International Journal of Innovative Computing, Information and Control
Volume **11**, Number **2**, April **2015**

ICIC International ©2015 ISSN 1349-4198
pp. 497–507

HARMONIC SUPPRESSION OF THREE-PHASE ACTIVE POWER FILTER USING BACKSTEPPING APPROACH

Yunmei Fang[1], Shixi Hou[2] and Juntao Fei[2]

[1]College of Mechanical and Electrical Engineering
[2]College of Computer and Information
Hohai University
No. 200, North Jinling Road, Changzhou 213022, P. R. China
bigboyscn@yahoo.com

Received April 2014; revised August 2014

Abstract. *A backstepping controller (BC) is developed to eliminate harmonic contamination and improve the quality of power supply for three-phase active power filter (APF) in this paper. To deal with the nonlinearity of APF, the backstepping method is applied in the design of current tracking control system. The proposed backstepping controllers can ensure proper tracking of the reference current, and impose a desired dynamic behavior, giving robustness and insensitivity to parameter variations. Simulation studies using the MATLAB/SimPowerSystems Toolbox demonstrate the high performance of the proposed control strategy.*

Keywords: Backstepping control, Harmonic compensation, Total harmonic distortion, Active power fitler

1. **Introduction.** Power electronic technology brings great convenience to our daily life, however nonlinear loads often bring harmonic-related problems to the industrial power systems including low power factor, phase distortion, waveform surges and so on. Shunt active power filters are the most widely used solution because they can efficiently eliminate current distortion and the reactive power. The APF operates by injecting compensation current which 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 designed to improve the dynamic response, such as sliding control, and adaptive control.

In recent years, scholars have in-depth studied the application of different methods in APF control system, including topology, harmonic detection, AC side current control and DC side voltage control. Braiek et al. [1] utilized feedback linearization technique to improve power balance in source side and APF sides. Komucugil and Kukrer [2] presented a new control strategy for single-phase shunt active power filters (SAPF) based on Lyapunov 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 feedback linearization technique for 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 the current harmonic distortion. Marconi et al. [8] designed a robust nonlinear controller for SAPF to absorb harmonics. Hu et al. [9] introduced a multiresolution control method for an APF which is controlled by digital signal processor to meet the requirements for reducing the real-time computation. Advanced controllers have been investigated in APF to improve the power quality [10-13].

Backstepping [14-16] is similarly a recursive Lyapunov-based design procedure which breaks a design problem for the full system into a sequence of design problems for lower order systems. Nevertheless, backstepping design has two advantages over sliding mode control: One is that the matching condition appeared in the design of sliding mode control can be relaxed for a class of systems satisfying the so called strict feedback form; The other is that backstepping design can avoid cancellation of useful nonlinearities. The strategy of backstepping is to develop a controller recursively by considering some of the state variables as "virtual controls" and designing intermediate control laws. Adaptive neural network was also incorporated into backstepping design for nonlinear control system [17]. Backstepping technique was applied to the tracking control of industrial system in [18]. Backstepping can achieve the goals of stabilization and tracking. However, so far, adaptive backstepping method has not been employed to eliminate harmonics of active power filter. Our work will explore an adaptive backstepping control for active power filter. The contributions of the paper can be emphasized as follows:

(1) There are no relevant research works combining adaptive backstepping control to APF before. Backstepping control is applied to a three-phase active power filter in this paper. For the APF, the design of backstepping controller contains two steps. First, a virtual control function is proposed by a Lyapunov function and then real controller is designed.

(2) The adaptive control, and backstepping control are combined to improve the robust design of control law. The adaptive backstepping control improves the power dynamic performance such as current tracking and THD performance. Combination of these methods has a general sense and can be extended to other power electronic converter topology.

(3) Backstepping approach makes the control law design simpler and easier to be implemented. Therefore, the proposed control system has important theoretical and practical significance for promoting the application of APF, improving total harmonic distortion (THD) and strengthening the quality of power supply.

This paper is organized as follows. In Section 2, dynamic model of APF is established. In Section 3, backstepping controller is designed. Simulation results are shown in Section 4 to demonstrate the performance of the proposed method. In the last section conclusions are given.

2. **Principles of Active Power Filter.** Shunt active power filters are usually applied to three-phase system where a large capacity is required. The most widely used parallel voltage type of APF is mainly discussed. In consideration of the practical application, the SAPF is most applied in the three-phase systems because of its excellent performance and easy implementation. A dynamic analytical model of the APF is developed.

APF is equivalent to a flow control current source. The APF contains three sections, 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 harmonic current detection module. The main circuit consisting 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 the same magnitudes and opposite phases with the harmonic currents. Figure 1 shows the structure of three-phase three-wire APF.

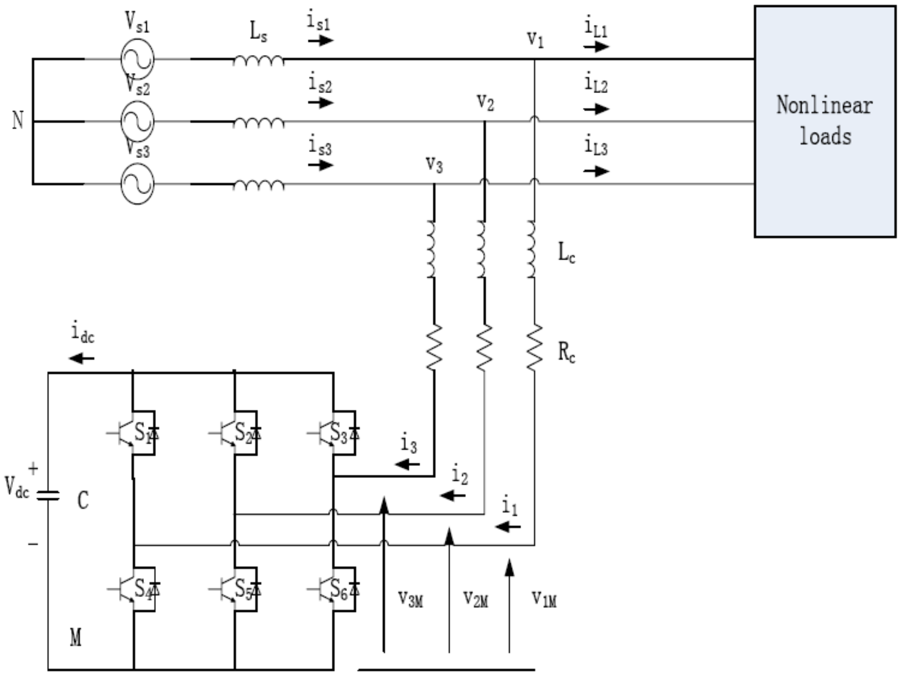

FIGURE 1. Block diagram for APF in practical operation

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

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

The parameter of L_c and R_c are the inductance and resistance of the APF respectively, ν_{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:

$$v_{MN} = -\frac{1}{3}\sum_{m=1}^{3} v_{mM} \tag{2}$$

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

$$c_k = \begin{cases} 1 & \text{if } S_k \text{ is on and } S_{k+3} \text{ is off} \\ 0 & \text{if } S_k \text{ is off and } S_{k+3} \text{ is on} \end{cases} \tag{3}$$

where $k = 1, 2, 3$.

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

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

Then we define the switching state function d_{nk} which is given as

$$d_{nk} = \left(c_k - \frac{1}{3} \sum_{m=1}^{3} c_m \right)_n \tag{5}$$

So d_{nk} depends on the switching function c_k, and based on the eight permissible switching states of the IGBT, we can obtain that

$$\begin{bmatrix} d_{n1} \\ d_{n2} \\ d_{n3} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} \tag{6}$$

Equation (4) becomes

$$\begin{cases} \dfrac{di_1}{dt} = -\dfrac{R_c}{L_c} i_1 + \dfrac{v_1}{L_c} - \dfrac{v_{dc}}{L_c} d_{n1} \\ \dfrac{di_2}{dt} = -\dfrac{R_c}{L_c} i_2 + \dfrac{v_2}{L_c} - \dfrac{v_{dc}}{L_c} d_{n2} \\ \dfrac{di_3}{dt} = -\dfrac{R_c}{L_c} i_3 + \dfrac{v_3}{L_c} - \dfrac{v_{dc}}{L_c} d_{n3} \end{cases} \tag{7}$$

Furthermore, we can define

$$\begin{cases} x_1 = i_k \\ x_2 = \dot{x}_1 = \dot{i}_k \end{cases} \tag{8}$$

The derivative of x_1 and x_2 with respect to time yields:

$$\begin{aligned} \dot{x}_1 &= \dot{i}_k = -\frac{R_c}{L_c} i_k + \frac{v_k}{L_c} - \frac{v_{dc}}{L_c} d_k \\ \dot{x}_2 &= \ddot{x}_1 = \ddot{i}_k = \frac{d\left(-\frac{R_c}{L_c} i_k + \frac{v_k}{L_c} - \frac{v_{dc}}{L_c} d_k\right)}{dt} \\ &= -\frac{R_c}{L_c} \dot{i}_k + \frac{1}{L_c}\frac{dv_k}{dt} - \frac{1}{L_c}\frac{dv_{dc}}{dt} d_k \\ &= -\frac{R_c}{L_c}\left(-\frac{R_c}{L_c} i_k + \frac{v_k}{L_c} - \frac{v_{dc}}{L_c} d_k\right) + \frac{1}{L_c}\frac{dv_k}{dt} - \frac{1}{L_c}\frac{dv_{dc}}{dt} d_k \\ &= \frac{R_c^2}{L_c^2} i_k - \frac{R_c}{L_c^2} v_k + \frac{1}{L_c}\frac{dv_k}{dt} + \left(\frac{R_c}{L_c^2} v_{dc} - \frac{1}{L_c}\frac{dv_{dc}}{dt}\right) d_k \end{aligned} \tag{9}$$

Then the dynamic model of APF can be written as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + bu \end{cases} \tag{10}$$

where $f(x) = \frac{R_c^2}{L_c^2} i_k - \frac{R_c}{L_c^2} v_k + \frac{1}{L_c}\frac{dv_k}{dt}$, $b = \frac{R_c}{L_c^2} v_{dc} - \frac{1}{L_c}\frac{dv_{dc}}{dt}$, $u = d_k$.

3. **Design of Backstepping Controller.** The backstepping method is an efficient control approach for nonlinear systems, which uses the virtual control to simplify the design of control laws. In general, we transform the complex nonlinear systems into several subsystems through backstepping design, then design virtual control for each subsystem based on Lyapunov functions. So in each step, what we need is just to cope with an easier control law.

In this section, a backstepping controller is designed for APF to ensure the proper tracking of reference current and the stability of the closed-loop system is guaranteed based on Lyapunov analysis.

For the APF, the design of backstepping controller contains two steps. At first step, a virtual control function is proposed by a Lyapunov function V_1. The real control law is designed at the second step. In the following, the design procedure of the backstepping controller is given.

Step 1: Define the reference current is y_d, and y_d has continuous second order derivatives. And the tracking error can be defined as

$$e_1 = x_1 - y_d \tag{11}$$

Then

$$\dot{e}_1 = \dot{x}_1 - \dot{y}_d = x_2 - \dot{y}_d \tag{12}$$

We select the virtual control as

$$\alpha_1 = -c_1 e_1 + \dot{y}_d \tag{13}$$

where c_1 is a non-zero positive constant.

Define the error as

$$e_2 = x_2 - \alpha_1 \tag{14}$$

We consider the first Lyapunov function as

$$V_1 = \frac{1}{2} e_1^2 \tag{15}$$

and the derivative of V_1 becomes

$$\begin{aligned} \dot{V}_1 &= e_1 \dot{e}_1 = e_1(x_2 - \dot{y}_d) \\ &= e_1(e_2 + \alpha_1 - \dot{y}_d) \\ &= e_1(e_2 - c_1 e_1 + \dot{y}_d - \dot{y}_d) \\ &= -c_1 e_1^2 + e_1 e_2 \end{aligned} \tag{16}$$

If $e_2 = 0$, then $\dot{V}_1 = -c_1 e_1^2 \leq 0$. So we must construct the next step.

Step 2: Based on (16), we obtain

$$\begin{aligned} \dot{e}_2 &= \dot{x}_2 - \dot{\alpha}_1 \\ &= f(x) + bu - \dot{\alpha}_1 \\ &= f(x) + bu - \ddot{y}_d + c_1 \dot{e}_1 \end{aligned} \tag{17}$$

Define the second Lyapunov function as

$$V_2 = V_1 + \frac{1}{2} e_2^2 \tag{18}$$

and the derivative of V_2 is

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + e_2 \dot{e}_2 \\ &= -c_1 e_1^2 + e_1 e_2 + e_2[f(x) + bu - \ddot{y}_d + c_1 \dot{e}_1] \end{aligned} \tag{19}$$

In order to obtain $\dot{V}_2 \leq 0$, the desired backstepping control law is designed as

$$u = \frac{1}{b}[-f(x) + \ddot{y}_d - c_1 \dot{e}_1 - c_2 e_2 - e_1] \tag{20}$$

where c_2 is a positive scalar.

Then

$$\dot{V}_2 = -c_1 e_1^2 - c_2 e_2^2 \leq 0 \tag{21}$$

Define $c = \min\{c_1, c_2\}$, one obtains from (22)

$$\dot{V}_2 \leq -c e_1^2 - c e_2^2 = -2cV_2 \tag{22}$$

Since $\dot{V}_2 \le 0$, $\dot{V}_2$ is negative semidefinite which ensures that e_1 and e_2 are bounded. Define the following term:

$$W(t) = c_1 e_1^2 + c_2 e_2^2 \le -\dot{V}_2 \tag{23}$$

Then

$$\int_0^t W(\tau) d\tau \le V_2(0) - V_2 \tag{24}$$

Since $V_2(0)$ is bounded and V_2 is nonincreasing and bounded, it can be concluded that $\lim_{t\to\infty} \int_0^t W(\tau)d\tau < \infty$. Moreover, $\dot{W}(t)$ is also bounded. Then $W(t)$ is uniformly continuous. According to Barbalat's lemma, one can be obtained: $\lim_{t\to\infty} W(t) = 0$. It can imply that e_1 and e_2 will asymptotically converge to zero as $t \to \infty$.

4. **Simulation Study.** In order to validate the effectiveness and advantage of the proposed control strategies, the designed APF control system is implemented using Matlab/Simulink with SimPower Toolbox. 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 backstepping control. In the backstepping control, $c_1 = 120000$, $c_2 = 100000$. Other parameters are: $V_{s1} = V_{s2} = V_{s3} = 220$V, $f = 50$Hz. The resistance in the nonlinear load is 10Ω and the inductance is 2mH. The inductance in the compensation circuit is 10mH and the capacitance is 100μF. When $t = 0.04$s, the switch of compensation circuit is closed and APF begins to work. In practice, nonlinear loads are usually time varying, so it is necessary to study the dynamic performance of the APF when variations in the nonlinear loads are considered. When $t = 0.12$s, the same nonlinear load is added into the circuit.

Figure 2, Figure 4 and Figure 5 show the load current (only one phase current is represented for the clearness) and its harmonics spectrum. It is clearly shown that there is serious distortion of load current and the Total Harmonic Distortion (THD) is relatively high (24.71% and 22.24%). Figure 3, Figure 6 and Figure 7 plot the source current and its

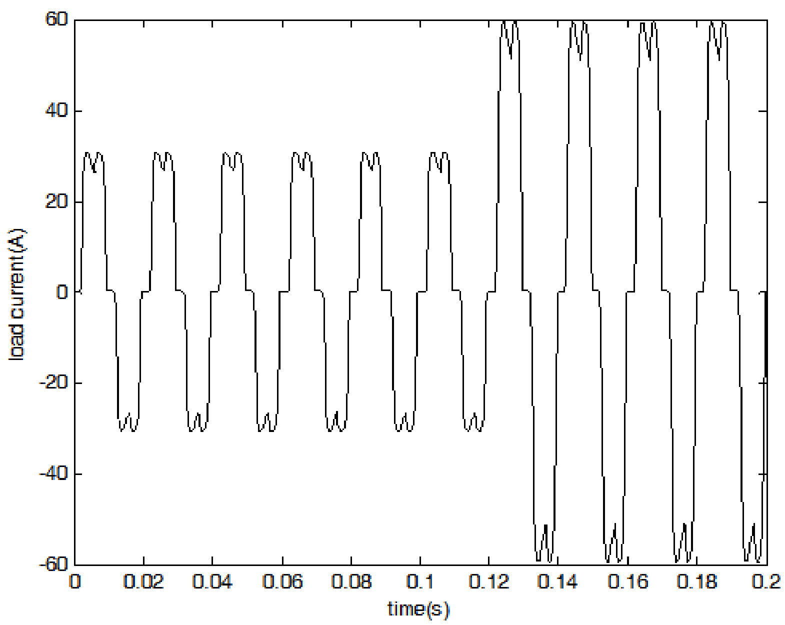

FIGURE 2. A phase load current

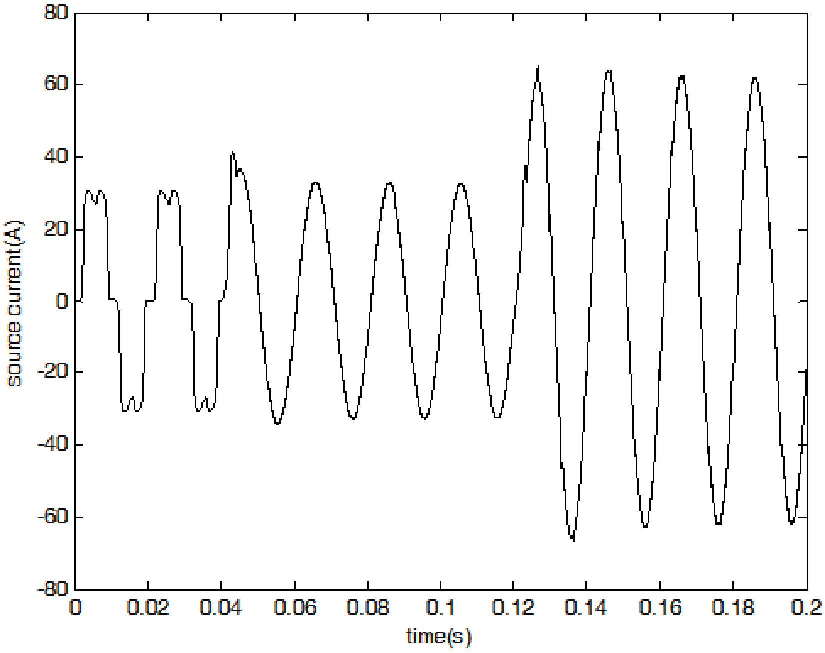

FIGURE 3. A phase source current suing backstepping control

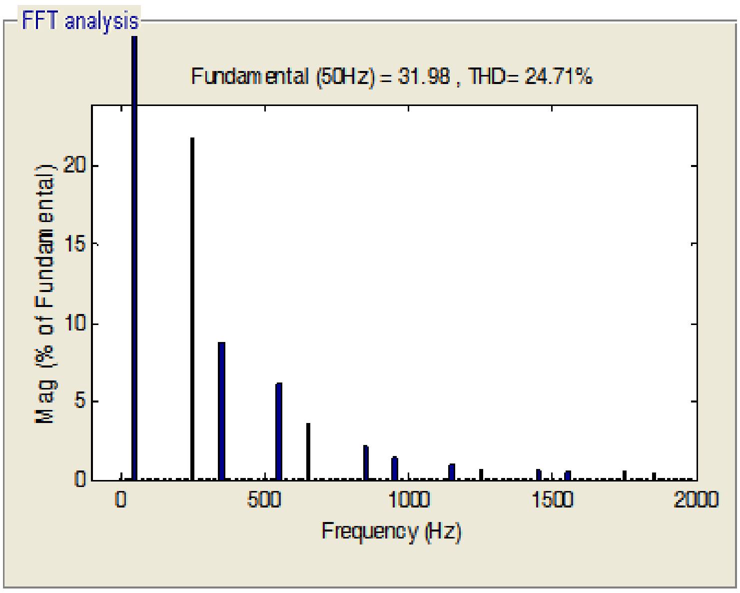

FIGURE 4. Load current harmonic analysis when $t = 0$s

harmonics spectrum using backstepping approach. It is observed that the source currents are close to sinusoidal wave and become balanced after compensation even with loads changing. The THD is reduced to 1.47%, 1.66%, 1.69% and 1.55% all within the limit of the harmonic standard of IEEE of 5%. The results confirm the capability of the control strategy to cancel the harmonics.

Figure 8 shows the instruction current and compensation current, and compensation current tracking error is drawn in Figure 9. It is shown that compensation current can properly track the instruction current using the proposed backstepping controllers. It indicates that the proposed backstepping control can ensure the proper tracking of the

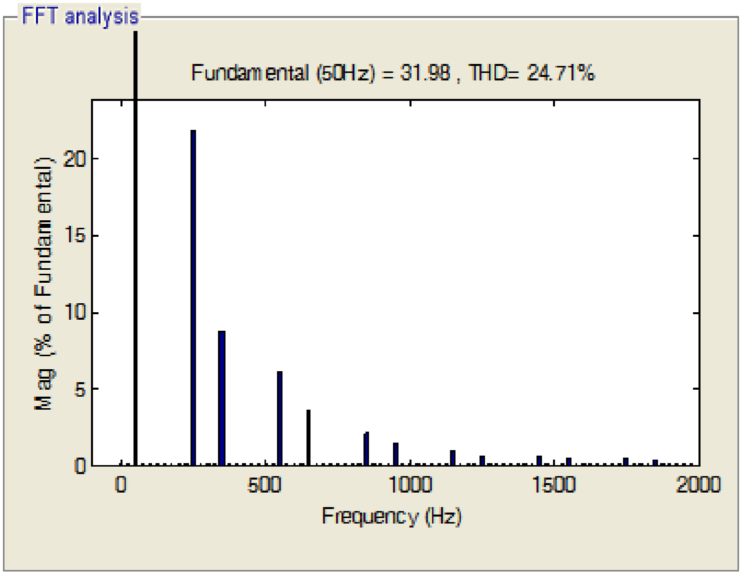

FIGURE 5. Source current harmonic analysis when $t = 0$s

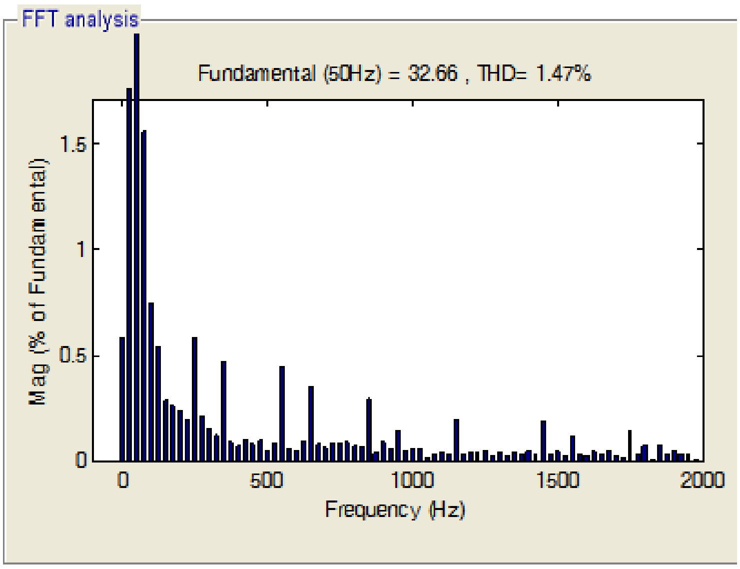

FIGURE 6. Source current harmonic analysis when $t = 0.06$s using backstepping control

reference current. Figure 9 demonstrates that the DC capacitor voltage can track the reference voltage, and it tends to be steady state quickly when loads change.

5. **Conclusions.** In this paper, an adaptive backstepping control strategy for the APF is presented. The stability of the closed-loop system can be guaranteed with the proposed control strategy. The proposed controllers are able to keep the THD of the supply current below the limits specified by the IEEE-519 standard, and impose a desired dynamic behavior. The obtained results have demonstrated the high performance of the APF under both dynamic and steady state operations. The emergence of digital signal processor makes the application of the proposed adaptive robust tracking control possible and it also is the goal that we will achieve the next stage.

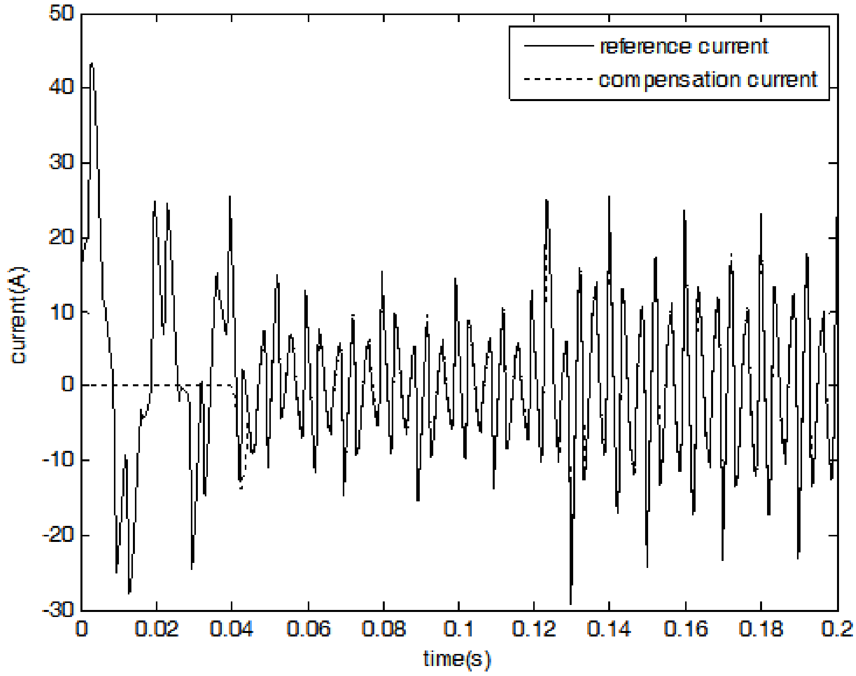

Figure 7. Instruction current and compensation current using backstepping control

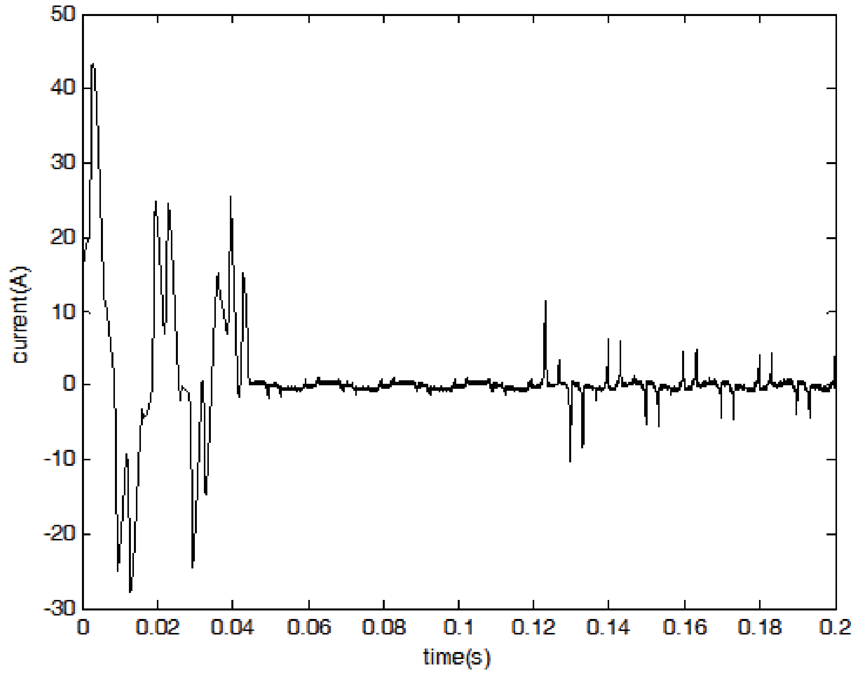

Figure 8. Compensation current tracking error using backstepping control

Acknowledgment. This work is partially supported by National Science Foundation of China under Grant No. 61374100; Natural Science Foundation of Jiangsu Province under Grant No. BK20131136. The Fundamental Research Funds for the Central Universities under Grant No. 2013B19314.

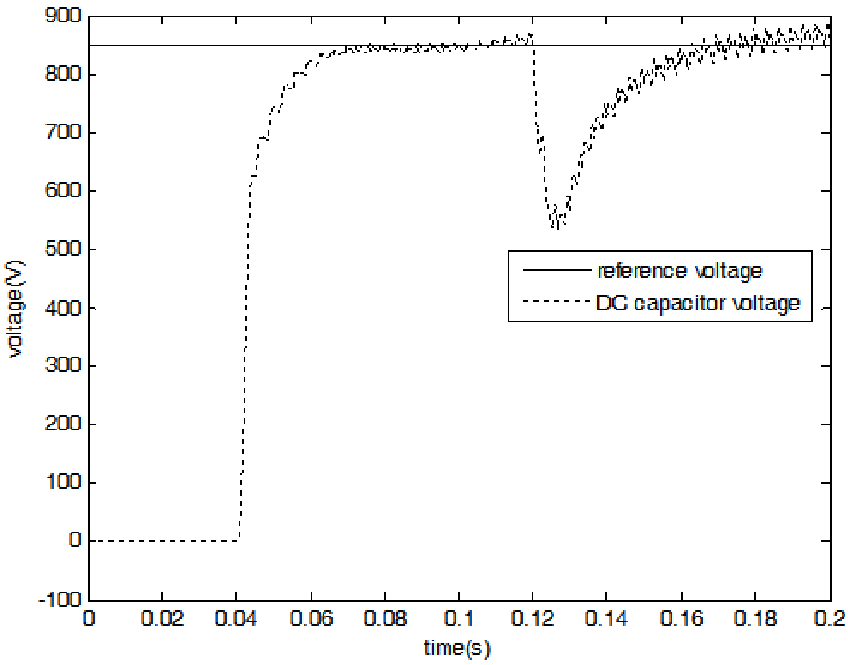

FIGURE 9. DC capacitor voltage using backstepping control

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