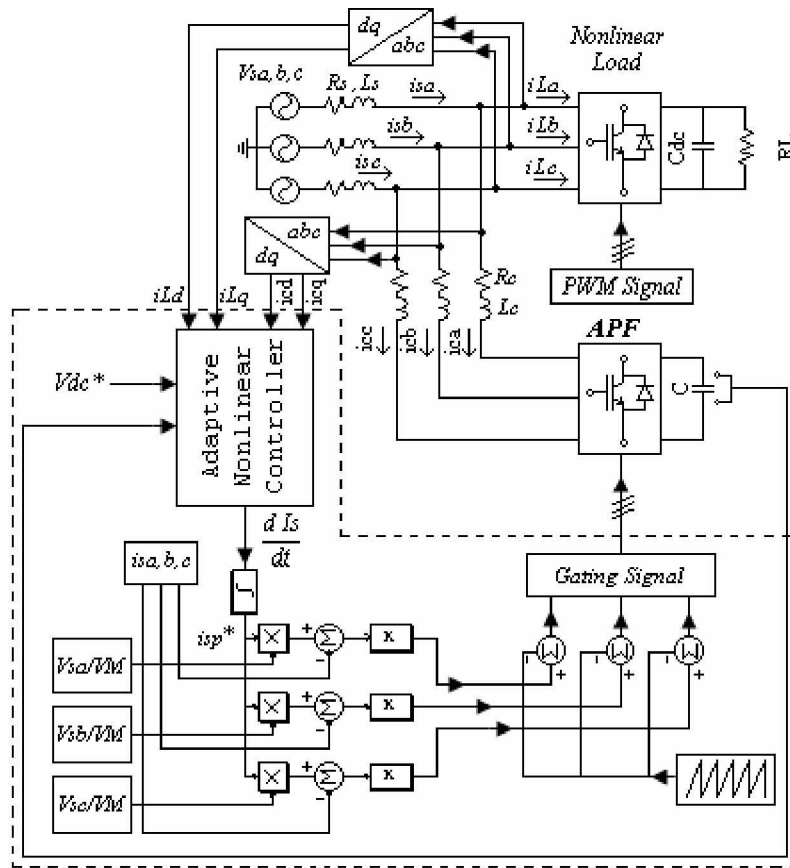


Fig. 2 Overall diagram of proposed control system of APF

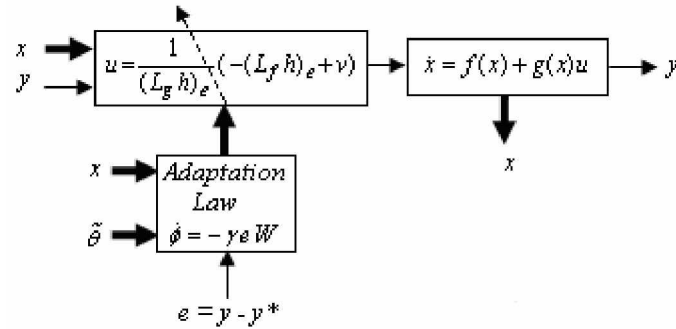


Fig.3 Block diagram of adaptive nonlinear controller

Table 1

<u>The PWM Converter parameters</u>	
Supply's Voltage & frequency	220v (rms), 50hz
Line's inductance & resistance	0.1mH, 2m Ω
DC link resistance	20 Ω
Output capacitors	370 μ F
PWM carrier frequency	1KHz
<u>Shunt active filter parameters</u>	
Line's inductance & resistance	0.1 mH, 0.05 Ω
Output capacitors	300 μ F
PWM carrier frequency	1 KHz

4. The Simulation Results

In this section, we implemented the adaptive nonlinear controller in Matlab/Simulink to verify the stability and show the asymptotic tracking performance. We introduce in Table 1 the actual parameters values used in simulation.

The overall configuration of the control system for the three phase shunt active power filter is shown in Fig.2. The block diagram of the nonlinear adaptive control of the APF is given in Fig. 3.

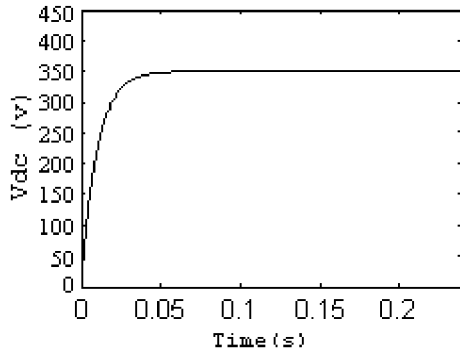


Fig.4 Output DC link voltage response

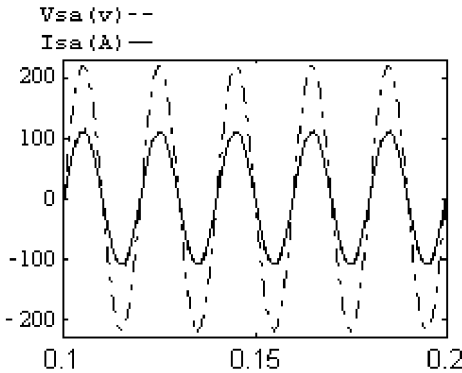


Fig.5 Supply current and supply voltage without uncertain

The output Dc link voltage of APF, the supply voltage and the input line current responses of the ideal input-output feedback linearization are presented in Fig.4 and Fig.5, respectively.

If there is no uncertainty the actual output DC voltage response can track the DC voltage reference resulting from the reference model perfectly. The ideal input-output feedback linearisation is based on the exact cancellation of the nonlinearity, for this reason, the ideal nonlinear control cannot deal with the system uncertainties.

1. Uncertain of L_c

Figures (6-7and 8) gives the simulation results of the proposed adaptive nonlinear controller when the uncertainty L_c is introduced with (10%) of the nominal value ($L_c=0.1$ mH). Figure (8) presents the output DC link voltage of APF with adaptation law, where the transition of L_c is occurred at $t=0.07$ s.

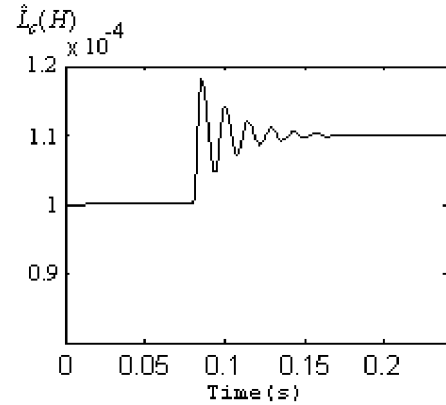


Fig.6 Estimation of the parameter $\hat{L}_c(t)$

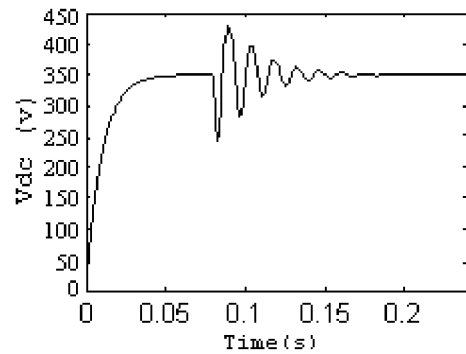


Fig.7 Output DC link voltage response with adaptation law

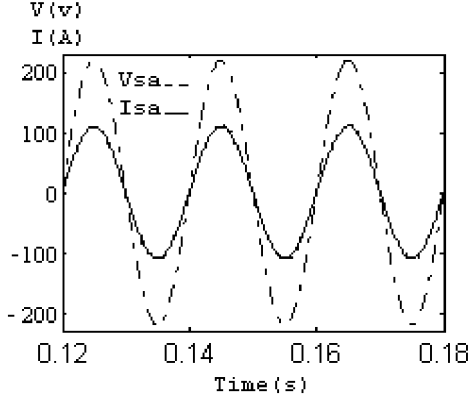


Fig.8 Supply current and supply voltage with adaptation law

2. Uncertain of R_c

Figure (9and10) gives the simulation results of the proposed adaptive nonlinear controller when the uncertainty R_c is introduced with (10%) of the nominal value ($R_c=0.5 \text{ m}\Omega$). Figure (10) presents the output DC link voltage of the APF with adaptation law, where the transition of R_c is occurred at $t=0.07\text{s}$.

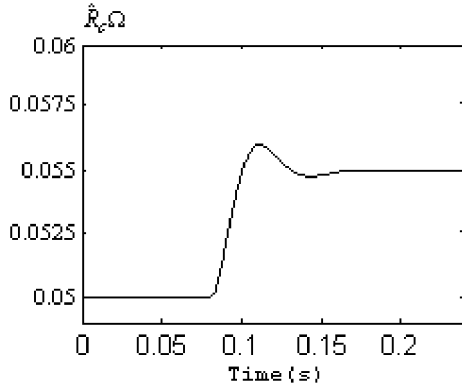


Fig.9 Estimation of the parameter $\hat{R}_c(t)$

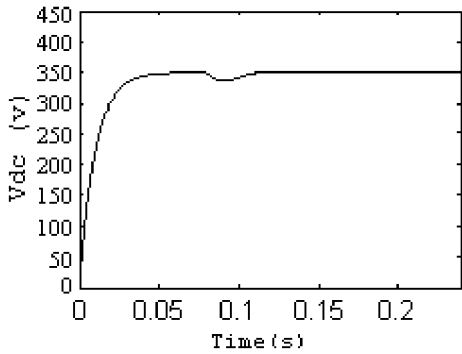


Fig.10 Output DC link voltage response with adaptation law

3. Uncertain of R_c and L_c

Figure (11, 12, and13) gives the simulation results of the proposed adaptive nonlinear controller when the uncertainty R_c and L_c is introduced with (20%) and (10%) respectively of the nominal value ($R_c=0.6\text{m}\Omega$, $L_c=0.11\text{mH}$).

Figure (13) presents the output DC link voltage with adaptation law, where the transition of (R_c and L_c) is occurred at $t=0.07\text{s}$.

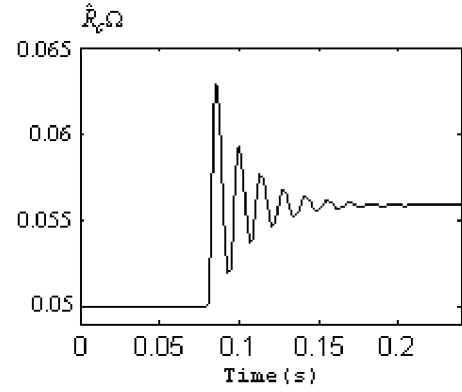


Fig.11 Estimation of the parameter $\hat{R}_c(t)$

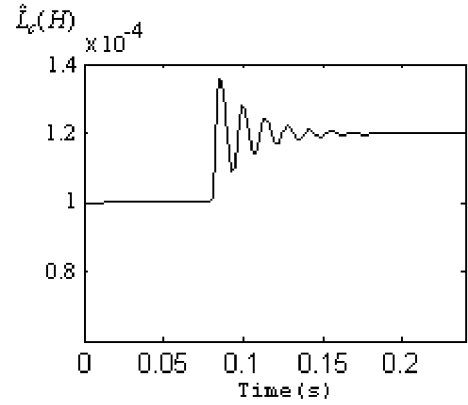


Fig.12 Estimation of the parameter $\hat{L}_c(t)$

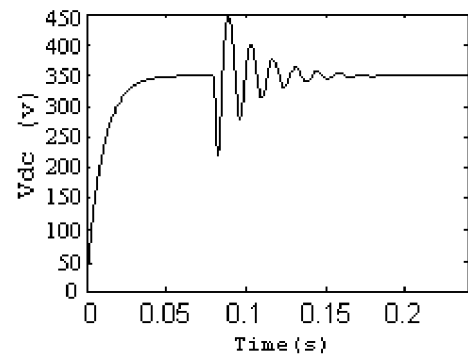


Fig.13 Output DC link voltage response with adaptive law

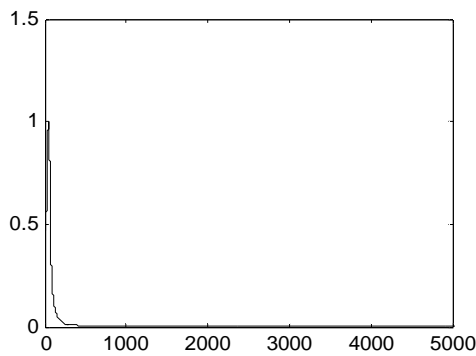


Fig.14 Harmonic spectra of line current

5. Conclusion

We have implemented and simulated the adaptive nonlinear control for an uncertain three phase shunt active power filter, which provides an efficient control design for both tracking and regulation. Global asymptotic stability of the block system is guaranteed. Simulation results obtained were in good performance as it is expected. The strategy control was very robust to uncertain parameters and gave a very high power factor and small ripple in current line supply.

6. References

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