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SHIXI HOU

JUNTAO FEI

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## Robust adaptive fuzzy control of a three-phase active power filter based on feedback linearization

Shixi HOU<sup>1,2,\*</sup>, Juntao FEI<sup>1,2</sup>

<sup>1</sup>College of IOT Engineering, Hohai University, Changzhou, P.R. China

<sup>2</sup>College of Energy and Electrical Engineering, Hohai University, Nanjing, P.R. China

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**Abstract:** In this paper, a robust adaptive fuzzy control system using feedback linearization is proposed for a three-phase active power filter (APF). The APF system is divided into two separate loops: the current dynamic inner loop and the DC voltage dynamic outer loop. Adaptive fuzzy tracking control using feedback linearization is employed for the current dynamic inner loop to overcome the drawbacks of the conventional method. The proposed controller can ensure proper tracking of the reference current and impose desired dynamic behavior, giving robustness and insensitivity to parameter variations. Adaptive fuzzy proportional–integral control is applied to the DC voltage dynamics outer loop to improve the dynamic response and reduce the error of the stable state. Simulation results demonstrate the high performance of the proposed adaptive fuzzy control strategies.

**Key words:** Adaptive fuzzy control, feedback linearization, active power filter

### 1. Introduction

Nonlinear loads often bring harmonic-related problems to industrial power systems, including low power factor, phase distortion, waveform surges, and so on. Shunt active power filters are the most widely used solution since they can efficiently eliminate current distortion and the reactive power. The active power filter (APF) operates by injecting compensation current that is of the same magnitudes and opposite phases with the harmonic currents into the power system to eliminate harmonic contamination and improve the power factor. Compared with conventional current control methods including hysteresis control, single cycle control, and space vector control, many new control strategies have been presented to improve the dynamic response, such as fuzzy control, neural network control, sliding mode control, and adaptive control. Braiek et al. [1] improved the control of an APF using feedback linearization technique by using power balance on the source side and APF sides. Komucugil et al. [2] presented a new control strategy for single-phase shunt active power filters (SAPFs) based on Lyapunov's stability theory. Rahmani et al. [3] proposed a nonlinear control technique for a three-phase SAPF and tested it on a laboratory prototype of an SAPF. Shyu et al. [4] introduced a model reference adaptive control for a single-phase SAPF. Matas et al. [5] developed the application of feedback linearization to a single-phase SAPF. Montero et al. [6] compared different methods for extracting the reference currents for SAPF in three-phase four-wire systems. Valdez et al. [7] showed an adaptive controller for a single-phase APF to compensate for current harmonic distortion. Marconi et al. [8] designed a robust nonlinear controller for SAPF to absorb harmonics.

\*Correspondence: shixi\_hou@yahoo.com

Fuzzy control has achieved many practical successes in industrial processes and many other fields. Wang [9] demonstrated that the fuzzy system can approximate an arbitrary function of a certain set of functions with arbitrary accuracy. Guo et al. [10] developed an adaptive fuzzy sliding mode controller for robot manipulator. Wang et al. [11] proposed indirect adaptive fuzzy sliding mode control by using sliding mode control. Zhou et al. [12] developed adaptive fuzzy tracking control by output feedback for strict nonlinear systems. Jiang et al. [13] developed adaptive fault-tolerant tracking control of a near space vehicle using T-S fuzzy models. Fuzzy control studies have been performed for APF systems in recent years. Bhende et al. [14] proposed the application of a TS fuzzy controller for a three-phase SAPF. Singh et al. [15] developed a fuzzy logic control system based on robust control for an APF to minimize the harmonics. Kumar et al. [16] compared three soft computing control techniques for tracking the reference current of an APF. Lu et al. [17] proposed a simple adaptive fuzzy controller for a single-phase SAPF but the adaptive parameters cannot be insured to be stable. Adaptive fuzzy current control and adaptive control for APF have been investigated in [18].

It is difficult to establish an accurate mathematical model for an APF because of its nonlinearity and coupling, and so there is a great potential applying fuzzy control and other intelligent control to an APF. Fuzzy control is a kind of learning-based control and has strong reasoning ability and so we can apply it to APF. In this paper, a Lyapunov-based adaptive fuzzy logic controller is applied to approximate the unknown nonlinear functions in APF dynamic systems because a conventional linear controller cannot achieve the desired dynamic behavior. An adaptive fuzzy control strategy is utilized to ensure real-time tracking of reference current and strengthen the system robustness. Moreover, adaptive fuzzy control combined with feedback linearization is proposed to improve the current tracking performance and guarantee the Lyapunov stability of the closed-loop system. The motivation of the study regarding robust adaptive fuzzy control using feedback linearization for APF can be emphasized as follows:

- 1) Feedback linearization is applied to a three-phase active power filter, and few works have exploited this control technique in APFs before. This control technique is implemented through adaptive fuzzy control to avoid building an accurate mathematical model of the APF. This makes the control law design simpler and easier to implement. Thus the proposed control system has important theoretical and practical significance for promoting the application of APFs, improving THD, and strengthening the quality of power supply.
- 2) The current inner loop and the DC voltage outer loop are controlled independently using two different nonlinear controllers, named adaptive fuzzy tracking control and adaptive fuzzy PI control. There is only one nonlinear adaptive controller applied to APFs in most in the literature before. The proposed controllers can enhance the dynamic response and robustness of the APF system. Combination of these methods has a general sense and can be extended to other power electronic converter topology.
- 3) There are no relevant research works that combine fuzzy control and sliding mode control with feedback linearization and apply these control methods to APFs so far. This paper combines adaptive control, sliding mode control, fuzzy control, and feedback linearization. A fuzzy controller is proposed to approximate the unknown dynamic model term and feedback linearization is applied to improve the robust design of the control law. The adaptive robust tracking control improves the power dynamic performance such as current tracking and THD performance.

## 2. Principle of active power filter

Shunt active power filters are usually applied to three-phase systems where a large capacity is required. This paper mainly discusses the parallel voltage type of APF, which is the most widely used. In consideration of practical applications, the SAPF is most applied in three-phase systems since it has excellent performance and is easy to be implemented, and so a three-phase three-wire system will be studied in this part and a dynamic analytical model of the APF will be developed.

In practical operation, the APF is equivalent to a flow control current source. The APF contains three sections: a harmonic current detection module, control system, and main circuit. The rapid detection of harmonic current based on instantaneous reactive power theory is most widely used in the harmonic current detection module. The main circuit, which consists of power switching devices, produces compensation currents according to the control signal from the control system. For the sake of absorbing the harmonics created by the nonlinear loads, the compensation currents should be of the same magnitudes and opposite phases as the harmonic currents. Figure 1 shows the structure of the three-phase three-wire APF.

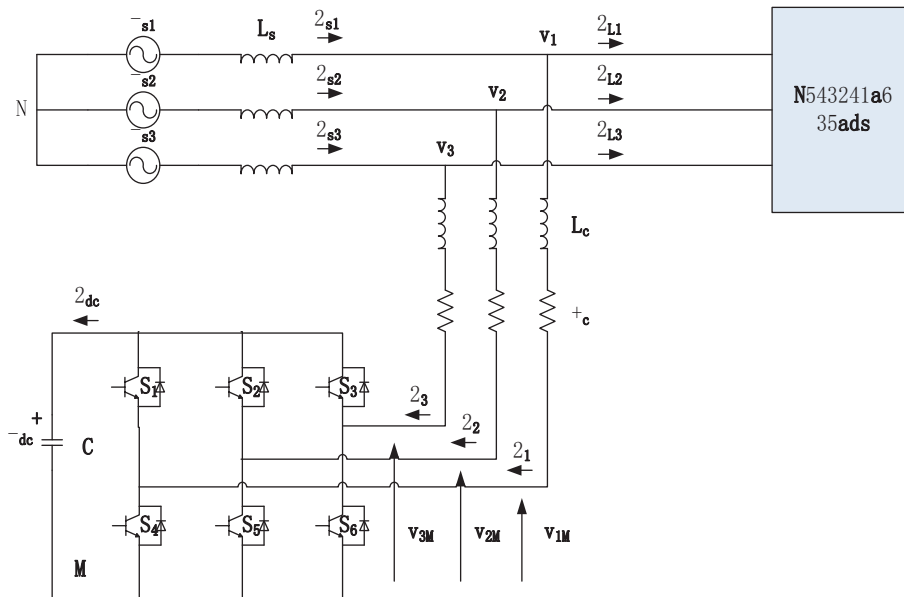


Figure 1. Block diagram for the APF.

The dynamic analytical model of the APF will be proposed in the following section. According to Kirchhoff's voltage and current laws we can get the following circuit equations:

$$\begin{cases} v_1 = L_c \frac{di_1}{dt} + R_c i_1 + v_{1M} + v_{MN} \\ v_2 = L_c \frac{di_2}{dt} + R_c i_2 + v_{2M} + v_{MN} \\ v_3 = L_c \frac{di_3}{dt} + R_c i_3 + v_{3M} + v_{MN} \end{cases} , \quad (1)$$

While  $L_c$  and  $R_c$  are the inductance and resistance of the APF, respectively,  $v_{MN}$  is the voltage between point M and N.

By summing the three equations in (1), taking into account the absence of the zero-sequence in the

three-wire system currents, and assuming that the AC supply voltages are balanced, we can obtain

$$v_{MN} = -\frac{1}{3} \sum_{m=1}^3 v_{mM}, \quad (2)$$

The switching function  $c_k$  denotes the ON/OFF status of the devices in the two legs of the IGBT bridge. We can define  $c_k$  as

$$c_k = \begin{cases} 1, & \text{if } S_k \text{ is On and } S_{k+3} \text{ is Off} \\ 0, & \text{if } S_k \text{ is Off and } S_{k+3} \text{ is On} \end{cases}, \quad (3)$$

where  $k = 1, 2, 3$ .

Hence, by writing  $v_{kM} = c_k v_{dc}$ , (1) becomes

$$\begin{cases} \frac{di_1}{dt} = -\frac{R_c}{L_c} i_1 + \frac{v_1}{L_c} - \frac{v_{dc}}{L_c} (c_1 - \frac{1}{3} \sum_{m=1}^3 c_m) \\ \frac{di_2}{dt} = -\frac{R_c}{L_c} i_2 + \frac{v_2}{L_c} - \frac{v_{dc}}{L_c} (c_2 - \frac{1}{3} \sum_{m=1}^3 c_m) \\ \frac{di_3}{dt} = -\frac{R_c}{L_c} i_3 + \frac{v_3}{L_c} - \frac{v_{dc}}{L_c} (c_3 - \frac{1}{3} \sum_{m=1}^3 c_m) \end{cases}. \quad (4)$$

### 3. Adaptive fuzzy current tracking control

In this section, adaptive robust fuzzy control using feedback linearization is derived to achieve the control purpose and Lyapunov analysis is implemented to guarantee the stability of the closed-loop system.

#### 3.1. Feedback linearization

Consider a single-input single-output (SISO) nonlinear system

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

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

Hence,

$$\begin{aligned} \dot{y} &= \frac{\partial h}{\partial x} \dot{x} = \frac{\partial h}{\partial x} f(x) + \frac{\partial h}{\partial x} g(x)u \\ &\stackrel{\text{def}}{\rightarrow} \tilde{f}(x) + \tilde{g}(x)u. \end{aligned} \quad (6)$$

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

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

Substituting (7) into (6) generates a linear system  $\dot{y} = R$ .

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

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

where  $\alpha > 0$ .

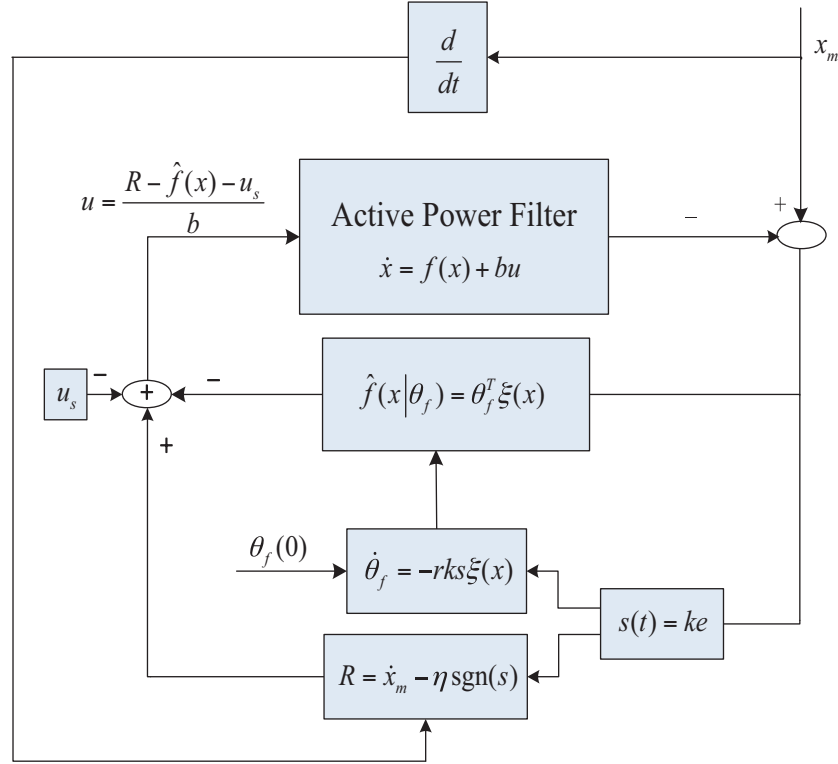
Then we can obtain

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

where  $e = y - y_m$ . That implies  $\lim_{t \rightarrow \infty} e(t) = 0$ . If  $e(0) = \dot{e}(0) = 0$ ,  $e(t)$  will be zero at all times.

### 3.2. Design of adaptive robust fuzzy tracking control

We will show how to construct adaptive robust tracking control using feedback linearization to achieve the control objectives. Figure 2 shows the block diagram of adaptive robust tracking control for the APF. Systematic stability analysis is performed in the design of proposed adaptive robust tracking control. In the following paragraphs, the detailed design steps will be developed.



**Figure 2.** Adaptive robust fuzzy tracking control for the APF.

We can transform the dynamic model of (4) into the following form:

$$\dot{x} = f(x) + bu, \quad (10)$$

where  $x = [i_1 \ i_2 \ i_3]$ ,  $f(x) = -\frac{R_c}{L_c} i_k + \frac{v_k}{L_c}$ ,  $k=1,2,3$ ,  $b = -\frac{v_{dc}}{L_c}$ .

The control target is to make currents  $x$  track the given reference current signal  $x_m$ . The tracking error is defined as  $e = x - x_m$  and the sliding function is designed as

$$s(t) = ke. \quad (11)$$

We choose the control law as

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

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

Define the Lyapunov function candidate:

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

Then

$$\dot{V} = sk(\dot{x} - \dot{x}_m) = sk(f(x) + bu - \dot{x}_m). \quad (15)$$

Substituting (12) into (15) yields

$$\dot{V} = -sk\eta \operatorname{sgn}(s) = -k\eta |s|. \quad (16)$$

Then we can obtain  $\dot{V} \leq 0$ .

However, since  $f(x)$  is unknown, the control law (12) cannot be implemented directly. Therefore, the fuzzy logic system  $\hat{f}(x)$  is employed to estimate  $f(x)$  as

$$\hat{f}(x|\theta_f) = \theta_f^T \xi(x), \quad (17)$$

where  $\xi_j(x) = \frac{\left(\prod_{i=1}^n \mu_j(x_i)\right)}{\sum_{j=1}^m \left(\prod_{i=1}^n \mu_j(x_i)\right)}$  is named the fuzzy basis function.  $\theta_f^T$  can be updated by the following adaptive

law:

$$\dot{\theta}_f = -rks\xi(x), \quad (18)$$

where  $r$  is a positive constant.

To enhance the robustness of the control effect, we add the compensation control  $u_s$  to the control law. Thus the control law can be obtained as

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

Then we will give the proof for the adaptive law in (18).

Proof: Define the optimal parameter vector

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

where  $\Omega_f$  is assembled for  $\theta_f$ .

Define the fuzzy approximation error:

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

where  $|\omega| \leq \omega_{\max}$ .

Then the derivative of sliding surface can be derived as

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

where  $\varphi_f = \theta_f - \theta_f^*$ .

Define the Lyapunov function candidate:

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

Then the derivative of  $V$  can be obtained as

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{r}\varphi_f^T\dot{\varphi}_f \\ &= sk[\varphi_f^T\xi(x) - u_s - \eta\text{sgn}(s) + \omega] + \frac{1}{r}\varphi_f^T\dot{\varphi}_f \\ &= sk\varphi_f^T\xi(x) + \frac{1}{r}\varphi_f^T\dot{\varphi}_f + ksw - k\eta\text{sgn}(s) - ksu_s \\ &= \frac{1}{r}\varphi_f^T(rks\xi(x) + \dot{\varphi}_f) + ksw - ksu_s - k\eta\text{sgn}(s), \end{aligned} \quad (24)$$

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

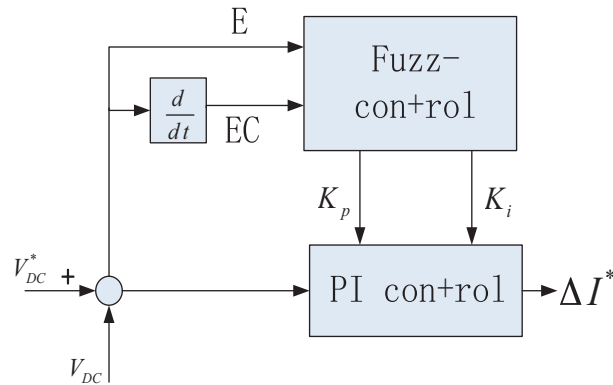
Substituting (18) into (24) yields

$$\dot{V} = -k\eta|s| + ks(\omega - u_s) \leq -k\eta|s| + k|s|(\sup_{t \geq 0}|\omega| - u_s). \quad (25)$$

Let  $u_s \geq \sup_{t \geq 0}|\omega|$ ; then  $\dot{V} \leq -k\eta|s| \leq 0$  and  $\dot{V}$  is negative definite, implying that  $V$ ,  $s$ , and  $\omega$  converge to zero.  $\dot{V}$  is negative semidefinite, ensuring that  $V$ ,  $s$ , and  $\omega$  are all bounded.  $\dot{s}$  is also bounded.  $\dot{V} \leq 0$ , implying 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, then  $\lim_{t \rightarrow \infty} \int_0^t \|s\| dt$  is bounded. Since  $\lim_{t \rightarrow \infty} \int_0^t \|s\| dt$  is bounded and  $\dot{s}$  is also bounded, according to Barbalat's lemma,  $s(t)$  will asymptotically converge to zero,  $\lim_{t \rightarrow \infty} s(t) = 0$ ; then according to the definition of sliding surface (11),  $e(t)$  also converges to zero asymptotically.

#### 4. Adaptive fuzzy PI control for DC voltage

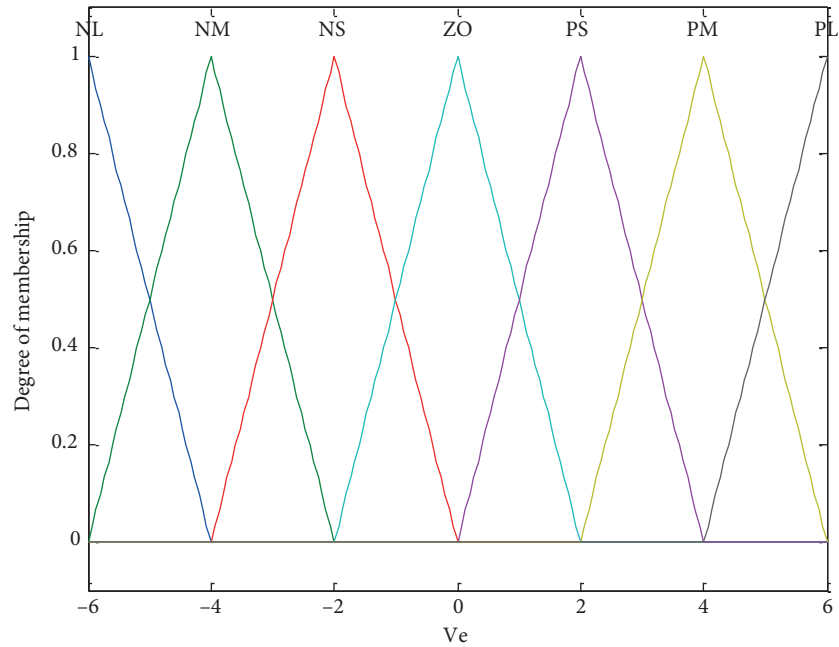
PI control has been widely used for DC voltage in APFs as a traditional control method, but it is not an on-line adaptive tuning algorithm so that its control effect cannot be improved. Therefore, we propose adaptive fuzzy PI control, which combines fuzzy control and PI control. It can change the PI parameter automatically according to the fuzzy control rule. The strategy has strong robustness and ideal control accuracy. The block of adaptive fuzzy PI control is given in Figure 3.



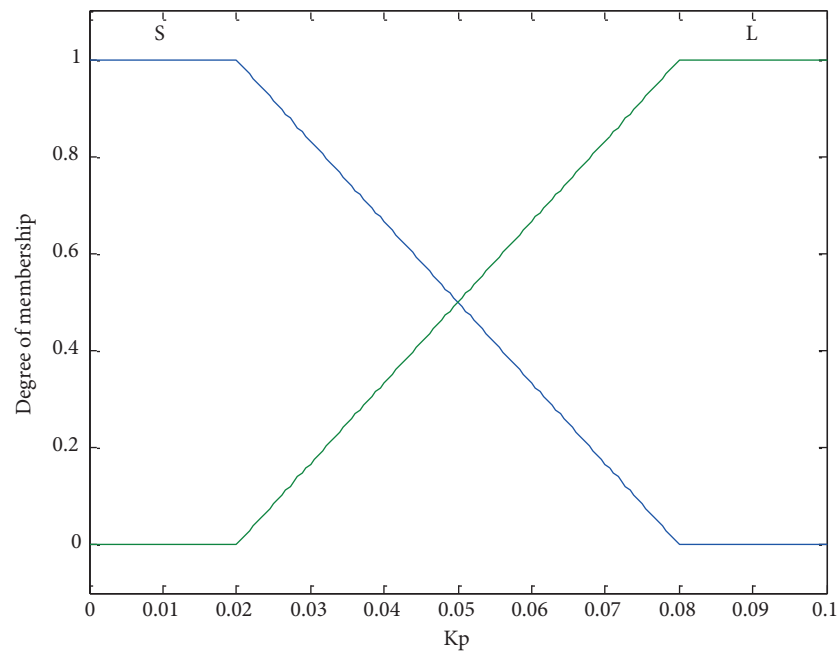
**Figure 3.** The block diagram of adaptive fuzzy PI control.



We choose E and EC as inputs in the range  $(-6, 6)$ , and  $K_p$  and  $K_i$  as outputs in the range  $(0, 0.1)$ . The membership functions are chosen in Figures 4 and 5. The linguistic rules chosen for  $K_p$  and  $K_i$  are shown in Table 1.



**Figure 4.** Membership function for E and EC.



**Figure 5.** Membership function for  $K_p$  and  $K_i$ .

**Table 1.** Fuzzy rules for  $K_p$  and  $K_i$ .

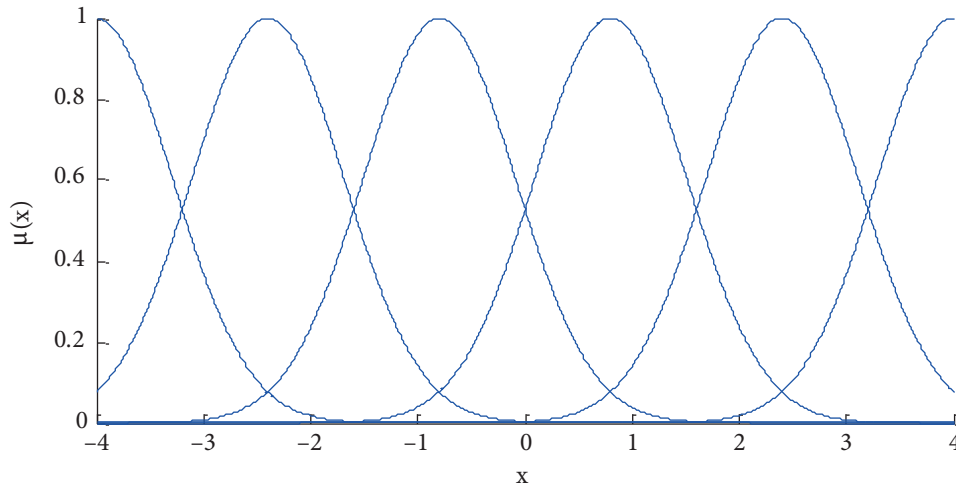
EC \ E	NL	NM	NS	Z	PS	PM	PL
NL	L/L	L/L	L/L	L/L	L/L	L/L	L/L
NM	S/L	L/L	L/S	L/S	L/S	L/L	S/L
NS	S/L	S/L	L/L	L/S	L/L	S/L	S/L
Z	S/L	S/L	S/L	L/S	S/L	S/L	S/L
PS	S/L	S/L	L/L	L/S	L/L	S/L	S/L
PM	S/L	L/L	L/S	L/S	L/S	L/L	S/L
PL	L/L	L/L	L/L	L/L	L/L	L/L	L/L

## 5. Simulation results

In order to validate the correctness and advantage of the proposed two control strategies, the system is simulated using the MATLAB/Simulink package with the SimPower Toolbox. The current loop is controlled via adaptive robust fuzzy control with feedback linearization and the DC voltage loop is controlled through adaptive fuzzy PI control. In the simulation, the behavior of each method and its performances during steady and transient state are analyzed to verify the effectiveness of the proposed adaptive fuzzy strategies.

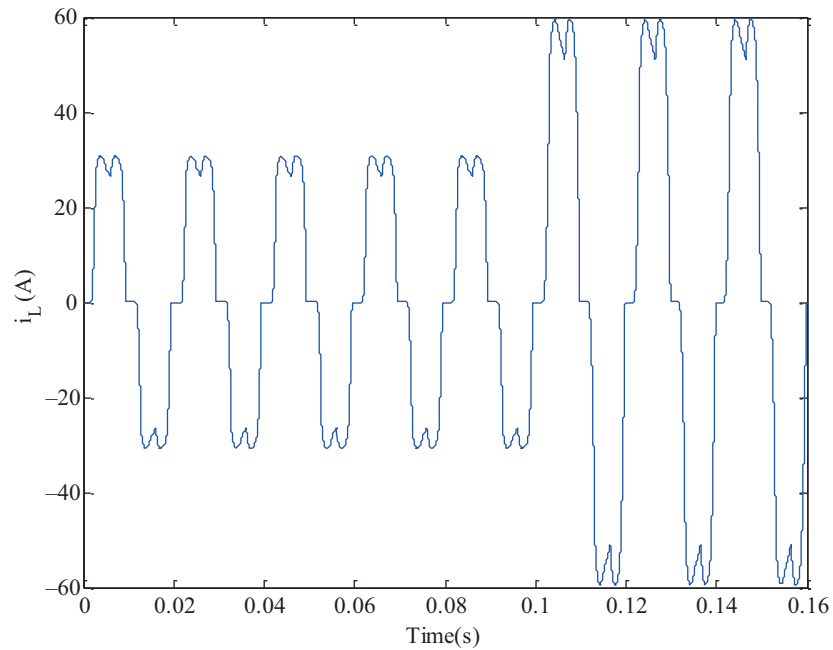
In the adaptive robust tracking control, we choose six membership function as  $\mu(x) = \exp[-(x + 4 - 1.6(i - 1))^2]$ ,  $i = 1, \dots, 6$  which is shown in Figure 6. The sliding function is chosen as  $s = ke$ , where  $k = 100$ ,

$$\text{adaptive gain } r = 10000, u_s = 2.5, \eta = 10, \theta_f = \begin{bmatrix} \theta_{fa} \\ \theta_{fb} \\ \theta_{fc} \end{bmatrix} = \begin{bmatrix} \theta_{fa1} & \theta_{fa2} & \theta_{fa3} & \theta_{fa4} & \theta_{fa5} & \theta_{fa6} \\ \theta_{fb1} & \theta_{fb2} & \theta_{fb3} & \theta_{fb4} & \theta_{fb5} & \theta_{fb6} \\ \theta_{fc1} & \theta_{fc2} & \theta_{fc3} & \theta_{fc4} & \theta_{fc5} & \theta_{fc6} \end{bmatrix}.$$

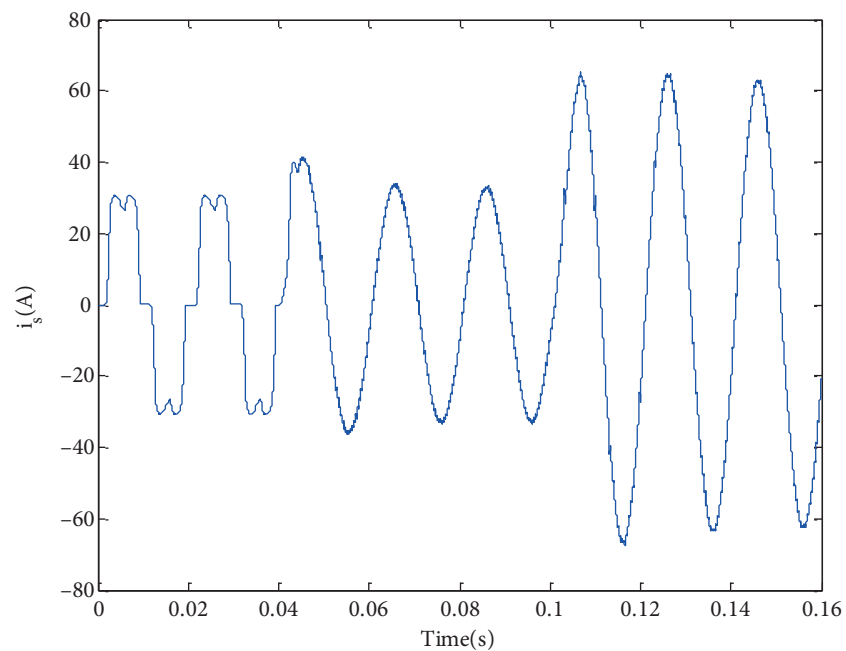

**Figure 6.** Membership function of  $x$ .

The parameters in the adaptive fuzzy PI control are chosen as in section 4.  $V_{s1}=V_{s2} = V_{s3} = 220 V, f = 50 Hz$ . The resistance in the nonlinear load is  $10 \Omega$  and the inductance is  $2 mH$ . The inductance in the compensation circuit is  $10 mH$  and the capacitance is  $100 \mu F$ . When  $t=0.04 s$ , the switch of compensation circuit is closed and the APF begins to work. In practice, nonlinear loads are usually time varying in nature, and so it is necessary to study the dynamic performance of the APF when variations in the nonlinear loads are considered. When  $t=0.1 s$ , the same nonlinear load is added to the circuit.

Figures 7 and 8 show the load current and source current (only one phase current is represented for clarity). It is clearly shown that there is a serious distortion of load current and the total harmonic distortion (THD) is relatively high (24.71% at  $t = 0\text{ s}$  and 22.24% at  $t = 0.1\text{ s}$ ). Moreover, it is observed that the source current is close to the sinusoidal wave and balanced after compensation. The THD is reduced from 24.71% and 22.24% to 1.51% and 1.36% within the limit of the harmonic standard of IEEE of 5%. The results



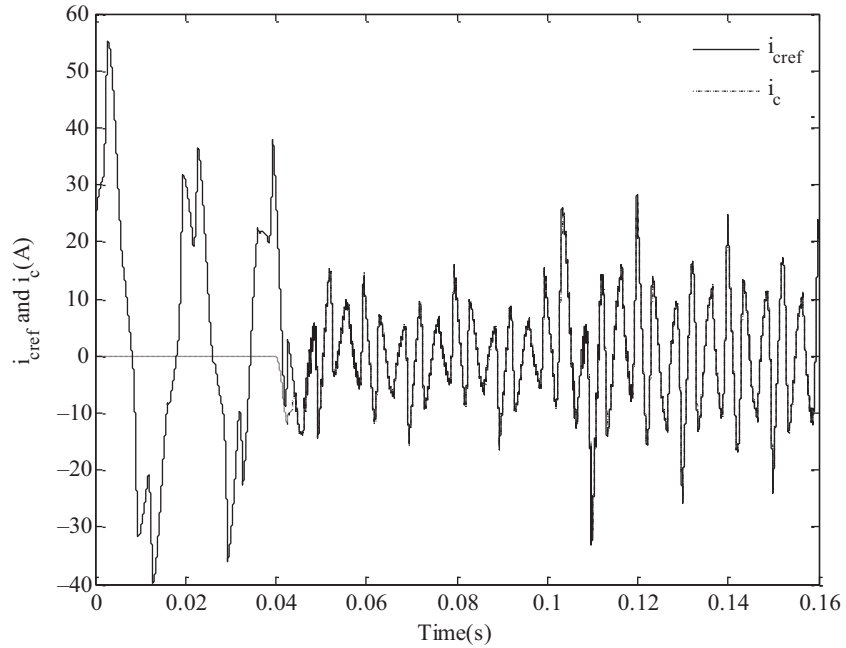
**Figure 7.** Load current.



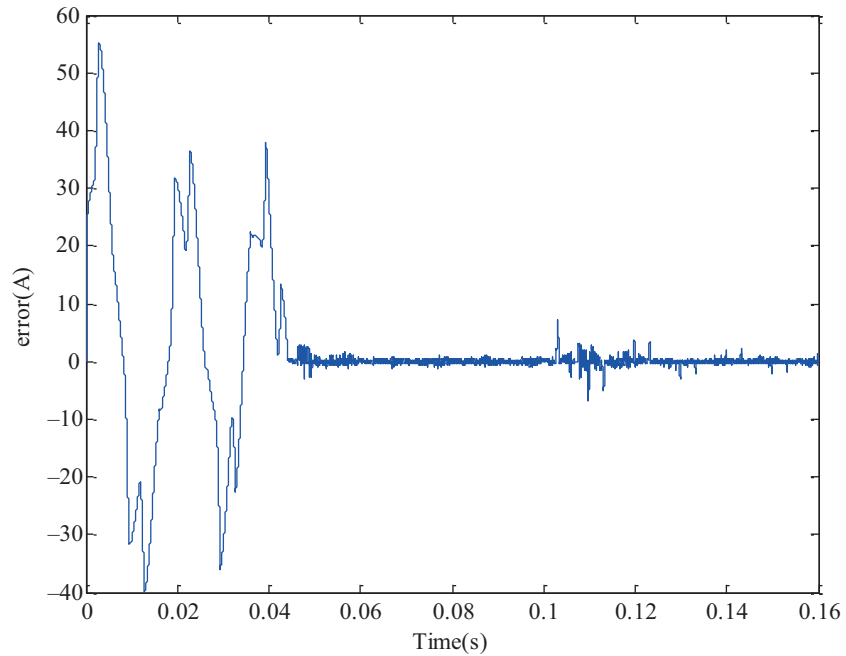
**Figure 8.** Source current.

confirm the capability of the control strategy for the APF to cancel harmonics. In Figure 8, we can see that the transient response time is very short when the nonlinear loads change at  $t=0.1\text{ s}$ , demonstrating that the dynamic performance of the adaptive robust fuzzy control is good.

Figure 9 shows the instruction current and compensation current, and the compensation current tracking error is drawn in Figure 10. It is shown that the compensation current can properly track the instruction current.



**Figure 9.** Instruction current and compensation current.



**Figure 10.** Compensation current tracking error.

It indicates that the proposed adaptive robust tracking control can confirm the capability of asymptotic state tracking. Figure 11 shows the DC capacitor voltage. As shown in Figure 11, the DC capacitor voltage can track the reference voltage, and it tends to be steady state quickly when loads change. It can be concluded that adaptive fuzzy PI control can improve dynamic responses of the system and guarantee accurate voltage tracking. Adaptive parameters of  $\theta_f$  are depicted in Figure 12. The results show that the parameters of the proposed adaptive robust tracking control tend to be constant.

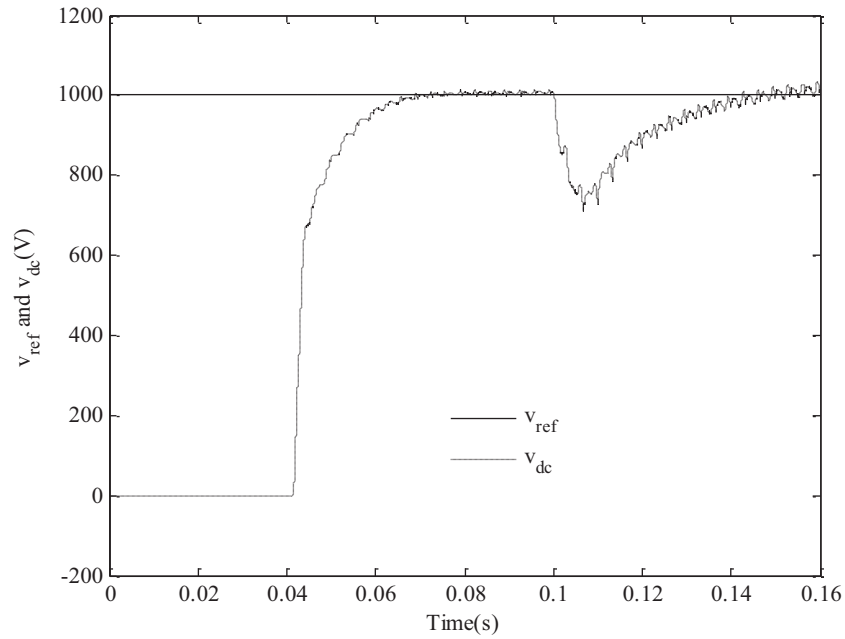


Figure 11. DC capacitor voltage.

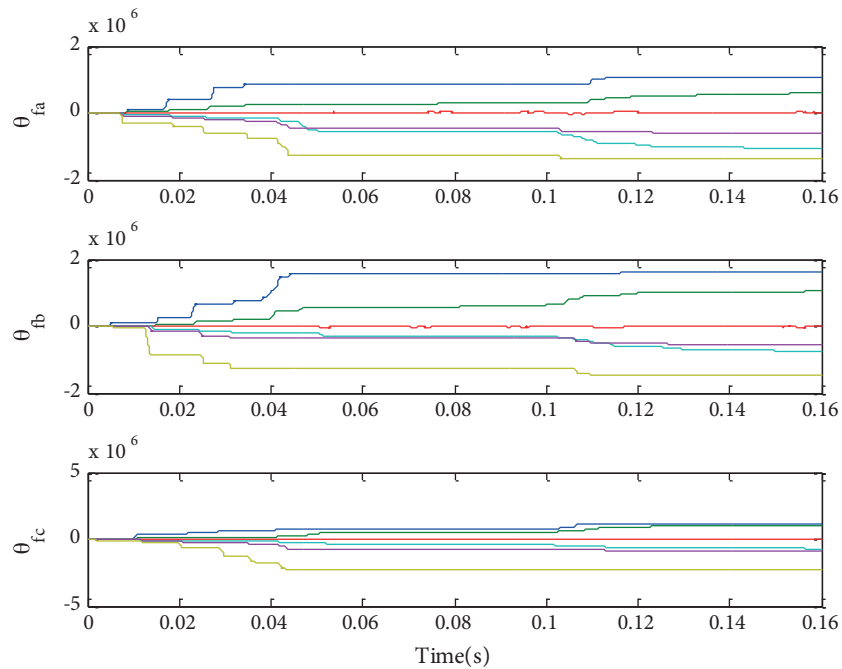


Figure 12. Adaptive law  $\theta_f$ .

In order to illustrate that the proposed adaptive robust tracking control (ARTC) can achieve better performance than the conventional hysteresis control method, we test the APF with parameter variations. Table 2 shows the performance at  $t=0.12$  s. It is noted that THD is always lower than that using hysteresis control with parameter variations. We can say that the adaptive robust tracking control has better control performance compared with the conventional method.

**Table 2.** Performance for variation in filter inductance and DC capacitor using adaptive robust tracking control and hysteresis control.

L (mH) LmH	C ( $\mu F$ ) C (uF)	THD (%)	
		ARTC	Hysteresis control
10	100	1.36	1.41
10	200	1.03	1.24
10	500	0.91	1.53
8	100	1.18	1.31
5	100	1.15	1.33

The results prove that the dynamic response for the APF can be improved based on the proposed adaptive robust tracking control. Moreover, in consideration of practical applications, it is difficult to establish an accurate mathematical model for the APF because of its nonlinearity and coupling, and so there is great potential to apply fuzzy control and other intelligent control to the APF. Fuzzy control is a kind of learning-based control and has strong reasoning ability and so it can be applied to power electronic systems such as APFs. The emergence of the digital signal processor makes the application of the proposed adaptive robust fuzzy control possible, which is the goal in the next stage. Therefore, the proposed control system has important theoretical and practical significance for promoting the application of APFs, improving THD, and strengthening the quality of power supply.

## 6. Conclusion

In this paper, two independent controllers for controlling the current loop and the DC voltage loop of the APF are presented. The current loop uses adaptive robust fuzzy control using feedback linearization and the DC voltage loop utilizes adaptive fuzzy PI control. The parameters of the adaptive robust fuzzy control can be adaptively updated based on Lyapunov analysis. The stability of the closed-loop system can be guaranteed with the proposed control strategy. The proposed adaptive robust fuzzy control is able to keep the THD of the supply current below the limits specified by the IEEE-519 standard, and impose the desired dynamic behavior. The adaptive fuzzy PI control can ensure proper tracking of the reference voltage. The obtained results have demonstrated the high performance of the APF under both dynamic and steady state operations.

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