



# A Hybrid Control Method for Stable Operation of Active Power Filters in Three-Phase Four-Wire Networks

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## Abstract

The main goal of this study is the use of Lyapunov's stability theory to a three-phase four-wire shunt active power filter (SAPF), since this method has been applied effectively to other areas of converter. The dynamic model of the SAPF is first established, after that, a combination of fuzzy tracking control and Lyapunov function is suggested in order to impose a desired transient waveform on the considered three-phase four-wire distribution grid, providing robustness and insensitivity to parameter changes. Furthermore, the suggested control technique guarantees appropriate tracking of the reference current components and simplifies the global control design. The feasibility of the suggested control method is validated using comprehensive simulation studies on a four-wire SAPF in order to compensate for nonlinear and unbalanced grid-connected loads in an electrical power distribution network.

**Keywords:** Shunt active power filter (SAPF); Lyapunov function; fuzzy tracking control; three-phase four-wire distribution grid.

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## 1. Introduction

The extreme application of power-electronic devices, that represent nonlinear loads, in an electrical power distribution grid has led to many disturbances in the power quality such as unbalanced currents, pollutions of harmonic currents, and reactive power drawbacks [1]. Consequently, low power factor, weakening efficiency, overheating of transformers and motors, breakdown of sensitive equipments are encountered.

Thus, it is essential to improve the power quality in the electrical grids. Currently, it is well known that harmonic cancelation by means of a shunt active power filter (SAPF) provides superior and more flexible performance in comparison with a passive filter. As a result, the SAPF will be considered in order to enhance the power quality in the paper.

The most significant step for designing the control approach of active filters is the current loop. There are a number of control approaches suggested in the literature for current control of power-electronic converters with SAPF capability namely, proportional-integral (PI) control [2], [3], Lyapunov

function control [4], [5], sliding mode control (SMC) [6], feedback linearization control [7] and hysteresis control [8]. Utilizing the repetitive control technique is an usual scheme for SAPF control, that is generally according to single repetitive control (SRC). By means of the internal model principle [9], SRC has been found to be zero-error controller for the following or cancelation of harmonic currents for pulse width modulated (PWM) converters [10]-[12] and active power filters [13]. Reference [14] has improved the control of SAPFs by the use of feedback linearization method through utilizing power balance in grid side and SAPF sides. In [15], a nonlinear control method for a three-phase three-wire SAPF has been proposed and implemented on an experimental prototype of an SAPF. In [16], different techniques have been compared in order to extract the reference current components for SAPF in four-wire systems. A fuzzy sliding mode control for robot manipulator has reported in [17].

In the proposed research, a hybrid approach for stable operation of an SAPF in three-phase four-wire electrical power distribution networks has been



Consider a single-input single-output system:

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases} \quad (5)$$

where  $x \in R^n$ ,  $f(x), g(x): R^n \rightarrow R^n$ ,  $h(x): R^n \rightarrow R^n$ ,  $f(0) = h(0) = 0$ .

Hence:

$$\dot{y} = \frac{\partial h}{\partial x} \dot{x} = \frac{\partial h}{\partial x} f(x) + \frac{\partial h}{\partial x} g(x)u \quad (6)$$

$$\xrightarrow{\text{def}} \tilde{f}(x) + \tilde{g}(x)u$$

If  $\tilde{g}(x) \neq 0$ , we can write the feedback linearization control law as follows:

$$u = \frac{R - \tilde{f}(x)}{\tilde{g}(x)} \quad (7)$$

Replacing (7) into (6) gives a linear system  $\dot{y} = R$

If position instruction is  $y_m$ , we set  $R$  as:

$$R = \dot{y}_m - \alpha(y - y_m), \alpha > 0 \quad (8)$$

Consequently:

$$\dot{e} + \alpha e = 0 \quad (9)$$

where  $e = y - y_m$ . This implies  $\lim_{t \rightarrow \infty} e(t) = 0$ .

If  $e(0) = \dot{e}(0) = 0$ ,  $e(t)$  is always equal to zero.

#### A) Design of adaptive fuzzy tracking control

We will display how to build adaptive tracking control according to Lyapunov's stability theory to obtain the control objectives. The block diagram of the adaptive tracking control for the SAPF is demonstrated in Fig. 2. Moreover, stability analysis of the considered SAPF is performed for designing the suggested adaptive tracking control.

The dynamic model of the SAPF can be transformed as follows:

$$\begin{aligned} \dot{x} &= f(x) + bu \\ x &= [i_{fa} \quad i_{fb} \quad i_{fc} \quad i_{fn}]^T, \\ f(x) &= -\frac{R_f}{L_f} i_{fk} - \frac{V_{PCCk}}{L_f}, \quad b = \frac{v_{dc}}{L_f}. \end{aligned} \quad (10)$$

The control target is to force the output currents of the SAPF  $x$  track their reference currents  $x_m$ . The tracking error is obtained as  $e = x - x_m$  and the sliding function can be defined in the following form:

$$s(t) = Ke \quad (11)$$

We select the control law as follows:

$$u = \frac{R - \hat{f}(x)}{b} \quad (12)$$

$$R = \dot{x}_m - \eta \text{sgn}(s), \eta > 0 \quad (13)$$

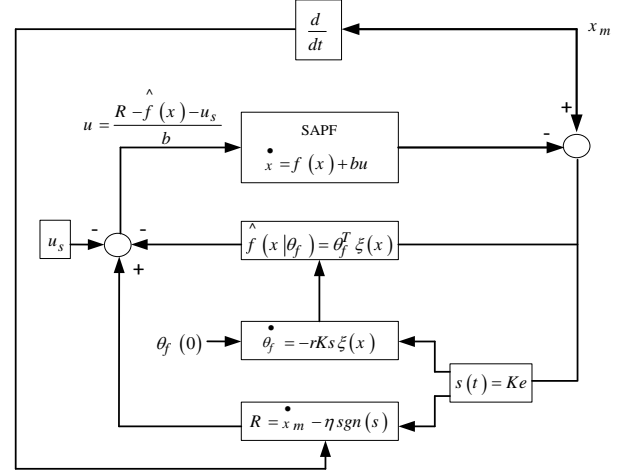


Fig. 2. Adaptive fuzzy tracking control for the SAPF.

Let us define the Lyapunov function as follows:

$$V = \frac{1}{2} s^2 \quad (14)$$

$$\dot{V} = sK \left( \dot{x} - \dot{x}_m \right) = sK \left( f(x) + bu - \dot{x}_m \right) \quad (15)$$

By substituting (12) into (15), we can achieve:

$$\dot{V} = -sK \text{sgn}(s) = -K\eta |s| \quad (16)$$

Subsequently, we deduce  $\dot{V} \leq 0$ . But, since  $f(x)$  is unknown, the control rule, i.e. (12), cannot be used directly. Therefore, the fuzzy logic system  $\hat{f}(x)$  is implemented in order to estimate  $f(x)$  into the following form:

$$\begin{aligned} \hat{f}(x|\theta_f) &= \theta_f^T \xi(x) \\ \xi_j(x) &= \frac{\left( \prod_{i=1}^n \mu_j(x_i) \right)}{\sum_{j=1}^m \left( \prod_{i=1}^n \mu_j(x_i) \right)} \end{aligned} \quad (17)$$

$\xi(x)$  is fuzzy basis function and  $\theta_f^T$  is updated using the following adaptive law:

$$\dot{\theta}_f = -rKs \xi(x), r > 0 \quad (18)$$

In order to enhance the robustness of the proposed control technique, the compensation control  $u_s$  is added to the control law. Thus, the control law can be attained as:

$$u = \frac{R - \hat{f}(x) - u_s}{b} \quad (19)$$

Then we will prove the adaptive law in (18).

Proof : By considering optimal parameter vector:

$$\theta_f^* = \arg \min_{\theta_f \in \Omega_f} \left[ \sup_{x \in R^n} \left| \hat{f} \left( x \mid \theta_f \right) - f(x) \right| \right] \quad (20)$$

where  $\Omega_f$  is assemble for  $\theta_f$  . By considering fuzzy approximation error as follows:

$$E = f(x) - \hat{f}(x, \theta_f^*) \quad (21)$$

where  $E \leq E_{max}$  .

Consequently, the derivative of sliding surface is expressed in the following form:

$$\begin{aligned} \dot{s} &= K \dot{e} = K \left( \dot{x} - \dot{x}_m \right) = K \left[ f(x) + bu - \dot{x}_m \right] \\ &= K \left[ f(x) + R - \hat{f}(x) - u_s - \dot{x}_m \right] \\ &= K \left[ \hat{f}(x, \theta_f^*) - \hat{f}(x) - u_s - \eta \operatorname{sgn}(s) + E \right] \\ &= K \left[ \varphi_f^T \xi(x) - u_s - \eta \operatorname{sgn}(s) + E \right] \end{aligned} \quad (22)$$

where  $\varphi_f = \theta_f - \theta_f^*$  . Let us consider the Lyapunov function as follows:

$$V = \frac{1}{2} \left( s^2 + \frac{1}{r} \varphi_f^T \varphi_f \right) \quad (23)$$

So, the derivative of the Lyapunov function can be achieved as:

$$\begin{aligned} \dot{V} &= s \dot{s} + \frac{1}{r} \varphi_f^T \dot{\varphi}_f \\ &= sK \left[ \varphi_f^T \xi(x) - u_s - \eta \operatorname{sgn}(s) + E \right] + \frac{1}{r} \varphi_f^T \dot{\varphi}_f \\ &= \frac{1}{r} \varphi_f^T \left( rKs \xi(x) + \dot{\varphi}_f \right) + KsE - Ksu_s - Ks\eta \operatorname{sgn}(s) \end{aligned} \quad (24)$$

where  $\dot{\varphi}_f = \dot{\theta}_f$  .

Replacing (18) into (24) yields:

$$\begin{aligned} \dot{V} &= -K\eta|s| + Ks(E - u_s) \leq -K\eta|s| \\ &+ K|s| \left( \sup_{t \geq 0} |E| - u_s \right) \end{aligned} \quad (25)$$

Let  $u_s \geq \sup_{t \geq 0} |E|$  , so  $\dot{V} \leq -K\eta|s| \leq 0$  ,  $\dot{V}$  is negative definite implies that  $V$ ,  $s$  and  $E$  converge to zero.  $\dot{V}$  is negative semi-definite that guarantees  $V$ ,  $s$  and  $E$  are all bounded. Also,  $\dot{s}$  is bounded.  $\dot{V} \leq 0$  implies that  $s$  is integrable as  $\int_0^t \|s\| dt \leq \frac{1}{\rho} [V(0) - V(t)]$ . Since  $V(0)$  is bounded and  $V(t)$  is nonincreasing and bounded,

so  $\lim_{t \rightarrow \infty} \int_0^t \|s\| dt$  is bounded. Since  $\lim_{t \rightarrow \infty} \int_0^t \|s\| dt$  and  $\dot{s}$  are bounded, with regard to Barbalat lemma,  $s(t)$  asymptotically converges to zero,  $\lim_{t \rightarrow \infty} s(t) = 0$ . As a consequence,  $e(t)$  will converge to zero asymptotically by considering the definition of sliding surface, i.e. (11).

#### 4. Results and Discussions

This section represents the results of the simulation carried out in order to validate the performance of the suggested control method for the SAPF for load current balancing, neutral current elimination, harmonic current filtering and reactive power compensation. The simulation parameters are given in appendix's table. The load parameters can be found in [7]. Also, the considered membership function is indicated in Fig. 3.

The grid currents related to three phases and their harmonic spectrum before and after compensation are shown in Figs. 4 and 5. It can be observed that the active filter reduces the total harmonic distortion (THD) of the grid currents from 14.58%, 18.43% and 21.57% to 0.71%, 0.72% and 0.72%, which demonstrates the effectiveness of the suggested nonlinear control technique.

Fig. 6 illustrates the dynamic behavior of the SAPF for the suggested nonlinear controller, where the four-leg active filter has been switched on 0.1 sec later. After 0.1 sec, an extra load has been added in the form of a three-phase diode bridge rectifier.

It can be seen that the grid currents have been balanced and sinusoidal after connection of the SAPF to the system (Fig. 6(a)). As indicated in Fig. 6(d), the neutral current has been almost removed with a low ripple in case where the suggested control method has been applied.

In Fig. 6(e and f), one can see that the reactive power becomes zero and the active power tracks its reference value when the SAPF is connected at  $t=0.1$  sec. For clarity, the grid currents and their corresponding voltages are illustrated in Fig.7. As shown, the unity power factors have been attained successfully.

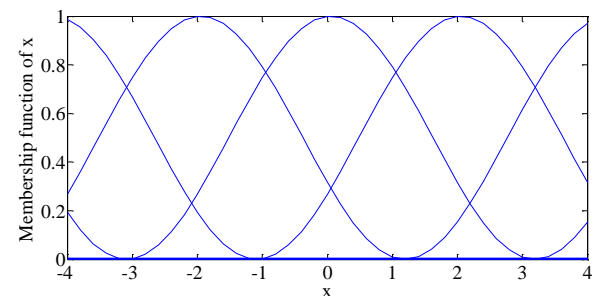


Fig. 3. Membership functions of x.

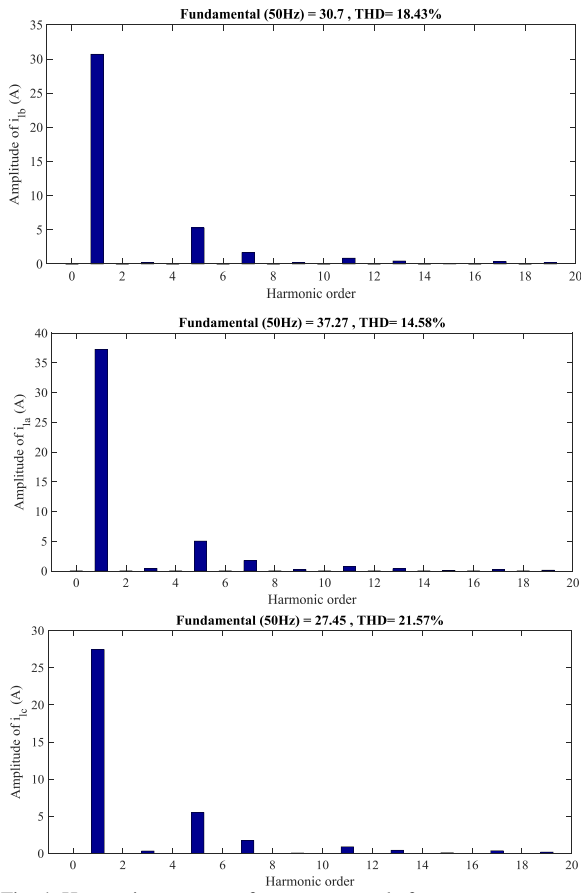


Fig. 4. Harmonic spectrum of source current before compensation.

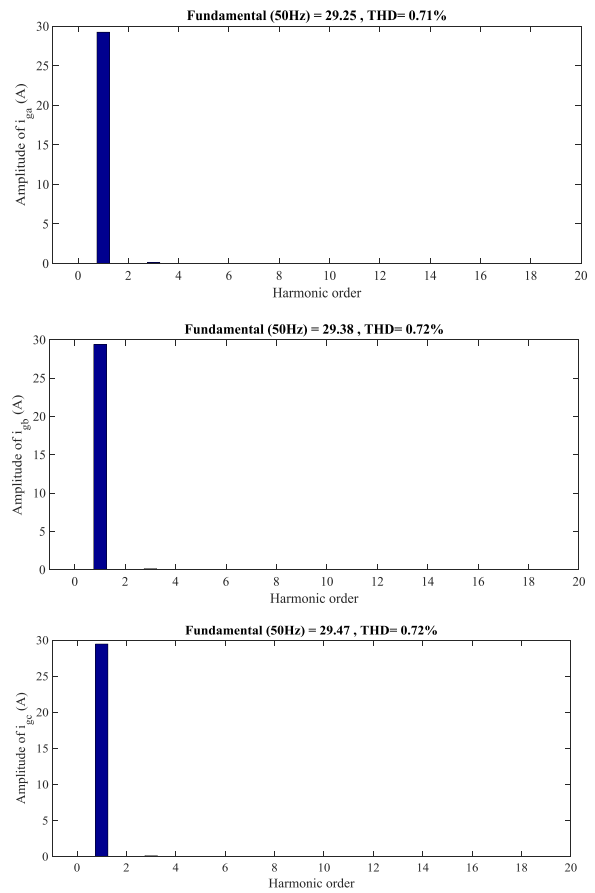
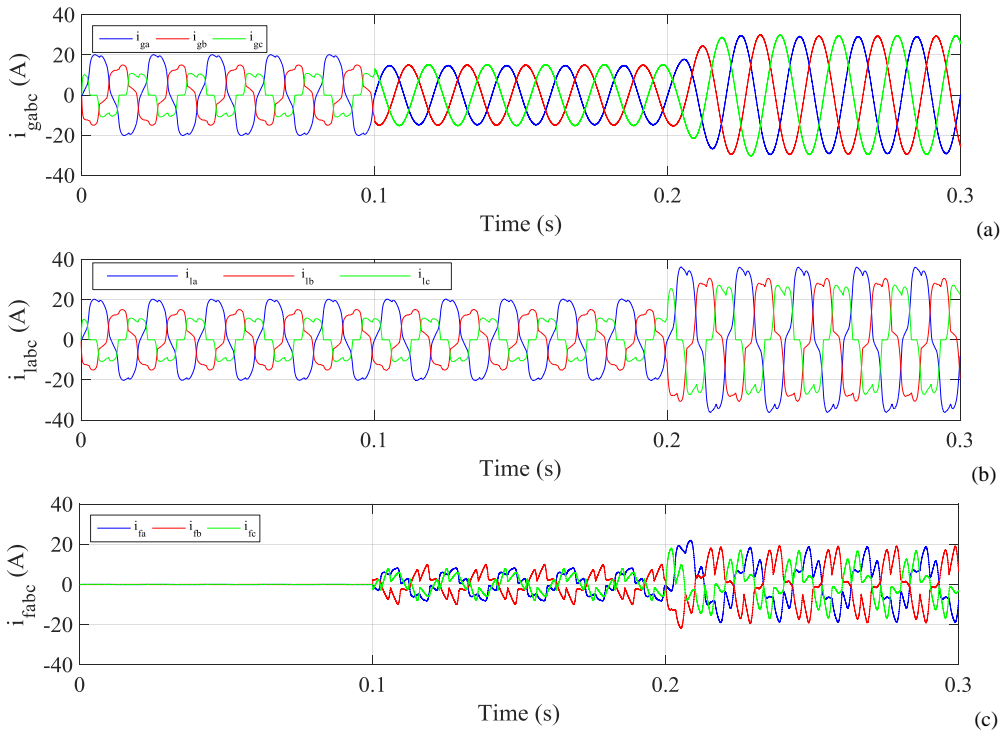


Fig. 5. Harmonic spectrum of source current after ompensation.



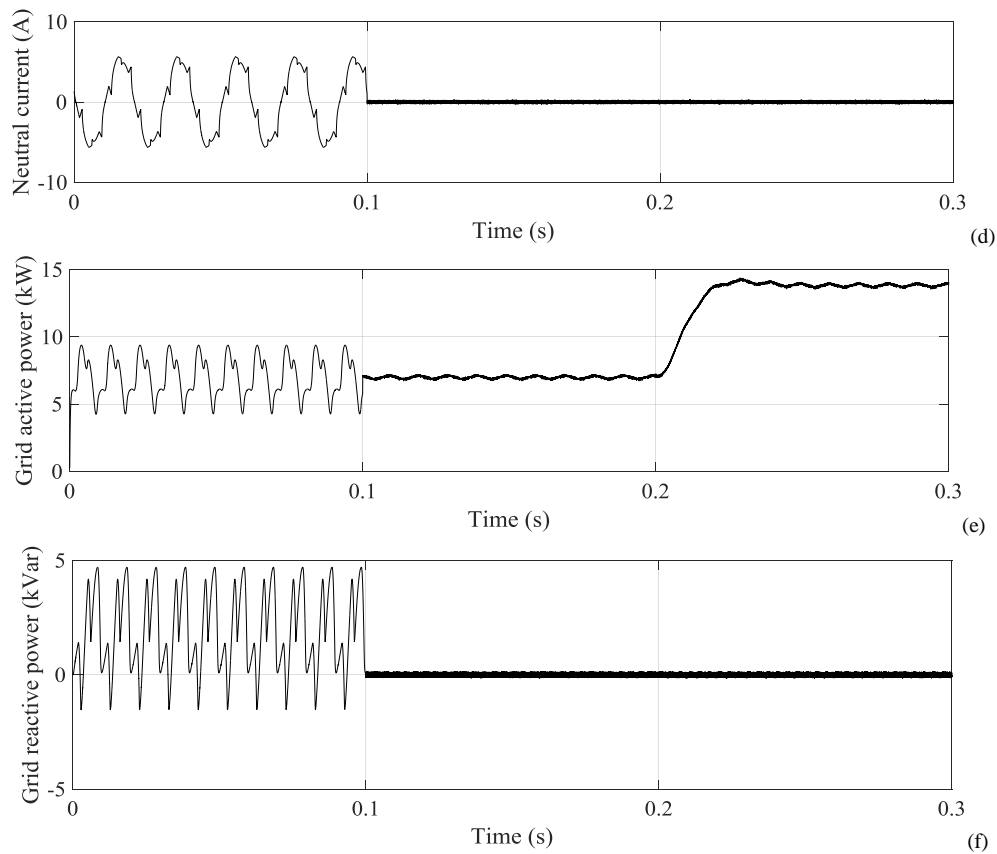


Fig. 6. Simulation results of the proposed SAPF.

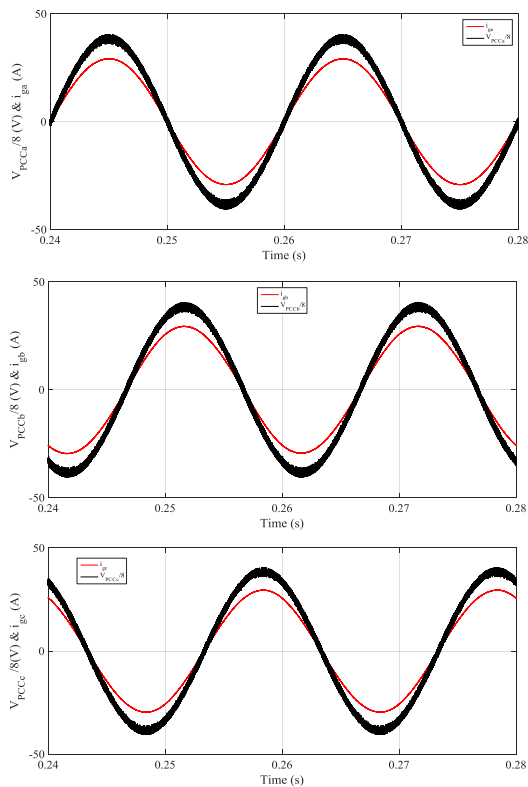


Fig. 7. The Grid currents and voltages

However, the absence of overshoots in the current waveforms under load variation, and low power ripples and neutral current, confirm the appropriate performance of the suggested controller.

**V. Conclusion**

This paper has represented a theoretical study with simulation of adaptive robust fuzzy control combined with Lyapunov’s stability theory for a four-leg SAPF. The performance of the active power filtering system based on the suggested nonlinear control method has been analyzed. The major outcome of the suggested control method is maintenance of the system as stable against the disturbance. Furthermore, the proposed scheme gives good performance during both transient and steady-state operations in terms of the reactive power compensation, grid neutral current cancelation, harmonic currents filtering, and grid current balancing.

## Appendix

Table.1.  
Simulation Parameters

Grid voltage	380 rms V
Grid frequency	50 Hz
Switching frequency	12 kHz
Rated dc-bus voltage	750 V
Filter resistance	0.1 $\Omega$
Filter inductance	0.45 mH
$K$	100
$r$	10000
$u_s$	2.5
$\eta$	10

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