Hindawi Publishing Corporation
Journal of Applied Mathematics
Volume 2012, Article ID 654937, 13 pages
doi:10.1155/2012/654937

Research Article

Adaptive Fuzzy Control with Supervisory Compensator for Three-Phase Active Power Filter

Juntao Fei and Shixi Hou

Jiangsu Key Laboratory of Power Transmission and Distribution Equipment Technology, College of Computer and Information, Hohai University, Changzhou 213022, China

Correspondence should be addressed to Juntao Fei, jtfei@yahoo.com

Received 30 August 2012; Revised 21 October 2012; Accepted 3 November 2012

Academic Editor: Huijun Gao

An adaptive fuzzy control system with supervisory controller is proposed to improve dynamic performance of three-phase active power filter (APF). The proposed adaptive fuzzy controller for APF does not build an accurate mathematical model but approximates the nonlinear characteristics of APF using fuzzy approximation. The adaptive law based on the Lyapunov analysis can adaptively adjust the fuzzy rules; therefore the asymptotical stability of the adaptive fuzzy control system can be guaranteed. Simulation results demonstrate that the APF control system has excellent dynamic performance such as small current tracking error, reduced total harmonic distortion (THD) index, strong robustness in the presence of parameters variation, and nonlinear load.

1. Introduction

A variety of nonlinear and time-varying electronic devices bring power quality problems to the power system such as low power factor, waveform distortion, surges, and phase distortion problems. Active power filter can be used for power system harmonic suppression and reactive current compensation. The basic principle of APF is to produce compensation current that is of the same amplitude and opposite phase with the harmonic currents to eliminate the unexpected harmonic currents. Therefore active power filters are widely used in many applications to compensate the harmful harmonic currents produced by nonlinear loads on industrial, commercial, and residential equipment.

In the last few years, fuzzy control has been extensively applied in a wide variety of industrial systems and consumer products because of its model-free approach. Wang [1] proposed universal approximation theorem and demonstrated that an arbitrary function of a certain set of functions can be approximated with arbitrary accuracy using fuzzy system on a compact domain. Therefore fuzzy logic system to approximate arbitrary nonlinear functions makes it a useful tool for adaptive application. Guo and Woo [2] proposed adaptive fuzzy sliding mode controller for robot manipulator. Yoo and Ham [3] developed adaptive controller for robot manipulator using fuzzy compensator. In this paper, intelligent controllers like fuzzy logic controller will be investigated to approximate nonlinear dynamic systems as APF. There are many current tracking control methods, such as single cycle control, hysteresis current control, space vector control, sliding mode control, deadbeat control, repetitive control, predictive control, fuzzy control, adaptive control, iterative learning control, and artificial neural network control. Singh et al. [4] presented a simple fuzzy logic-based robust APF for harmonics minimization under random load variation. Bhende et al. [5] developed a TS fuzzy controller for load compensation of APF. Komucugil and Kukrer [6] proposed a new control strategy for single-phase shunt APFs using a Lyapunov function. Rahmani et al. [7] introduced an experimental design of a nonlinear control technique for three-phase shunt APF. Fei and Hou [8] derived robust adaptive fuzzy control for three-phase active power filter. Kumar and Mahajan [9] summarized soft computing techniques for the control of an APF. Chang and Shee [10] proposed novel reference compensation current strategy for shunt APF control. Shyu et al. [11] developed a model reference adaptive control design for a shunt active power filter system. Matas et al. [12] showed a feedback linearization approach of a single-phase APF via sliding mode control. Hua et al. [13] gave control analysis of an APF using Lyapunov candidate. Lu and Xia [14] applied a simple adaptive fuzzy control into the single-phase APF but the asymptotical Lyapunov stability cannot be guaranteed. Montero et al. [15] compared different control strategies for shunt APF in three-phase four-wire systems. Marconi et al. [16] designed an adaptive controller for shunt active filter in the presence of a dynamic load and the line impedance. Different control methods and harmonic suppression approaches for APF have been investigated [17–19]. However, systematic stability analysis and controller design of the adaptive fuzzy controller with application to APF have not been found in the literature. Therefore it is necessary to utilize the adaptive fuzzy control scheme to improve the current tracking and filtering performance. In this paper, a novel adaptive fuzzy control with supervisory controller [3, 20] is developed to improve the control performance and guarantee the Lyapunov stability of the closed-loop system. The contribution of this paper is that it can comprehensively apply adaptive control, fuzzy control, and supervisory compensator to the harmonic current compensation. The control strategy proposed here has the following advantages.

(1) The proposed control strategy does not build accurate mathematical model of APF, which is difficult to obtain and may not give satisfactory performance under parameter variations. In order to eliminate nonzero problem of the fuzzy approximation errors, a supervisory compensator is incorporated into the adaptive fuzzy control scheme in the Lyapunov framework, so the asymptotical stability of closed-loop system can be guaranteed.

(2) An adaptive fuzzy control with supervisory compensator is proposed to deal with system nonlinearities and nonlinear load in order to improve the current tracking and robustness of the control system compared with conventional control method. The robust adaptive fuzzy control method has been extended to the control of APF in this paper. This is a successful application using adaptive control, fuzzy control, and robust compensator with application to the APF. Both of these features are the

innovative development of intelligent adaptive control methods incorporated with conventional control for the APF.

(3) The proposed adaptive fuzzy controller has good application prospects such that it can improve harmonic current tracking and total harmonic distortion (THD). APF system nonlinearities such as nonlinear loads and parameter variations can be compensated, and power dynamic performance and power quality can be improved.

This paper investigates fuzzy control with application to APF; future research directions include neural network control and adaptive fuzzy neural network control which can be utilized to eliminate harmonic current. The paper is organized as follows. Firstly, the principle of SAPF is introduced. Then, adaptive fuzzy controller based on fuzzy logic and Lyapunov method is proposed. Finally, simulations show that the proposed adaptive fuzzy controller not only has good dynamic performance but also improves the robustness of the APF under parameters variation.

2. Principle of Active Power Filter

The shunt APF can be considered to be the most basic structure of APF. This paper mainly studies the most widely used parallel voltage type of APF. In the practical application, the three-phase is the most widely used shunt APF because of its excellent performance characteristics and simplicity in implementation; therefore three-phase three-wire system will be investigated in this section.

In practical operation, APF is equivalent to a flow control current source. The whole APF system consists of three sections, harmonic current detection module, current tracking control module, and compensation current generating circuit. Harmonic current detection module usually uses instantaneous reactive power theory based on rapid detection of harmonic current. Three-phase three-wire APF produces compensation currents with three bridge-arm circuits. In order to eliminate the harmonic components in the currents froms power supply, compensation circuit produces compensation currents that have same amplitude and opposite phase to the harmonic currents.

The block diagram of the three-phase three-wire active power system is given in Figure 1. The principle of APF is to detect voltage and current of compensation object, get command signal i_c^* of compensation current by using operation circuit for instruction current, and then obtain compensation current i_c by PWM generator in order to offset harmonic current and achieve ideal source current.

The mathematical model of APF is described in the next steps. According to circuit theory and Kirchhoff's theorem, the following state equations can be obtained:

$$\begin{aligned}
\dot{i}_{ca} &= -\frac{ri_{ca} + v_{sa}}{L} + \frac{v_{dc}}{L}s, \\
\dot{i}_{cb} &= -\frac{ri_{cb} + v_{sb}}{L} + \frac{v_{dc}}{L}s, \\
\dot{i}_{cc} &= -\frac{ri_{cc} + v_{sc}}{L} + \frac{v_{dc}}{L}s,
\end{aligned} \tag{2.1}$$

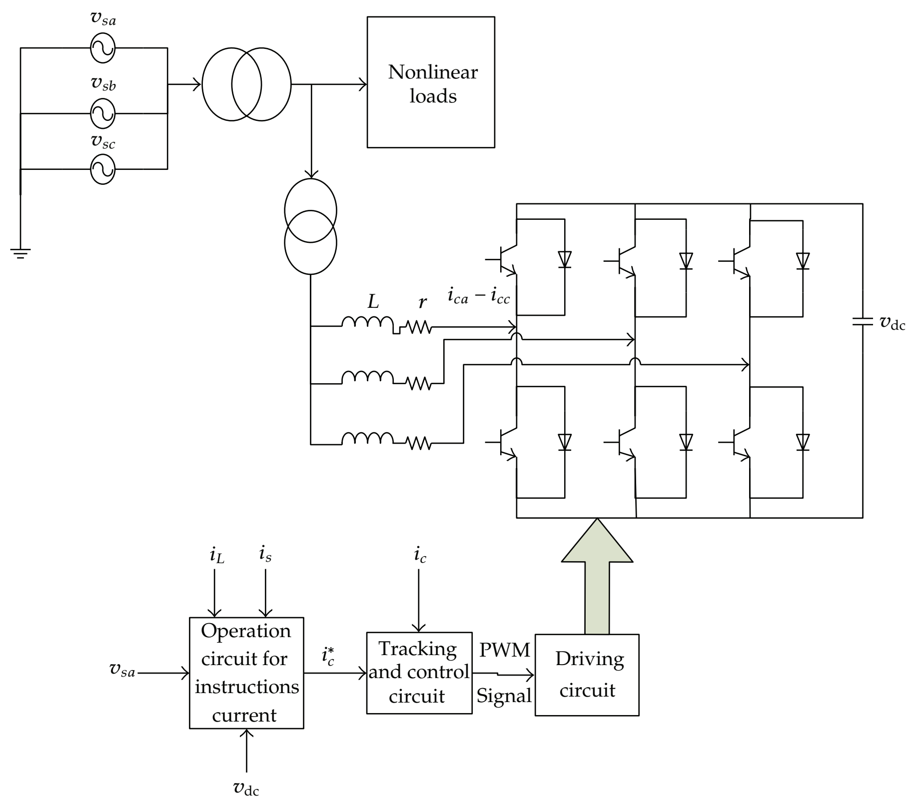

Figure 1: Block diagram for main circuit of APF.

where s is the switching function, denoting the on/off status of the devices in the two legs of the IGBT bridge. We can define s as

$$s = \begin{cases} 1 & Q_N = 1 \\ 0 & Q_N = 0. \end{cases} \tag{2.2}$$

The main voltage of v_{sa}, v_{sb}, and v_{sc} supplies the power for the APF and the nonlinear loads. The parameters of L and r are the inductance and resistance of the APF, respectively.

3. Adaptive Fuzzy Control with Supervisory Compensator

In this section, an adaptive fuzzy control is derived based on Lyapunov analysis to guarantee the asymptotical stability of the closed-loop system. The adaptive control will be approximated by adjusting the parameters of an adequate fuzzy logic system.

3.1. Fuzzy Controller

A fuzzy controller is composed of the following four elements: fuzzier, some fuzzy if-then rules, a fuzzy inference engine, and a defuzzifier. The fuzzy rule basically consists of a collection of fuzzy if-then rules that can be expressed as

$$R^l: \text{ If } x_1 \text{ is } A_1^l \text{ and } \dots\ x_n \text{ is } A_n^l, \text{then } y \text{ is } B^l, \tag{3.1}$$

where A_i^l and B^l are fuzzy sets and $l = 1, \dots, M$, M denotes the number of fuzzy if-then rules. In this paper, the Singleton fuzzifier mapping is adopted, x_i and y have the same kind of member functions that are all Gaussian membership functions defined as

$$\mu_{A_i^l}(x_i) = \exp\left(-\frac{(x_i - c_i)^2}{2\sigma_i^2}\right), \tag{3.2}$$

where c_i and σ_i are the centre and width of the ith fuzzy set A_i^l, respectively.

From the knowledge of the fuzzy systems, the output of the fuzzy system can be expressed using center-average defuzzifier, product inference, and Singleton fuzzifier. Consider

$$y(x) = \frac{\sum_{l=1}^{M} h_l\left(\prod_{i=1}^{n}\mu_{A_i^l}(x_i)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\mu_{A_i^l}(x_i)\right)} = \theta^T\xi(x), \tag{3.3}$$

where $\mu_{A_i^l}(x_i)$ is the membership function value of the fuzzy variable x_i, d_l is the point at which the membership function of B^l achieves its maximum value, $\theta^T = (h_1, h_2, \dots, h_M)$ is adaptive parameter vector, and $\xi(x) = (\xi_1(x), \xi_2(x), \dots, \xi_M(x))^T$ is the vector of the fuzzy basis functions.

3.2. Adaptive Fuzzy Control with Supervisory Compensator

We will show how to construct adaptive fuzzy-sliding control in next steps. The block diagram of adaptive fuzzy control system with supervisory controller for APF is shown in Figure 2. Systematic stability analysis is performed in the design of proposed adaptive fuzzy control with supervisory controller.

We can transform the dynamic model of (2.1) into the following form:

$$\dot{x} = f(x) + bu, \tag{3.4}$$

where $x = [i_{ca}\ i_{cb}\ i_{cc}]$, $f(x) = -(ri_{ck} + v_{sk})/L$, $k = a, b, c$, $b = v_{dc}/L$, and control target is to make current x track the given reference current signal x_m.

The controller is designed as

$$u = u_D(x \mid \theta) + u_s(x) = \theta^T\xi(x) + k_s \operatorname{sgn}\left(e^T P b\right), \tag{3.5}$$

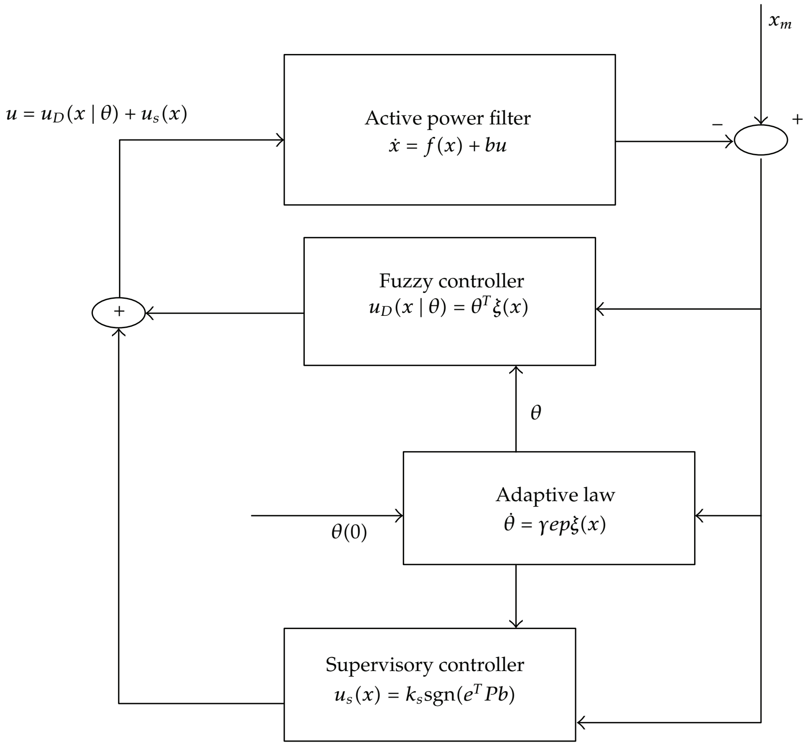

Figure 2: Adaptive fuzzy control block for APF.

where $e = x_m - x$ is tracking error, fuzzy controller $u_D(x \mid \theta) = \sum_i^n \theta_i \xi_i(x) = \theta^T \xi(x)$ as in (3.3), $\xi(x)$ is fuzzy basis function, and supervisory controller $u_s(x) = k_s \,\mathrm{sgn}(e^T P b)$.

Substituting (3.5) into (3.4) yields

$$\dot{e} = -ke + b[u^* - u_D(x \mid \theta) - u_s(x)]. \tag{3.6}$$

Define optimal parameter vector

$$\theta^* = \arg \min_{\theta \in R^m} \left[\sup_{x \in R} |u^* - u_D(x \mid \theta)| \right]. \tag{3.7}$$

Define fuzzy approximation error

$$\omega = u_D(x \mid \theta^*) - u^*. \tag{3.8}$$

Then (3.6) becomes

$$\begin{aligned} \dot{e} &= -ke + b[u_D(x \mid \theta^*) - u_D(x \mid \theta)] - bk_s \mathrm{sgn}\left(e^T P b\right) - b\omega \\ &= -ke + b(\theta^* - \theta)^T \xi(x) - bk_s \mathrm{sgn}\left(e^T P b\right) - b\omega. \end{aligned} \tag{3.9}$$

Theorem 3.1. *A feedback control $u = u_D(x \mid \theta)$ and adaptive law for adjusting parameters vector $\theta(t)$ are designed to satisfy that the closed-loop system must be asymptotically stable in the sense that all variables, $x(t)$, $\theta(t)$, and $u_D(x \mid \theta)$ must be uniformly stable and the current tracking error $e(t)$ should be as small as possible.*

Proof. Define Lyapunov function candidate

$$V = \frac{1}{2}pe^2 + \frac{b}{2\gamma}\tilde{\theta}^T\tilde{\theta}, \tag{3.10}$$

where γ is a positive constant, $\tilde{\theta} = \theta^* - \theta$, and p is the positive constant satisfying the following condition:

$$\left(-k^T\right)p + p(-k) = -q. \tag{3.11}$$

Then we can obtain $2pk = q$.

Differentiating V with respect to time yields

$$\dot{V} = -\frac{1}{2}qe^2 + \frac{b}{\gamma}\tilde{\theta}^T\left[\gamma ep\xi(x) - \dot{\theta}\right] - epbk_s\operatorname{sgn}\left(e^TPb\right) - epb\omega. \tag{3.12}$$

Then the adaptive law can be chosen as

$$\dot{\theta} = \gamma ep\xi(x), \tag{3.13}$$

where γ is the adaptive gain.

Substituting (3.13) into (3.12) yields

$$\dot{V} = -\frac{1}{2}qe^2 - epbk_s\operatorname{sgn}\left(e^TPb\right) - epb\omega \le -\frac{1}{2}qe^2 + |epb|\left(\sup_{t\ge 0}|\omega| - k_s\right). \tag{3.14}$$

Choosing $k_s \ge \sup_{t\ge 0}|\omega|$, (3.14) becomes

$$\dot{V} \le -\frac{1}{2}qe^2 < 0. \tag{3.15}$$

Then we can obtain $\dot{V} \le 0$; $\dot{V}$ is negative definite which implies that V, s, and ω converge to zero. The fact that $\dot{V}$ is negative semidefinite ensures that V, e, and $\tilde{\theta}$ are all bounded. $\dot{e}$ is also bounded. Inequality (3.15) implies that e is integrable as $\int_0^t e^2 dt \le (1/q)[V(0) - V(t)]$. Since $V(0)$ is bounded and $V(t)$ is nonincreasing and bounded, it can be concluded that $\lim_{t\to\infty}\int_0^t e^2 dt$ is bounded. Since $\lim_{t\to\infty}\int_0^t e^2 dt$ is bounded and $\dot{e}$ is also bounded, according to the Barbalat lemma, $e(t)$ will asymptotically converge to zero, $\lim_{t\to\infty} e(t) = 0$. □

Remark 3.2. From the universal approximation theorem, ω can be made to be arbitrarily small using fuzzy system on a compact domain. Because of fuzzy approximation error, ω cannot always be equal to zero. The fact that ω is equal to zero can only be realized in the ideal situation. This will result that the stability of the control system cannot be guaranteed. In order to solve such problem, a supervisory controller u_s is added with u_D as in (3.5) to eliminate the negative influence of the fuzzy approximation errors and guarantee the stability.

4. Simulation Study

The performance of the proposed adaptive fuzzy control will be tested using Matlab/Simulink package with SimPower Toolbox. Simulation results are presented to verify the effectiveness of the proposed adaptive fuzzy control.

Membership functions of fuzzy controller are chosen as

$$\mu = \exp\left(-\frac{x + 15 - (i-1)7.5}{3.75}\right), \quad i = 1, \ldots, 6. \tag{4.1}$$

We define membership function of sliding function s as

$$m_{\text{NM}}(s) = \frac{1}{1 + \exp(5(s+3))}, \qquad m_{\text{ZO}}(s) = \exp\left(-s^2\right), \qquad m_{\text{PM}}(s) = \frac{1}{1 + \exp(5(s-3))}. \tag{4.2}$$

The parameters in the simulation of adaptive fuzzy control of APF are chosen as follows: $k = 2$, $q = 50$ in (3.11), adaptive gain $\gamma = 500$ in (3.13), $k_s = 2.5$ in (3.14), PI control is adopted for DC voltage in active power filter and the parameters of PI controller are chosen as $k_p = 0.05$ and $k_i = 0.01$ to achieve satisfactory performance, the inductance in the circuit of APF is 10 mh, and the capacitance is 100 μF.

A phase-source current before and after APF works is shown in Figure 3. Current harmonic analysis for the first two circles and last two cycles are depicted in Figures 4–5. The APF begins to work at 0.04 s when the break is closed. It can be seen that the waves of source current distort because of 5th, 7th, 11th, and 13th harmonics before 0.04 s and the source currents recover steady state after half cycle about 0.01 s, then it can be observed that 5th, 7th, 11th, and 13th harmonics are fully eliminated as expected after 0.04 s. The THD is 24.71% before harmonic compensation and 1.72% after harmonic compensation that is within the limit of the harmonic standard of IEEE of 5%. It can be observed that the supply current is close to sinusoidal wave and it remains in phase with the supply voltage, demonstrating that APF can eliminate the harmonic current generated by the nonlinear loads and perform well in the steady state operation. It can be concluded that the proposed adaptive fuzzy control with supervisory controller has an excellent dynamic performance, such as satisfactory and quick responses.

Instruction current and compensation current are drawn in Figure 6, showing that the tracking error is large from 0.04 s to 0.045 s, but after 0.045 s the tracking error is almost zero, so compensation current can track the setting current very well. This means that the proposed adaptive fuzzy control with supervisory controller can guarantee asymptotic output tracking, so it is obvious that the proposed adaptive fuzzy control with supervisory controller can track the ideal current. Therefore the harmonic current can be effectively compensated, and harmonic distortion of source current can be reduced. The adaptation values of $\theta 1$, $\theta 2$, and $\theta 3$ of adaptive fuzzy controller in (3.13) are depicted in Figure 7, showing that the parameters

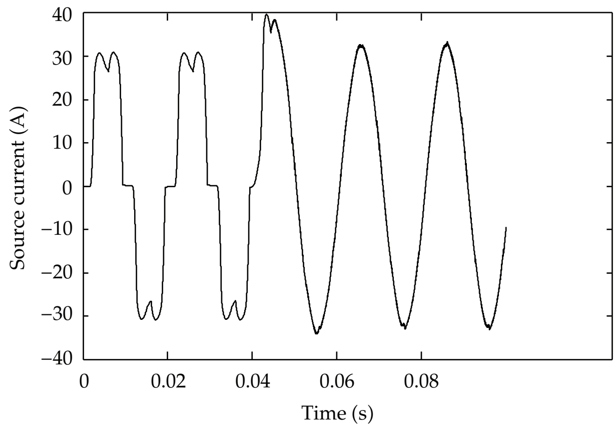

Figure 3: A phase source current.

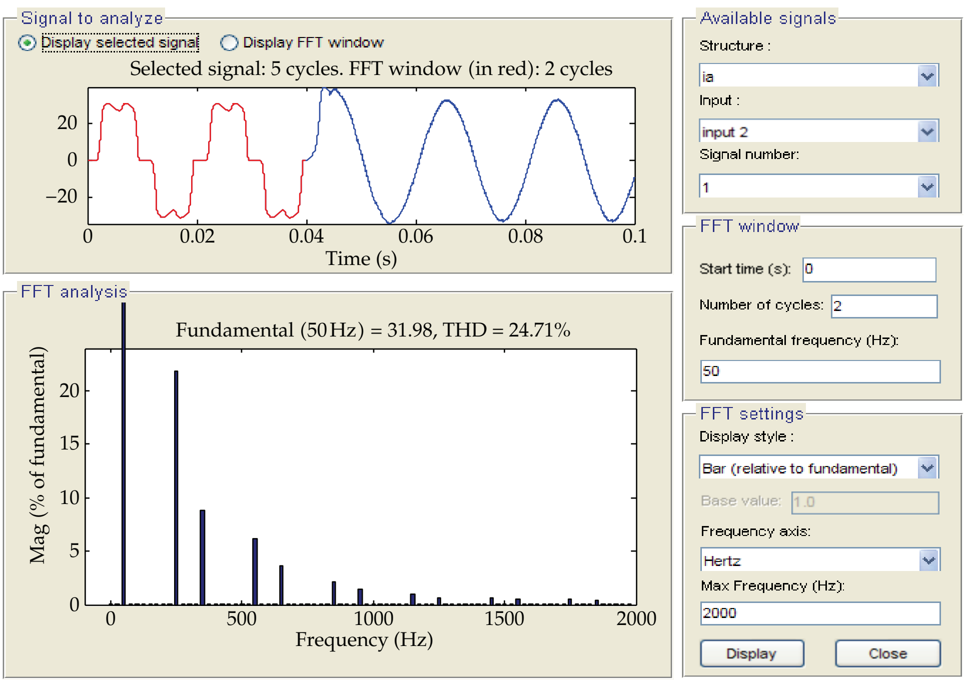

Figure 4: Current harmonic analysis for the first two circles.

respond fast after 0.04 s and most of the parameters can tend to be stable at 0.05 s. It is demonstrated that the parameters of the proposed adaptive fuzzy controller converge to stable constant values. Therefore the adaptive fuzzy control with supervisory compensator can guarantee that the closed-loop system is asymptotically stable. As can be seen from Figure 8, DC capacitor voltage is stable after 0.06 s by using PI controller. It can be seen that DC capacitor voltage is not constant, and it has ripples. But since it is approximately stable, it is acceptable in fact.

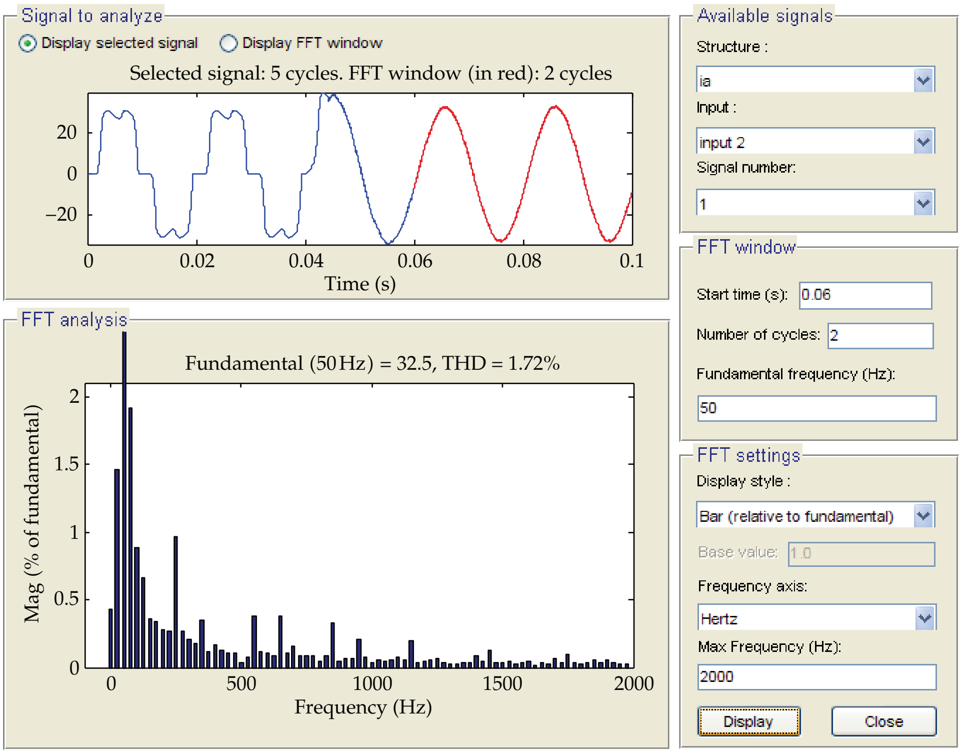

Figure 5: Current harmonic analysis for the last two circles.

Table 1: Performance for variation in filter inductance and DC capacitor.

L (mH)	C (uF)	THD (%)
10	100	1.72
10	200	1.51
10	1000	2.58
8	100	1.65
5	100	1.68

In order to demonstrate that the proposed adaptive fuzzy control with supervisory controller has strong robustness in the presence of parameters variation, we will test the APF with the parameters variation. Current waveforms are not presented, but the performance is listed in Table 1. The THD values are measured in the time range from 0.06 s to 0.1 s. It can also be seen that THD values are still in the normal range with the parameters variation. Therefore the proposed adaptive fuzzy control with supervisory controller has good robustness to the parameter uncertainties.

It can be concluded that the current tracking and THD performance can be improved by using the proposed adaptive fuzzy control with supervisor compensator. Thus the control performance and robustness to external disturbance can be improved, and the asymptotical stability of the APF control system can be guaranteed.

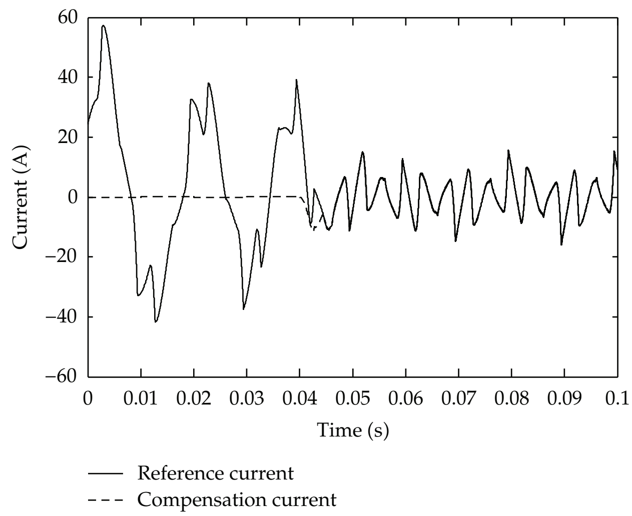

Figure 6: Instructions current and compensation current.

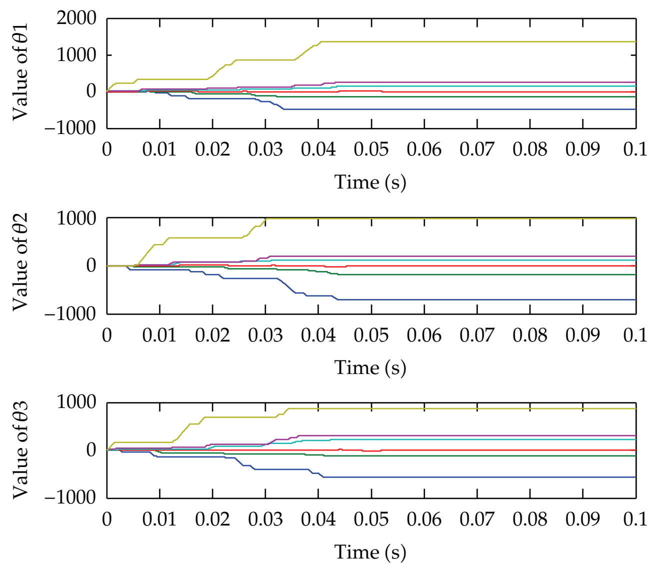

Figure 7: Adaptive values $\theta 1$, $\theta 2$, and $\theta 3$ of adaptive fuzzy controller.

5. Conclusion

An improved direct adaptive fuzzy control system with supervisory controller has been applied to the three-phase APF. The proposed adaptive fuzzy controller can effectively eliminate the reactive and harmonic component of the load current. The designed controller can guarantee the asymptotic output tracking of the closed-loop system, and the compensation current can follow the tracks of instruction current. The designed active power filter has superior harmonic treating performance and minimizes the harmonics for wide range of variation of load current under different nonlinear loads; therefore the

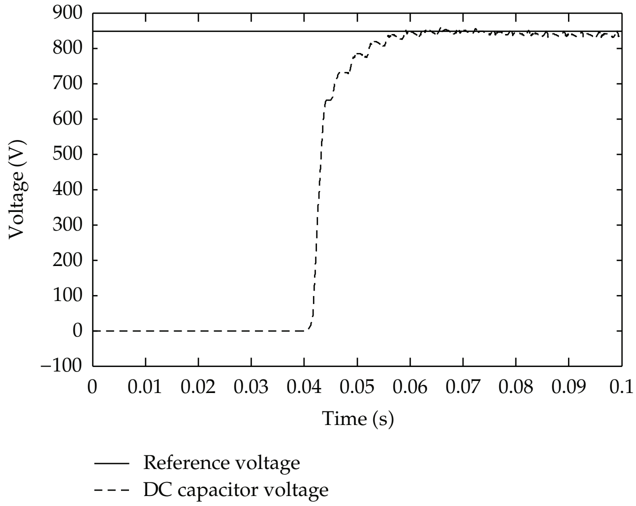

Figure 8: DC capacitor voltage.

proposed control scheme yields improved THD values. Simulation results demonstrated the excellent dynamic performance, stability, and strong robustness with the proposed controller. However, real-time experiment should be investigated to verify the performance of the harmonic suppression. Other intelligent control strategies such ad neural network control and adaptive fuzzy neural network control for the APF can be investigated to eliminate harmonic current.

Acknowledgments

The authors thank the anonymous reviewers for useful comments that improved the quality of the paper. This work is partially supported by National Science Foundation of China under Grant no. 61074056, the Graduate Science. Technology and Innovation project of Hohai University Changzhou under grand No. CGB014-05, the Scientific Research Foundation of High-Level Innovation and Entrepreneurship Plan of Jiangsu Province, and the Fundamental Research Funds for the Central Universities under Grant no. 2012B06714.

References

[1] L. Wang, *Adaptive Fuzzy Systems and Control-Design and Stability Analysis*, Prentice Hall, NJ, USA, 1994.
[2] Y. Guo and P. Y. Woo, "An adaptive fuzzy sliding mode controller for robotic manipulators," *IEEE Transactions on Systems, Man, and Cybernetics Part A*, vol. 33, no. 2, pp. 149–159, 2003.
[3] B. K. Yoo and W. C. Ham, "Adaptive control of robot manipulator using fuzzy compensator," *IEEE Transactions on Fuzzy Systems*, vol. 8, no. 2, pp. 186–199, 2000.
[4] G. K. Singh, A. K. Singh, and R. Mitra, "A simple fuzzy logic based robust active power filter for harmonics minimization under random load variation," *Electric Power Systems Research*, vol. 77, no. 8, pp. 1101–1111, 2007.
[5] C. N. Bhende, S. Mishra, and S. K. Jain, "TS-fuzzy-controlled active power filter for load compensation," *IEEE Transactions on Power Delivery*, vol. 21, no. 3, pp. 1459–1465, 2006.
[6] H. Komucugil and O. Kukrer, "A new control strategy for single-phase shunt active power filters using a Lyapunov function," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 1, pp. 305–312, 2006.

[7] S. Rahmani, N. Mendalek, and K. Al-Haddad, "Experimental design of a nonlinear control technique for three-phase shunt active power filter," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 10, Article ID 5373908, pp. 3364–3375, 2010.

[8] J. Fei and S. Hou, "Robust adaptive fuzzy control for three-phase active power filter," in *Proceedings of the 13th Workshop on Control and Modeling for Power Electronics (COMPEL '12)*, pp. 1–6, Kyoto, Japan, 2012.

[9] P. Kumar and A. Mahajan, "Soft computing techniques for the control of an active power filter," *IEEE Transactions on Power Delivery*, vol. 24, no. 1, pp. 452–461, 2009.

[10] G. W. Chang and T. C. Shee, "A novel reference compensation current strategy for shunt active power filter control," *IEEE Transactions on Power Delivery*, vol. 19, no. 4, pp. 1751–1758, 2004.

[11] K. K. Shyu, M. J. Yang, Y. M. Chen, and Y. F. Lin, "Model reference adaptive control design for a shunt active-power-filter system," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 1, pp. 97–106, 2008.

[12] J. Matas, L. G. de Vicuna, J. Miret, J. M. Guerrero, and M. Castilla, "Feedback linearization of a single-phase active power filter via sliding mode control," *IEEE Transactions on Power Electronics*, vol. 23, no. 1, pp. 116–125, 2008.

[13] C. C. Hua, C. H. Li, and C. S. Lee, "Control analysis of an active power filter using Lyapunov candidate," *IET Power Electronics*, vol. 2, no. 4, pp. 325–334, 2009.

[14] Y. Lu and C. Xia, "Improved direct adaptive fuzzy controller for single-phase active power filter," in *Proceedings of the 5th International Conference on Fuzzy Systems and Knowledge Discovery, (FSKD '08)*, pp. 90–94, Jinan Shandong, China, October 2008.

[15] M. I. M. Montero, E. R. Cadaval, and F. B. González, "Comparison of control strategies for shunt active power filters in three-phase four-wire systems," *IEEE Transactions on Power Electronics*, vol. 22, no. 1, pp. 229–236, 2007.

[16] L. Marconi, F. Ronchi, and A. Tilli, "Robust nonlinear control of shunt active filters for harmonic current compensation," *Automatica*, vol. 43, no. 2, pp. 252–263, 2007.

[17] L. Asiminoaei, F. Blaabjerg, S. Hansen, and P. Thøgersen, "Adaptive compensation of reactive power with shunt active power filters," *IEEE Transactions on Industry Applications*, vol. 44, no. 3, pp. 867–877, 2008.

[18] L. H. Tey, P. L. So, and Y. C. Chu, "Improvement of power quality using adaptive shunt active filter," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1558–1568, 2005.

[19] A. A. Valdez, G. Escobar, and R. Ortega, "An adaptive controller for the shunt active filter considering a dynamic load and the line impedance," *IEEE Transactions on Control Systems Technology*, vol. 17, no. 2, pp. 458–464, 2009.

[20] S. Tong and J. Zhou, "Design and stability of fuzzy indirect and direct adaptive control for nonlinear system," *Journal of Control and Decision*, vol. 15, no. 3, pp. 293–296, 2000.