International Journal of Innovative Computing, Information and Control
Volume **12**, Number **2**, April **2016**

ICIC International ©2016 ISSN 1349-4198
pp. 407–418

ACTIVE DISTURBANCE REJECTION CONTROL FOR CURRENT COMPENSATION OF ACTIVE POWER FILTER

Nixuan Liu, Xinxin Lyu, Yunkai Zhu and Juntao Fei

College of Internet of Things Engineering
Hohai University
No. 200, Jinling North Road, Changzhou 213022, P. R. China
jtfei@hhu.edu.cn

Received September 2015; revised January 2016

Abstract. *This paper presents an Active Disturbance Rejection Control (ADRC) technology and PI-fuzzy compound technology method for Active Power Filter (APF). The ADRC consists of Tracking Differentiator (TD), Extended State Observer (ESO) and Nonlinear State Error Feedback law (NLSEF). This control method makes full use of the error driven control law, the modern control theory and the nonlinear feedback control. The APF control system is designed with two closed loops: reference current tracking loop with ADRC and the voltage controlling loop with the PI-fuzzy compound controller. Comparing with the direct current control technique, simulation results verify that the proposed control method has excellent dynamic performance and strong robustness in the presence of model uncertainty as well as external disturbances.*
Keywords: Active power filter, Current compensation, Active disturbance rejection control, PI-fuzzy compound controller

1. Introduction.

Today electrical equipment is an important part of our daily lives. The massive harmonic and reactive power generated by device seriously affect the quality of grid power. As a result, the way to improve the grid power has become urgent issues. Comparing with traditional passive Inductance and Capacity (LC) filter, Active Power Filter (APF) as a new dynamic power electronic device has lots of advantages, such as good dynamic compensation and rapid response, little influence by the grid impedance and the small capacity of the power storage element.

The research on the APF started in the 1970s. Akagi and Nabae [1] proposed the instantaneous reactive power theory and described the basic principle of APF. With nearly 20 years' study on basic structure for APF, people began to study on the control methods on APF. Much of work has been done to enhance its function, especially in the current control on Alternating Current (AC) side and voltage control on Direct Current (DC) side [2-5]. Normally, the tracking issue for active power filter's DC voltage or AC current compensation cannot achieve accurate, rapid and highly adaptable global control objectives. However, when we encountered the fuzzy control which little depends on the system dynamics, we found out it has good transient and steady-state behavior, great robust performance [6].

Meanwhile, the harmonic detection has also become more and more important in the APF control system because when we find harmonic and reactive power, we can suppress them more effectively. Wang et al. [7] proposed a selective harmonic detection system which is appropriate to the source with various background harmonics. Vasudevan et al. [8] designed a method using band excitation scanning probe microscopy (SPM) to investigate higher order harmonics. However, the harmonic detection modular makes the APF control a bit complex and the control modules in APF working with each other cannot be easy; as a result, the control system itself including less parts is ideal in practical applications. The ADRC [9] is the method that we want with no harmonic detection. Nowadays, scholars started to combine the intelligent control methods for better effects on APF. Fei et al. [10] designed an adaptive current control with PI-fuzzy compound controller for single-phase APF and Fei and Hou [11] set up adaptive fuzzy control with supervisory compensator for Three-Phase APF. As a result, we decided to combine the ADRC and PI-Fuzzy compound controller for APF.

ADRC is firstly proposed by Han [12]. This controller consists of Tracking- Differentiator (TD), Extended State Observer (ESO) and Nonlinear Error State Feedback law (NLSEF) [13-16]. This control method inherits good qualities from PID [17]. It is a nonlinear control structure based on the process error instead of the plant model. This feature brings the ADRC to wider fields of the engineering application than the PID. Zhu and Pang [18] designed an airship horizontal trajectory tracking control based on ADRC. Recently more and more scholars began to study ADRC technology [19,20]. In this paper, ADRC technology and PI-fuzzy compound control method are designed for current compensation of active power filter (APF). The contributions can be emphasized as follows.

(1) The integration of the ADRC control and fuzzy control is first proposed for APF. The control method system can improve total harmonic distortion (THD) and strengthen the quality of the grid power. Compared with direct current control technique, it has simpler system structure and better harmonic treating performance.
(2) The ADRC method is only relevant with the input and output signals. Most of the system elements can be seen as the internal and external uncertainties, which can be processed as a whole in ADRC. Meanwhile, it is easy to be implemented since only the parameters concerned with the ADRC method are necessary to be adjusted.
(3) The APF control system has two control loops: reference current tracking loop with ADRC and the voltage controlling loop with the PI-fuzzy compound controller. The PI-fuzzy can improve the system speed and enhance the robustness under the premise of guaranteeing control precision.

In this paper, we start with, in Section 2, the basic theory of ADRC and discuss the control theory of PI-fuzzy compound control in Section 3. The APF control system is introduced in Section 4. The simulation results are presented in Section 5, followed by the conclusion in Section 6.

2. Active Disturbance Rejection Control.

The ADRC method has a strong robust performance and it can compensate disturbances and model parameters. It processes reference input and system output separately by TD and ESO. It also chooses suitable nonlinear combination method of state errors to obtain the ADRC control law. The framework of controller is shown in Figure 1. $Z_{1,1}, \ldots, Z_{1,n}$ are the tracking signals of derivatives of reference input $V(t)$ through TD, $Z_{2,1}, \ldots, Z_{2,n}$ are the state variables of plant estimated by ESO, $Z_{2,n+1}$ is a real-time function value. Subtracting $z_{1,n}$ and $z_{2,n}$, we can get the control law by inputting the difference into NLSEF.

2.1. Extended state observer (ESO).

For a first-order system as:

$$\left.\begin{array}{l} \dot{x} = Ax + Bu \\ y = C_O x \end{array}\right\} \tag{1}$$

A, B, C_O are known coefficients, u is the control variable of the system.

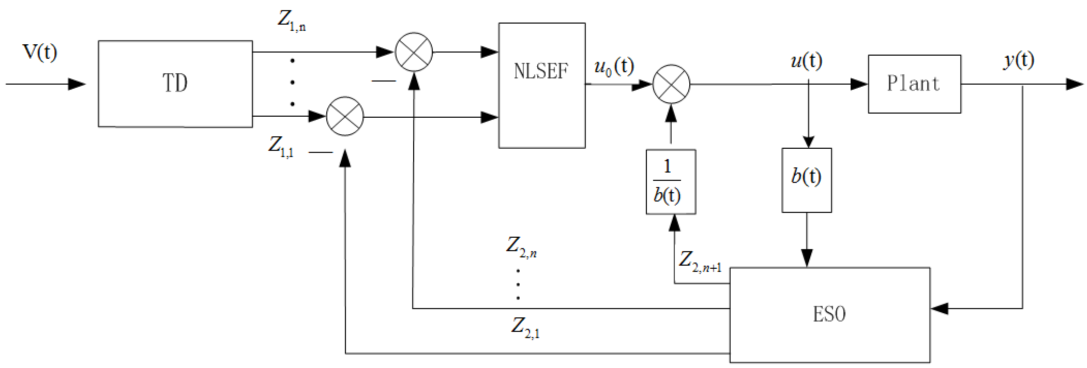


FIGURE 1. Structure diagram of ADRC

Design a classic observer and it can be written as:

$$\dot{z} = Az - L_O(C_O z - y) + Bu \tag{2}$$

Then we can obtain the error equation between systems (1) and (2):

$$\left.\begin{array}{l} \varepsilon = z - x \\ \dot{\varepsilon} = (A - L_O C_O)\varepsilon \end{array}\right\} \tag{3}$$

If the matrix $A - L_O C_O$ is stable, the estimated state variable of $z(t)$ is $x(t)$.

For a second-order system as:

$$\left.\begin{array}{l} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2, t) + Bu \\ y = x_1 \end{array}\right\} \tag{4}$$

When $f(x_1, x_2, t)$ is a known function, the observer can be designed as:

$$\left.\begin{array}{l} \varepsilon_1 = z_1 - y \\ \dot{z}_1 = z_2 - \beta_{01}\varepsilon_1 \\ \dot{z}_2 = f(z_1, z_2, t) - \beta_{01}\varepsilon_1 + Bu \end{array}\right\} \tag{5}$$

However, when $f(x_1, x_2, t)$ is unknown and the nonlinear plant contains uncertainty shown as:

$$y^{(n)} = f\left(y, \dot{y}, \ldots, y^{(n-1)}, t\right) + \omega(t) + bu \tag{6}$$

the state space equations can be described as the following:

$$\left.\begin{array}{l} \dot{x}_1 = x_2 \\ \qquad \vdots \\ \dot{x}_{n-1} = x_n \\ \dot{x}_n = f(x_1, x_2, \cdots, x_{n-1}, x_n) + \omega(t) + bu \\ y = x_1 \end{array}\right\} \tag{7}$$

where $f(x_1, x_2, \cdots, x_{n-1}, x_n) + \omega(t) + bu$ is unknown function, $\omega(t)$ is an unknown external disturbance, b is known parameter. Then we can design the nonlinear error state observer

(ESO) as:

$$\left.\begin{aligned} \dot{z}_{2,1} &= z_{2,2} - g_1(z_{2,1} - y(t)) \\ &\vdots \\ \dot{z}_{2,n} &= z_{2,n+1} - g_n(z_{2,1} - y(t)) + bu(t) \\ \dot{z}_{2,n+1} &= -g_{n+1}(z_{2,1} - y(t)) \end{aligned}\right\} \tag{8}$$

By setting $\alpha(t) = f(x_1, x_2, \cdots, x_{n-1}, x_n) + \omega(t)$, $x_1, x_2, \ldots, x_{n-1}, x_n, \alpha(t)$ can be seen as extended state variables. $z_{2,i}$, $i = 1, 2, \cdots, n+1$ are outputs of the observer and let them track extended variables:

$$z_{2,1}(t) \to x_1(t), \ldots, z_{2,n} \to x_n(t), z_{2,n+1} \to \alpha(t) \tag{9}$$

Choose the appropriate nonlinear functions $g_1(z), g_2(z), \ldots, g_n(z), g_{n+1}(z)$ to achieve the track target. Then, we write the equation as:

$$z_{2,n+1} = \widehat{\alpha}(t) \tag{10}$$

In fact, when $f(x, \dot{x}, \ldots, x^{(n-1)}, t)$ and $\omega(t)$ are unknown, $z_{2,n+1} = \widehat{\alpha}(t)$ can be seen as the estimated value of $a(t)$. It can compensate the uncertain external disturbance. Thus, we can find out ESO is actually such a process; it can derive $z_{2,i}(t)$, $(i = 1, 2, \cdots, n)$ as the derivative signals of the system output $y(t)$ and $z_{2,n+1}(t)$ as the estimated signal of system disturbance.

Subtracting (8) from (9), the nonlinear function $g_1(z)$, $g_2(z)$, …, $g_n(z)$, $g_{n+1}(z)$ can be obtained as:

$$\left.\begin{aligned} \delta\dot{x}_1 &= \delta x_2 - g_1(\delta x_1) \\ \delta\dot{x}_2 &= \delta x_3 - g_2(\delta x_1) \\ &\vdots \\ \delta\dot{x}_n &= \delta x_{n+1} - g_n(\delta x_1) \\ \delta\dot{x}_{n+1} &= -g_{n+1}(\delta x_1) - \dot{\alpha}(t) \end{aligned}\right\} \tag{11}$$

where $\delta x_1 = z_{2,1} - x_1$, $\delta x_2 = z_{2,2} - x_2$, $\cdots$, $\delta x_n = z_{2,n} - x_n$, $\delta x_{n+1} = z_{2,n+1} - \alpha(t)$, $\alpha'(t)$ is the derivation of $\alpha(t)$. Assuming $\dot{\alpha}(t)$ is bounded, when the nonlinear function $g_1(z)$, $g_2(z)$, …, $g_n(z)$, $g_{n+1}(z)$ could make Equation (11) asymptotically stable under the disturbance $\dot{\alpha}(t)$, the ESO is what the system need. In this paper, we set the nonlinear function as $fal(t)$.

The classical PID focuses on the error elimination and lacks an estimation of the process itself, having weak robustness. However, ADRC makes a real-time estimation of $\alpha(t)$ and compensates it, which can bring a stronger robustness than PID.

2.2. **Nonlinear state error feedback law (NLSEF).** According to the state feedback of the outputs of ESO and the nth TD, shown as:

$$\varepsilon_i = z_{1,i} - z_{2,i}, \quad (i = 1, \cdots, n) \tag{12}$$

the nonlinear feedback combination of the system error feedback can be written as:

$$u_0(t) = k_1 fal(\varepsilon_1, \alpha, \delta) + \cdots + k_n fal(\varepsilon_n, \alpha, \delta) \tag{13}$$

where k_i, α, δ are adjustable parameters. We set the nonlinear function $fal(t)$ as

$$fal\left(\varepsilon_i, \alpha, \delta\right) = \begin{cases} |\varepsilon_i|^{\alpha} sgn(\varepsilon_i), & |\varepsilon_i| > \delta \\ \frac{\varepsilon_i}{\delta^{1-\alpha}}, & |\varepsilon_i| \le \delta \end{cases} \tag{14}$$

Considering the nonlinear state error feedback combination and the compensation of the external disturbance $\dot{\alpha}(t)$, we can get the system control law:

$$u(t) = u_0(t) - \frac{\widehat{\alpha}(t)}{b} \tag{15}$$

This kind of compensation implements the linearization and determination of uncertain system feedback. It is also a nonlinear control structure which does not depend on the system model.

2.3. **Modeling and analysis of ADRC for APF.** According to the work principle, we can consider the switches as ideal one, and the model equivalent circuit could be shown as in Figure 2.

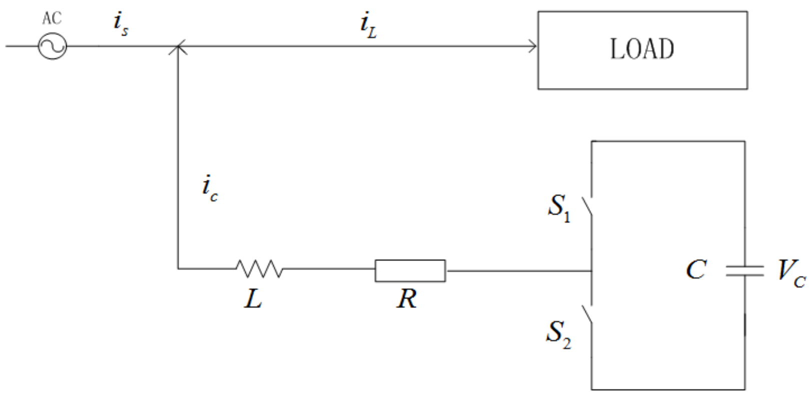


FIGURE 2. Diagram of equivalent circuit of APF

In Figure 2, i_L is the current of nonlinear load, i_s is the system current, i_c is the compensation current, C is the capacitance, S_1, S_2 are the switches in the model equivalent circuit.

Due to the fact that the switches can control the voltage of AC side, the model could be described as a controllable voltage source and impedance paralleling in the circuit. As a result, the model of APF can be written as:

$$L\frac{di_c}{dt} = u_s - Ri_c - u_c \tag{16}$$

where L is an inductance, R is a resistance and u_s is the voltage for AC side. The pulse-width-modulation (PWM) link can be seen as a proportional link, which could be written as:

$$u_c = u \cdot V_c \tag{17}$$

where u is the modulation signal of PWM which is the control variable of the system, V_c is the voltage for DC side.

3. **PI-Fuzzy Compound Voltage Control.** The PI-Fuzzy compound controller is designed for the DC side capacitor voltage control, shown in Figure 3, where $U_{dc}(k)$ is the real value of the DC capacitor voltage for the first time k, U_{ref} is the reference capacitor voltage. The compound controller worked due to the switch condition. When system is in the transient state, the switch turns down to improve the system dynamic performance. When the system is in the steady state, the switch turns up to eliminate steady-state error of the system. The condition of switch is defined by the absolute value of the voltage error. The control program can run continuously and monitor the input and output characteristics of the control system. It can also coordinate between the two control laws automatically.

In order to reduce the disturbance brought by the derivative action of the controller, we design a one-dimensional fuzzy controller. We set the deviation $e_u(t)$ as fuzzy input variables, u as the fuzzy output variables.

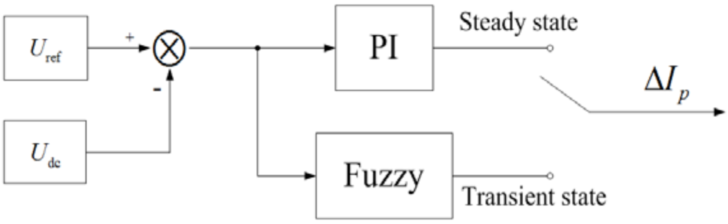


Figure 3. PI-fuzzy compound control structure

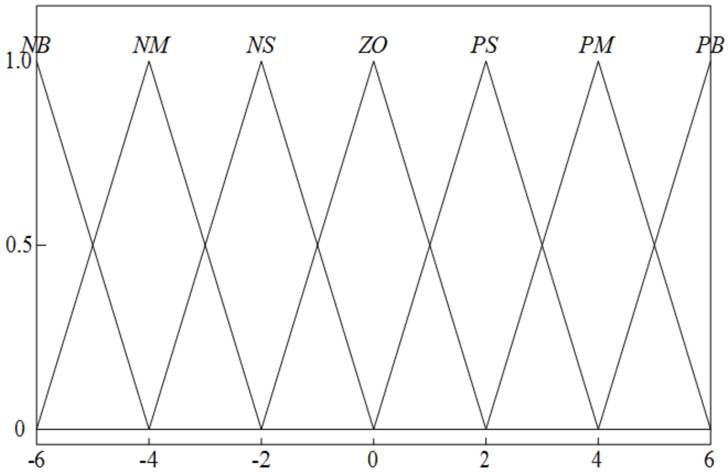


Figure 4. Triangular membership function

We defined the fuzzy input $e_u(k)$ as:

$$e_u(k) = U_{ref} - U_{dc}(k) \tag{18}$$

We can set the universe of $e_u(t)$ and output variables u of the fuzzy controller as:

$$X = \{\ -6 \quad -5 \quad -4 \quad -3 \quad -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6\ \} \tag{19}$$

Select seven of linguistic variables in the universe: NB, NM, NS, ZO, PS, PM, PB. The input variables $e_u(t)$ and output variables u are selected overlapping symmetrical triangle membership function, as shown in Figure 4.

The fuzzy control rules are the core of the fuzzy control; therefore, how to set up the fuzzy control rules has become a crucial issue.

We can develop fuzzy control rules based on the curve shown as Figure 5. Fuzzy control rules can be obtained according to the change process of the curve. The DC side capacitor voltage fuzzy control rules is shown in Table 1.

Table 1. DC side capacitor voltage fuzzy control rules

$e(t)$	NB	NM	NS	ZO	PS	PM	PB
u	NB	NM	NS	ZO	PS	PM	PB

The Mamdani type fuzzy inference system talks about the fuzzy relationship: "If e is A then u is C". We put this kind of fuzzy system into our module. For defuzzification method, the area of the center of gravity (centroid) is selected, then fuzzy controller output value can be obtained and that is ΔI_p as the grid controlled variable of the active current.

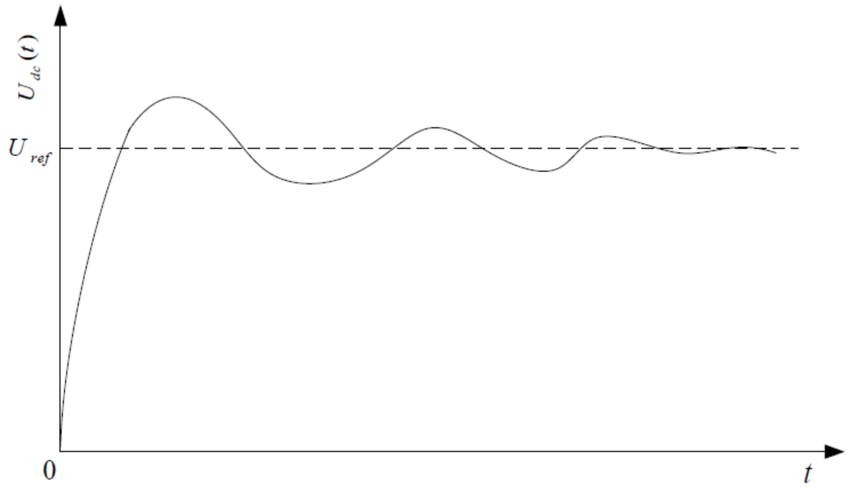


FIGURE 5. The change curve of APF DC capacitor voltage

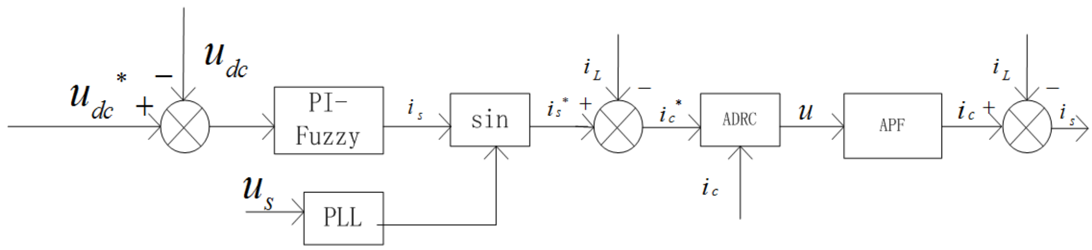


FIGURE 6. Diagram of two-loop control system

4. **Design of the Two-Loop Control System.** The control system consists of two parts – one is the internal loop of the reference current tracking and the other is the external loop of voltage control for DC side. The internal loop is to compensate the harmonic current by the switches in the main circuit. The PWM can control the conditions of those switches (ON/OFF) when the ADRC gives the modulation signals. The external loop can get the reference current by the PI-fuzzy compound control and imports to the internal loop. The diagram of the system controller is shown in Figure 4.

Due to the fact that response of internal loop is much faster than the external loop; we can assume the voltage for AC side is constant.

The error between the actual value and the reference value of the DC voltage, through the PI-fuzzy controller, can get the desired amplitude. i_s^* is the reference value of the grid current which is the same phase with the grid voltage.

Neglecting the impedance in the power line, we can deem u_s in Equation (16) as the model uncertain item. By making $\varpi(t) = u_s$, $b = \frac{u_{dc}}{L}$ and the system could be rewritten as:

$$L\frac{di_c}{dt} = -Ri_c - bu + \varpi(t) \tag{20}$$

Subtract the set value of the detected harmonic current i_c^* from the output compensation current of the system i_c and make result as the reference input of the ADRC loop. The switch function u is the system controlled variable. Let the compensation current of the AC side i_c track the set value i_c^*, then the control action can be done.

Assuming the first-order output of TD:

$$\dot{z}_{1,1} = -k_0 fal(z_{11} - ref, \alpha_0, \delta_0) \tag{21}$$

where k_0, α_0, δ_0 are the parameters to be selected, we can design the ESO as:

$$\left.\begin{array}{l} \dot{z}_{2,1} = z_{2,2} - k_{11}fal(\varepsilon, \alpha_1, \delta_1) + bu(t) \\ \dot{z}_{2,2} = -k_{12}fal(\varepsilon, \alpha_1, \delta_1) \end{array}\right\} \tag{22}$$

where, $\varepsilon = z_{2,1} - i_c$, k_{11}, k_{12}, α_1, δ_1 are the parameters to be selected. Though $\varepsilon = z_{1,1} - z_{2,1}$, as the system state error feedback, we can get the ADRC law as:

$$\left.\begin{array}{l} u_0 = k_2 fal(\varepsilon_1, \alpha, \delta) \\ u = u_0 - \frac{z_{2,2}}{b} \end{array}\right\} \tag{23}$$

where k_2, α, δ are also to be selected. From Equation (22), we could find out that the control law has nothing to do with the model uncertainties and external disturbances, only related to the given input and the system output.

5. **Simulation of Active Power Filter.** According to the analysis above, we choose the single-phase harmonic detection method, linear hysteresis control and ADRC algorithm to set up the simulation model by using Simpower Toolbox.

This model includes harmonic detection circuit, the main circuit and the ADRC module. We design the package forms in order to modify parameters conveniently. From the diagram of the two-loop control system, the work process can be described; i_h detected by the harmonic detection module subtract the compensation current i_L and the difference is the reference input. Then, it goes into the ADRC module to get the modulation signal u of the PWM. At last, the compensation current i_L is put into the grid to filter harmonic.

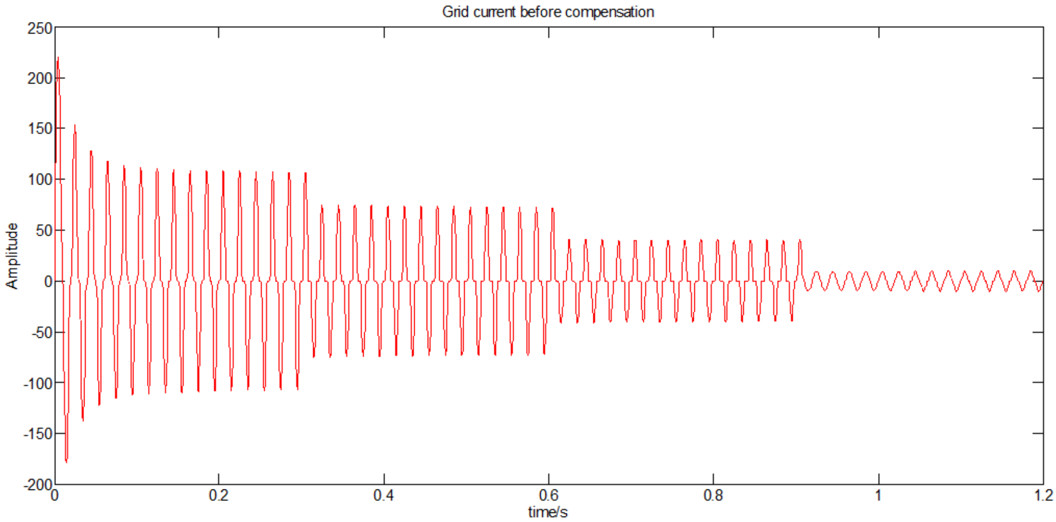
ADRC uses the extended state observer (ESO) to obtain the total system disturbance. In this model, the grid voltage is the total disturbance and there is no need to track it. The harmonic current can be compensated by the control system. The parameters in the control system are shown in Table 2.

Table 2. Simulation parameters

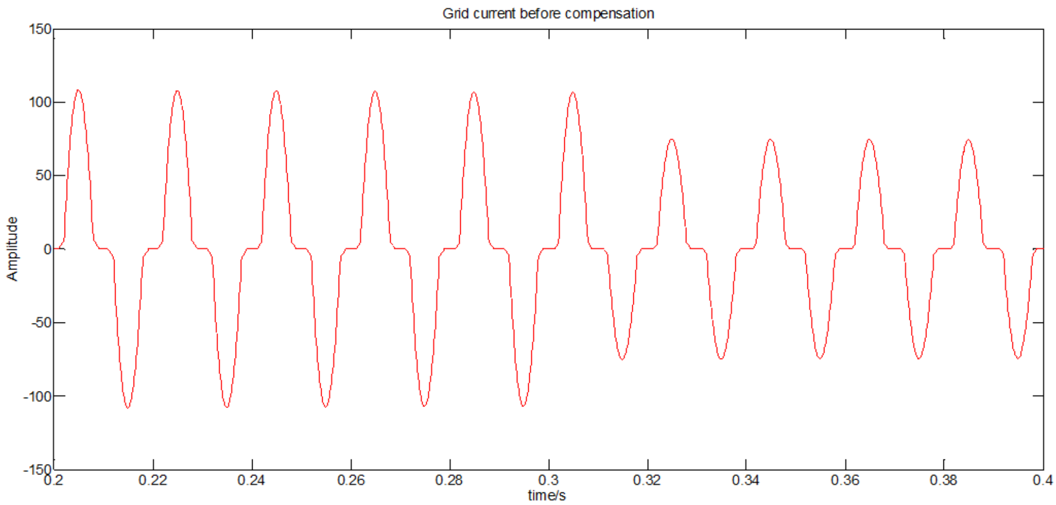
Parameter		Value
Power		$U_s = 220\text{V}_{\text{rms}}/50\text{HZ}$
DC capacitor voltage		$U_c = 600\text{V}$
PWM switching frequency		$f_s = 20\text{KHZ}$
Input inductor		$L = 6\text{mH}$
Input capacitor		$C = 0.003\mu\text{F}$
TD	α_0	0.2
	k_0	0.001
	δ_0	250000
ESO	α_1	1.5
	k_{11}	75000
	k_{12}	50000
	δ_0	0.005
Nonlinear State Error Feedback (NLSEF)	α	1
	k_2	1000000
	δ	0.0001

We can see the control effects obviously from two kinds of figures; ones are with no APF control and the others are with ADRC and PI-fuzzy compound control. The simulation results can be seen in the following figures.

Figure 7 shows the grid current waveform in APF without any control methods. It can be seen that due to the presence of nonlinear load, the grid current waveform has severe



(a) 0∼1.2s

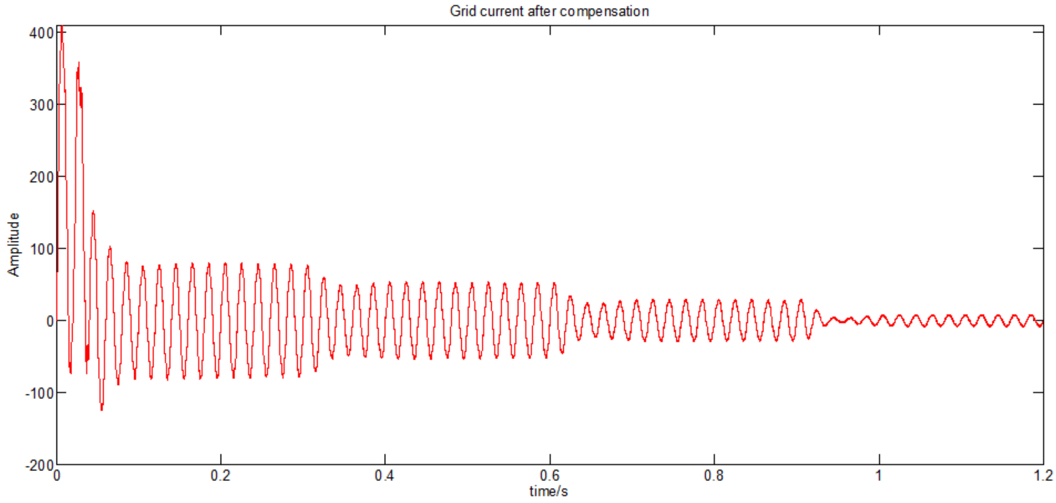


(b) 0.2∼0.4s

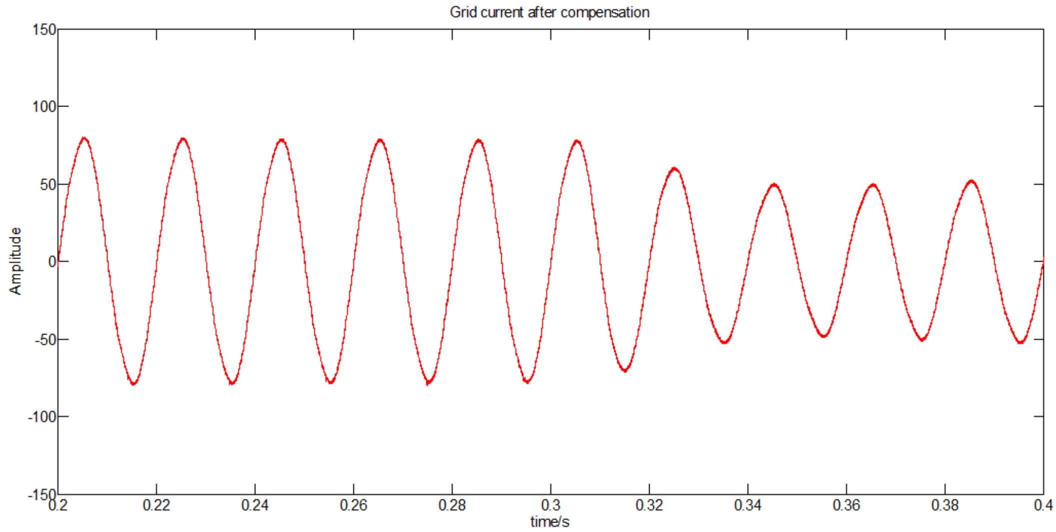
Figure 7. Load current waveform when the nonlinear load changes

distortion and it will affect the quality of grid power. From the waveform in Figure 8 compared with Figure 7, as can be seen the grid current distortion has been significantly improved when the ADRC and PI controller are used to the system. Figure 9 shows that nonlinear load leads grid current containing a large number of harmonics, where THD $= 45.82\%$. Figure 10 plots the harmonic content with ADRC control based on PI-fuzzy control, where THD $= 2.65\%$. It is shown that the ADRC and PI-fuzzy compound control is effective in harmonic suppression of APF.

6. **Conclusion.** ADRC and PI-fuzzy compound control technology are proposed and applied for the current compensation of APF. This control system can be described as: The voltage control with a PI-fuzzy compound controller gets the reference current and puts it into the ADRC control loop; the internal loop uses the ADRC method to get the modulation signal of PWM to control the switches in the main circuit of APF, which can obtain the compensation current. From the ADRC law, we can see that the law depends only on the inputs and outputs and it makes the law simple and easy to realize. Simulation results prove the proposed APF control system has better performance, including fast



(a) 0∼1.2s



(b) 0.2∼0.4s

Figure 8. Grid current waveform with ADRC and PI-fuzzy compound controller

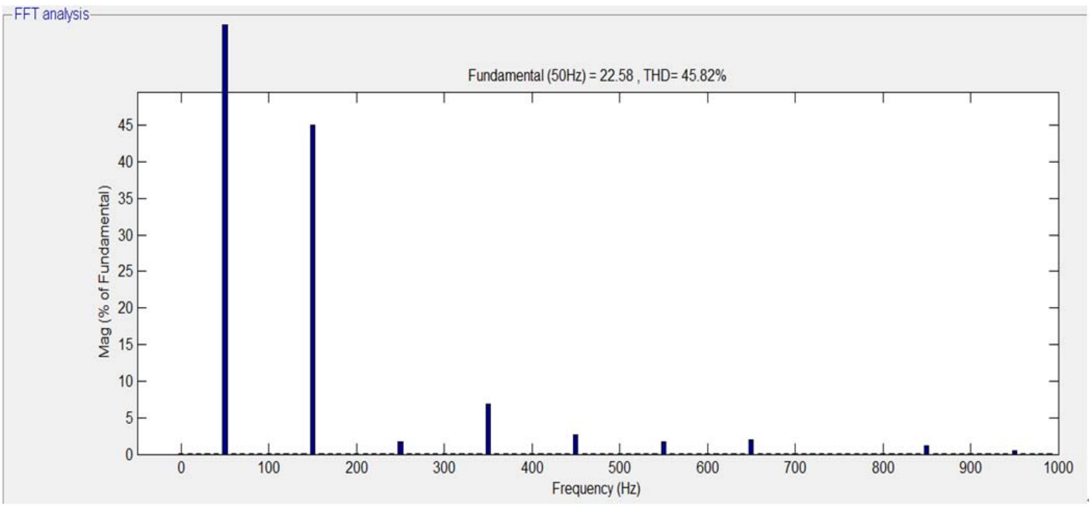


Figure 9. Initial grid current spectrogram without controller

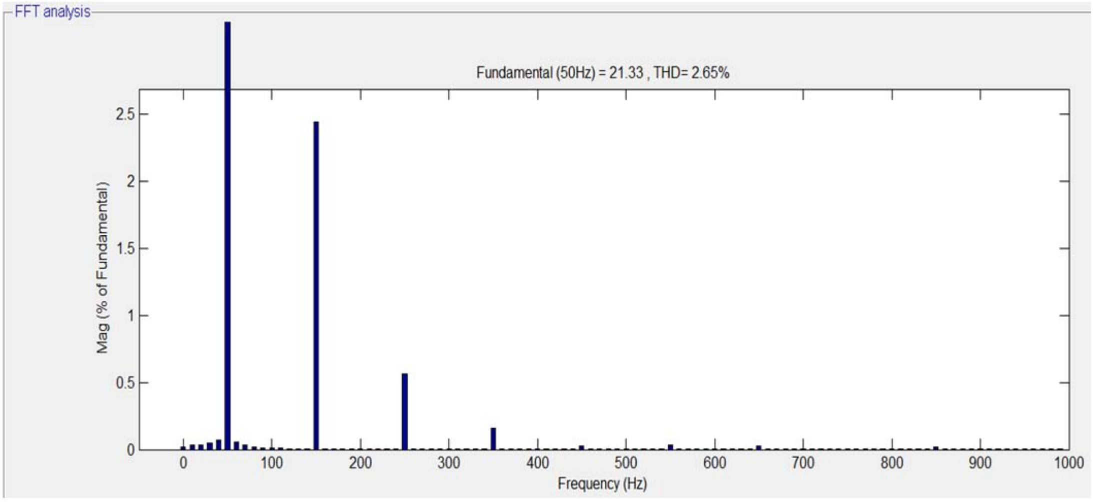


FIGURE 10. Grid current spectrogram with ADRC and PI-fuzzy compound controller

response, small overshoot for harmonic suppression. Since the ADRC design is simple and easy, it is applicable for the practical power field. However, the parameters in ADRC are complex; in the future, the regulation methods of ADRC's parameters should be studied extensively, which can make the control system work easily.

Acknowledgement. The authors thank the anonymous reviewers for their useful comments that improved the quality of the paper. This work is partially supported by National Science Foundation of China under Grant No. 61374100, the Natural Science Foundation of Jiangsu Province under Grant No. BK20131136.

REFERENCES

[1] H. Akagi and A. Nabae, Instantaneous reactive power compensators comprising switching dectives without energy storage components, *IEEE Trans. Industry Applications*, vol.20, no.3, pp.625-630, 1984.
[2] M. Angulo, D. A. Ruiz-Caballero, J. Lago, M. L. Heldwein and S. A. Mussa, Active power filter control strategy with implicit closed-loop current control and resonant controller, *IEEE Trans. Industrial Electronics*, vol.60, no.7, pp.2721-2730, 2013.
[3] S. Kim and P. N. Enjeti, A new hybrid active power filter topology, *IEEE Trans. Power Electronics*, vol.17, no.1, pp.48-54, 2002.
[4] J. Espi and J. Castello, An adaptive robust predictive current control for three-phase grid-connected inverters, *IEEE Trans. Industrial Electronics*, vol.58, no.8, 2011.
[5] A. Ribeiro, A robust DC-link voltage control strategy to enhance the performance of shunt active power filters without harmonic detection schemes, *IEEE Trans. Industrial Electronics*, vol.27, no.2, pp.718-730, 2012.
[6] G. Singh, A. 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, pp.1101-1111, 2007.
[7] Y. Wang, Three-phase cascaded delayed signal cancellation PLL for fast selective harmonic detection, *IEEE Trans. Industrial Electronics*, vol.60, no.4, pp.1452-1463, 2013.
[8] R. Vasudevan et al., Higher order harmonic detection for exploring nonlinear interactions with nanoscale resolution, *Sci. Rep.*, vol.10, no.3, p.2677, 2013.
[9] L. Ge and X. Yuan, Control system design of shunt active power filter based on active disturbance rejection and repetitive control techniques, *Mathematical Problems in Engineering*, vol.2014, Article ID 864989, 2014.
[10] J. Fei, K. Ma and S. Zhang, Adaptive current control with PI-fuzzy compound controller for shunt active power filter, *Mathematical Problems in Engineering*, vol.2013, 2013.

[11] J. Fei and S. Hou, Adaptive fuzzy control with supervisory compensator for three-phase active power filter, *Journal of Applied Mathematics*, pp.1-13, 2012.
[12] J. Han, Auto disturbances rejection controller and its applications, *Control Decis.*, vol.13, no.1, pp.19-23, 1998 (in Chinese).
[13] J. Han and W. Wang, Nonlinear tracking-differentiator, *Syst. Sci. Math.*, vol.14, no.2, pp.177-183, 1994 (in Chinese).
[14] J. Han, Extended state observer for a class of uncertain plants, *Control Decis.*, vol.10, no.1, pp.85-88, 1995 (in Chinese).
[15] Z. Gao, Active disturbance rejection control: A paradigm shift in feedback control system design, *Proc. of Amer. Control Conf.*, pp.2399-2405, 2006.
[16] D. Sun, Comments on active disturbance rejection control, *IEEE Trans. Industrial Electronics*, vol.54, no.6, pp.3428-3429, 2007.
[17] J. Han, From PID to ADRC, *IEEE Trans. Industrial Electronics*, vol.56, no.3, 2009.
[18] E. Zhu and J. Pang, Airship horizontal trajectory tracking control based on active disturbance rejection control, *Nonlinear Dynamics*, vol.75, no.4, pp.725-734, 2014.
[19] X. Shao, Active disturbance rejection based trajectory linearization control for hypersonic reentry vehicle with bounded uncertainties, *ISA Transactions*, vol.54, pp.27-38, 2015.
[20] W. Xue, W. Bai, S. Yang and K. Song, ADRC with adaptive extended state observer and its application to air-fuel ratio control in gasoline engines, *IEEE Trans. Industrial Electronics*, vol.62, no.9, pp.5847-5857, 2015.