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Experimental Investigation of Adaptive Fuzzy Global Sliding Mode Control of Single-Phase Shunt Active Power Filters

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ABSTRACT In this paper, an indirect adaptive fuzzy global sliding mode control methods (AFGSMC) are proposed for single-phase shunt active power filter as a current controller. First, a global sliding mode control applied to the current control loop is designed to guarantee global robustness. Then, a fuzzy system is used to approximate the unknown dynamics in order to eliminate the dependence on the prior knowledge, and another fuzzy system is used to replace the switching control term to reduce the chattering phenomenon. Moreover, the compensation control term is designed based on the fuzzy approximation error estimation, which ensures the tracking performance of the closed-loop system. The experimental results demonstrate that the proposed control methods offer a good behavior in both steady state and transient operation, reducing the THD of source current to less than 5% and improving the power quality in order to meet the recommendations of the IEEE 519 standard.

INDEX TERMS Active power filter, adaptive fuzzy control, global sliding mode control, adaptive estimation.

I. INTRODUCTION

Over the last few years, the increasing use of power converters put into application in power systems has deteriorated the power quality. Power quality is a broad term which can be categorized as voltage swell/sag, voltage unbalance, current harmonic, and so on. Current harmonics are the main power quality problems which can be eliminated by conventional solutions as passive filters. However, passive filters are kinds of fixed compensation, which is prone to over-compensation and under-compensation. It cannot realize dynamic compensation of reactive power and harmonic current at the same time, especially for traction load with large fluctuation. Furthermore, the standards that limit the ratio of harmonic current in the power grid have become more restricted, which promotes the development of active power filter (APF) [1]–[3].

Two tasks are crucial to an APF to perform well its function, namely, the generation of reference current and the ability to rapidly track the reference current [4], [5]. The main control objective is to minimize the error generated by the comparison of compensation currents with the reference signals. Since the APF must generate non-sinusoidal currents, the design of current controller for the APF is a challenging task. With the development of SAPF, numerous control strategies have been presented in the literature, such as proportional-integral(PI) control [6], one-cycle control [7], dead-beat control [8], repetitive control [9], resonance control [10]. PI control can adjust the output current without static error. However, the PI controller with fixed gain cannot effectively deal with external disturbance and parameter perturbation so that it cannot guarantee the robust filtering performance. In contrast, one-cycle control method is able to eliminate transient errors in one cycle at the expense of compensation accuracy. Due to the limitation of the response time, the influence of disturbance cannot be completely eliminated until the next fundamental period with repetitive control. Despite the advantage of selective harmonic compensation, resonance control needs multiple groups of generalized integrators to meet the requirements of high compensation

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accuracy, which makes the structure of the controller complex and is not conducive to industrial applications.

In recent years, diverse high-performance current control methods have been developed for APF to achieve good control performance due to their ability to handle complex problem at difficult situations. In [11], a H_∞ controller is discussed for current control loop to achieve high-disturbance rejection. In [12], [13], adaptive backstepping control method is developed for APF to enhance dynamic performance. Some researchers have turned to soft computing strategies to estimate unknown perturbations [14], [15]. In [16], [17], a comprehensive control method including neural network and fuzzy logic is proposed to improve the anti-interference and self-adaptive ability. Despite this, and with the aim of increasing robustness with a fast dynamic response, sliding-mode control (SMC) is the best alternative to be used [18], [19].

The response of the typical sliding mode control includes the reaching mode and the sliding mode. However, the robustness to parameter uncertainties and external disturbances exists only in the sliding mode phase. That is, the typical sliding mode control system has not the global robustness. Global sliding mode control (GSMC) is developed to overcome the weakness of the conventional sliding mode control and make the system be robust in the whole process. Liu *et al.* [20] introduced a novel discrete global sliding mode control in the tension control system of carbon fiber multilayer diagonal loom. Chu *et al.*[21] showed an adaptive backstepping neural global proportional integral derivative sliding mode control for APF. However, the control performance relies significantly on prior knowledge of controlled plant, which can be solved by well-designed uncertainty estimator [22]. In the current literatures, fuzzy logic and neural network are utilized to estimate unknown functions without detail information [23], [24]. Chen *et al.* [25] realized a sliding mode control scheme using adaptive fuzzy strategy to approximate unknown nonlinearity. Li *et al.* [26] proposed a kind of observer-based fuzzy integral sliding mode control to reduce the number of fuzzy rules.

In this paper, a strategy of adaptive fuzzy global sliding mode control (AFGSMC) for APF was developed. The motivation of the study can be emphasized as follows:

(1) In general, power system perturbations such as load fluctuations, parameters changes of APF, sudden failure of system components, and unknown disturbances such as measurement noise, harmonics, phase angle jump, will reduce the reliability and efficiency of APF. Thus, it is essential to design the APF control system that provide the superior robustness. Due to the property of global sliding surface that is fast response and global robustness, a global sliding mode control for APF is designed to provide global robustness.

(2) Adaptive fuzzy control designed to estimate the unknown dynamic characteristic makes the system robust to various unknown factors without the precise model. Further, another fuzzy system eliminates the chattering phenomenon effectively by replacing the switching control term with the continuous fuzzy control output. The fuzzy parameters are adjusted online by the adaptive law derived from the Lyapunov stability analysis, to guarantee tracking performance and stability of the closed-loop system.

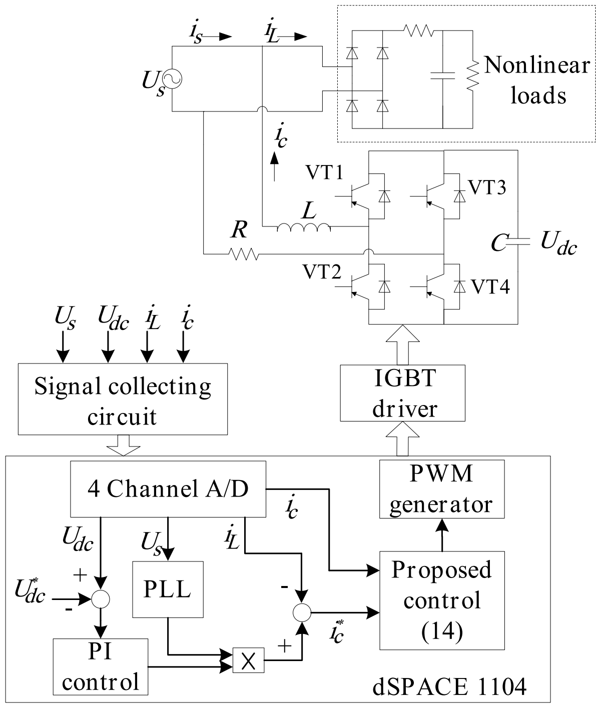


FIGURE 1. Structure diagram of single-phase active power filter prototype.

The paper is organized as follows. In section 2, mathematical model of single-phase APF is described, and global sliding mode controller is proposed. In section 3, the adaptive fuzzy global sliding mode control is presented and the globally asymptotic stabilities of the designed control systems are proved by the Lyapunov stability theory. Section 4 shows the experimental results of the proposed controllers. Conclusions are given in the last section.

II. PROBLEM STATEMENT

The single-phase APF is shown in Fig.1. Applying circuit theory and Kirchhoff rules to this system yields the following circuit equations [12], [14]:

$$\begin{cases} \dot{i}_c = -\frac{R}{L}i_c + \frac{U_s}{L} - \frac{U_{dc}}{L}u \\ \dot{U}_{dc} = \frac{ui_c}{C} \end{cases} \tag{1}$$

where the parameter of L and R are the inductance and resistance of the APF respectively,

$$u = \begin{cases} 1 & VT1, VT4\ on, VT2, VT3\ off \\ -1 & VT2, VT3\ on, VT1, VT4\ off \end{cases}$$

As mentioned in [16], control system can be divided into outer voltage loop and inner current loop. In this paper, conventional PI control is adopted to regulate U_{dc} at an expected value for outer voltage loop.

In order to design inner current loop, we consider the first equation in (1):

$$\dot{i}_c = -\frac{R}{L}i_c + \frac{U_s}{L} - \frac{U_{dc}}{L}u \tag{2}$$

In practical applications, the exact value of the equivalent resistance of the system cannot be obtained. Moreover the AC reactor and DC capacitor will also age gradually which will cause parameter perturbation. So considering the occurrence of unpredictable perturbation and external disturbances, (2) can be modified as

$$\dot{i}_c = -\frac{R_1 + \Delta R}{L_1 + \Delta L}i_c + \frac{U_s}{L_1 + \Delta L} - \frac{U_{dc}}{L_1 + \Delta L}u + g_1 \tag{3}$$

For convenience, rewriting (3):

$$\dot{i}_c = -\frac{R_1}{L_1}i_c + \frac{U_s}{L_1} - \frac{U_{dc}}{L_1}u + h_1 \tag{4}$$

where h_1 represent the lumped uncertainties, which are assumed to be bounded as $|h_1| \le H_M$.

Then (4) can be rewritten as

$$\dot{i}_c = f(i_c) + U_1 + h_1 \tag{5}$$

where $f(i_c) = -\frac{R_1}{L_1}i_c + \frac{U_s}{L_1}$.

The aim of this control problem is to find a control law to make the compensation current i_c track reference current i_c^*. The conventional sliding mode controller for APF is described in the following part by assuming all the parameters of the system are well known.

The tracking error is defined as:

$$e = i_c - i_c^* \tag{6}$$

and the derivative of e is:

$$\dot{e} = \dot{i}_c - \dot{i}_c^* \tag{7}$$

Design the global sliding surface as:

$$S = Ce - g(t) \tag{8}$$

where C is a given constant, $g(t)$ is a function that is specially designed for reaching the global sliding surface, satisfying the following three conditions:

(1) $g(0) = \dot{e}_0 + ce_0$, (2) If $t \to \infty$, $g(t) \to 0$,
(3) $g(t)$has a first derivative.

where e_0 is an initial value of the tracking error.

Hence we can design $g(t)$ as: $g(t) = g(0)e^{-kt}$, where k is a constant.

The time derivative of $\dot{S}$ is:

$$\begin{aligned}\dot{S} &= C\dot{e} - \dot{g}(t)\\ &= C(\dot{i}_c - \dot{i}_c^*) - \dot{g}(t)\\ &= C[f(i_c) + U_1 + h_1 - \dot{i}_c^*] - \dot{g}(t)\end{aligned} \tag{9}$$

Then design the global sliding mode control law U_{GSMC} as:

$$U_{GSMC} = \dot{i}_c^* - f(i_c) + \frac{1}{C}\dot{g}(t) - Dsgn(S) \tag{10}$$

where D is a known positive constant which can be designed. The global sliding mode controller can be obtained in the form of (10) if all the parameters of the system are well known.

Proof: Choose a Lyapunov function as:

$$V_1 = \frac{1}{2}S^2 \tag{11}$$

and the time derivative is

$$\dot{V}_1 = S[C[f(i_c) + U_1 + h_1 - \dot{i}_c^*] - \dot{g}(t)] \tag{12}$$

Substituting the control law (10) into (12) gives

$$\begin{aligned}\dot{V}_1 &= CS[h_1 - Dsgn(S)] = C[-D|S| + Sh_1]\\ &\le C[-D|S| + |S|H_M] = C|S|(H_M - D)\end{aligned} \tag{13}$$

The above inequality (13) meets $\dot{V}_1 \le 0$ under the situation of $D \ge H_M$. The negative semi-definite of $\dot{V}_1$ represents that V_1, S are bounded, from (9) we can conclude that $\dot{S}$ is also bounded. According to Lyapunov stability theory, the system obtains a perfect trajectory property with the global sliding mode controller and the closed-loop stability is guaranteed.

Unfortunately, the GSMC requires detailed system dynamics of the APF with unknown disturbances. Due to unknown equivalent resistance R_1 and uncertain U_s because of sensor fault in practical systems, the control law is usually difficult to be achieved. Moreover, due to the fact that it is hard to get the supremum of the lumped uncertainties, D can only be obtained through trial and error method. It should be noticed that too small D leads to system instability, and too large one will increase chattering. Hence, to overcome the drawbacks, an adaptive fuzzy global sliding mode control (AFGSMC) system is designed in the following section.

III. ADAPTIVE FUZZY GLOBAL SLIDING MODE CONTROLLER

Owing to the unknown dynamic characteristic of the APF, we introduce a fuzzy system to approximate $f(i_c)$. On the other hand, faced with the chattering caused by the global sliding mode controller, a fuzzy estimator is utilized to eliminate the chattering. A compensation control item is designed using adaptive estimation technique to overcome the influence of fuzzy approximation error. An adaptive fuzzy global sliding mode controller is designed in this section as shown in Fig.2.

Using indirect adaptive fuzzy framework, the overall controller is proposed as follows [19]:

$$U_{AFGSMC} = \dot{i}_c^* - \hat{f}(i_c) + \frac{1}{C}\dot{g}(t) - \hat{h}(S) - u_c \tag{14}$$

$$\hat{f}(i_c|\theta_f) = \theta_f^T \xi(i_c) \tag{15}$$

$$\hat{h}(S|\theta_h) = \theta_h^T \phi(S) \tag{16}$$

$$u_c = \hat{\omega} \tag{17}$$

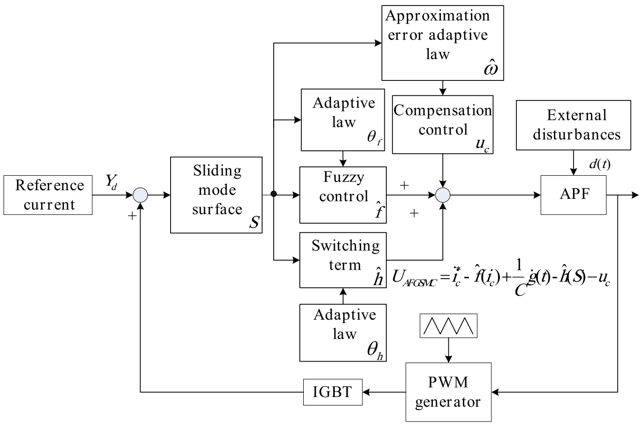


FIGURE 2. block diagram of AFGSMC for APF.

where $\xi(i_c)$ and $\phi(S)$ is fuzzy basis function, u_c is compensation control term.

Theorem 1: Consider shunt active power filter with disturbance represented by (5), if the control law is formulated as (14), with compensation control (17) and adaptive law (18-20), all signals in the closed-loop system is bounded and convergence of tracking errors can be guaranteed.

$$\dot{\theta}_f = r_1 CS\xi(i_c) \tag{18}$$

$$\dot{\theta}_h = r_2 CS\phi(S) \tag{19}$$

$$\dot{\hat{\omega}} = r_3 CS \tag{20}$$

Proof: Choose a Lyapunov function candidate as

$$V = \frac{1}{2}(S^2 + \frac{1}{r_1}\varphi_f^T\varphi_f + \frac{1}{r_2}\varphi_h^T\varphi_h + \frac{1}{r_3}\tilde{\omega}^T\tilde{\omega}) \tag{21}$$

where $r_1, r_2, r_3 > 0$ is a designed constant, $\varphi_f = \theta_f - \theta_f^*$, $\varphi_h = \theta_h - \theta_h^*$, $\tilde{\omega} = \hat{\omega} - \omega$.

Define optimal parameter vector

$$\theta_f^* = \arg\min_{\theta_f\in\Omega_f} [\sup_{x\in R^n} \left|\hat{f}(i_c \left| \theta_f \right.) - f(i_c)\right|] \tag{22}$$

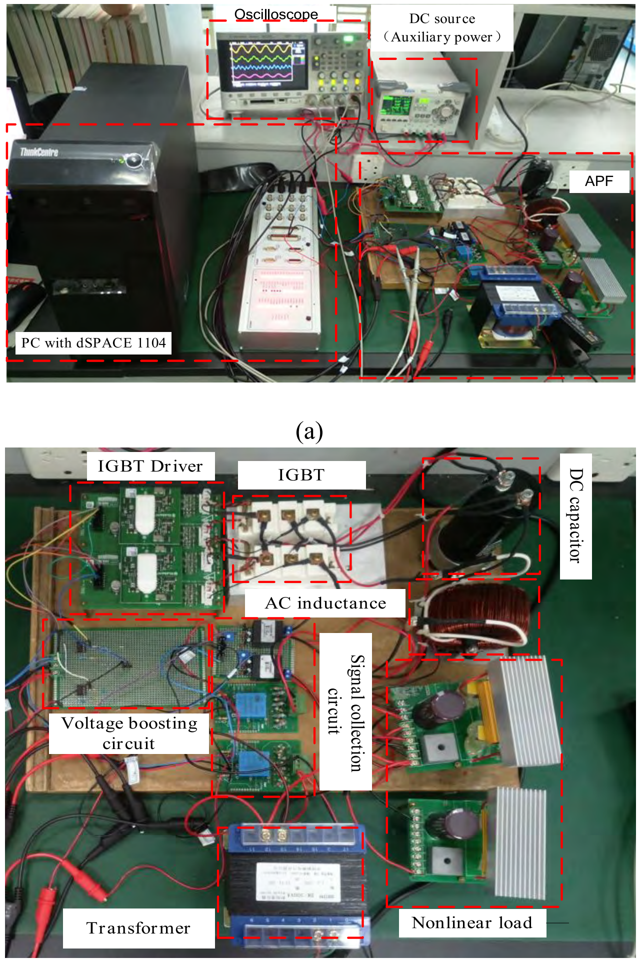
$$\theta_h^* = \arg\min_{\theta_h\in\Omega_h} [\sup_{x\in R^n} \left|\hat{h}(S \left| \theta_h \right.) - Dsgn(S)\right|] \tag{23}$$

Define optimal fuzzy approximation error

$$\omega = f(i_c) - \hat{f}(i_c \left|\theta_f^*\right.) + Dsgn(S) - \hat{h}(S\left|\theta_h^*\right.) \tag{24}$$

Based on (8) and (14), one can obtain

$$\begin{aligned}\dot{S} &= C\dot{e} - \dot{g}(t)\\ &= C(\dot{i}_c - \dot{i}_c^*) - \dot{g}(t)\\ &= C[f(i_c) + U_1 + h_1 - \dot{i}_c^*] - \dot{g}(t)\\ &= C[f(i_c) - \hat{f}(i_c) - \hat{h}(S\left|\theta_h\right.) + h_1 - u_c]\\ &= C[\hat{f}(i_c\left|\theta_f^*\right.) - \hat{f}(i_c) + \hat{h}(S\left|\theta_h^*\right.) - \hat{h}(S\left|\theta_h\right.)\\ &\quad + f(i_c) - \hat{f}(i_c\left|\theta_f^*\right.) + Dsgn(S) - \hat{h}(S\left|\theta_h^*\right.)\\ &\quad + h_1 - Dsgn(S) - \hat{\omega}]\\ &= C[-\varphi_f^T\xi(i_c) - \varphi_h^T\phi(S) + \omega + h_1 - Dsgn(S) - \hat{\omega}]\end{aligned} \tag{25}$$



(a)

(b)

FIGURE 3. Experimental prototype developed in the laboratory: (a) overall structure, (b) single-phase APF.

TABLE 1. System parameters and components for experiment.

Supply voltage and frequency	$V_s = 24V,\ f = 50Hz$
Single-phase nonlinear load	$R = 15\Omega$, $C = 1mF$
Active power filter parameters	$L_c = 10mH$, $R_c = 0.1\Omega$, $C = 2200\mu F$, $V_{dcref} = 50V$
Switching frequency	$f_{sw} = 20KHz$
AC source	IT7324, ITECH
Power IGBTs	SKM75GB12T4, SEMIKON
IGBT drivers	SKYPER_32_R, SEMIKON
Voltage sensors	CHV-25P, Beijing SENSOR
Current sensors	CSM003A, CHIEFUL
Auxiliary power supply	DP831, RIGOL

Differentiating (21) with respect to time gives

$$\begin{aligned}\dot{V} &= S\dot{S} + \frac{1}{r_1}\varphi_f^T\dot{\varphi}_f + \frac{1}{r_2}\varphi_h^T\dot{\varphi}_h + \frac{1}{r_3}\tilde{\omega}^T\dot{\tilde{\omega}}\\ &= SC[-\varphi_f^T\xi(i_c) - \varphi_h^T\phi(S) + \omega + h_1 - Dsgn(S) - \hat{\omega}]]\\ &\quad + \frac{1}{r_1}\varphi_f^T\dot{\varphi}_f + \frac{1}{r_2}\varphi_h^T\dot{\varphi}_h + \frac{1}{r_3}\tilde{\omega}^T\dot{\tilde{\omega}}\end{aligned}$$

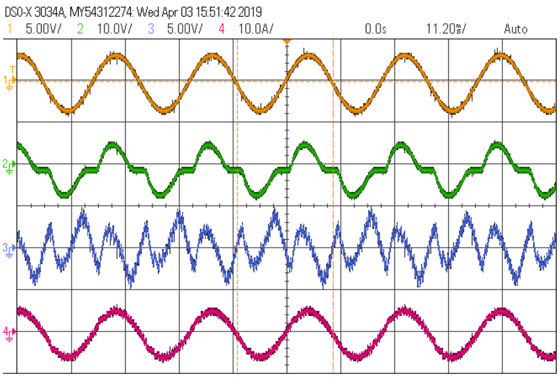


FIGURE 4. Steady-state experimental results. From top to bottom: Grid voltage, load current, compensation current, and source current.

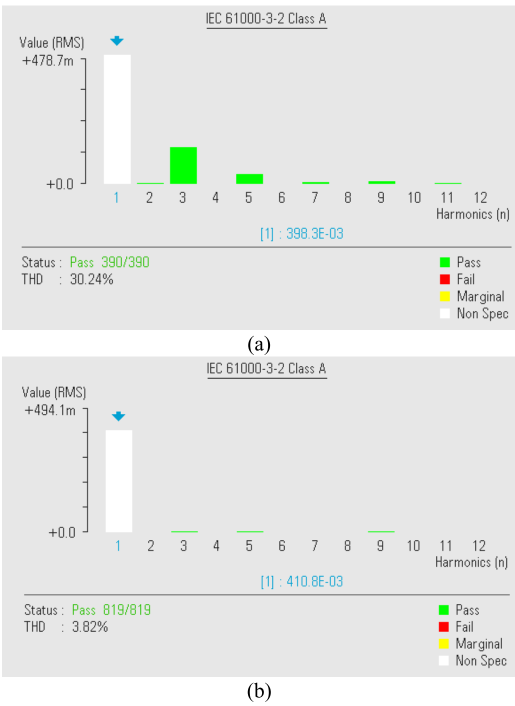


FIGURE 5. Harmonic spectrum of source current: (a) without APF, (b) with APF.

$$= -SC\varphi_f^T\xi(i_c) + \frac{1}{r_1}\varphi_f^T\dot{\varphi}_f - SC\varphi_h^T\phi(S) + \frac{1}{r_2}\varphi_h^T\dot{\varphi}_h + CS\omega - CS\hat{\omega} + \frac{1}{r_3}\tilde{\omega}^T\dot{\hat{\omega}} + CSh_1 - CSDsgn(S) \quad (26)$$

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

Substituting (18-20) into (26) leads to

$$\dot{V} = CS[h_1 - Dsgn(S)] = C[-D\,|S| + Sh_1] \leq C[-D\,|S| + |S|\,H_M] = C\,|S|\,(H_M - D) \quad (27)$$

The above inequality (27) meets $\dot{V}_1 \leq 0$ under the situation of $D \geq H_M$.The fact that $\dot{V}$ is negative semi-definite ensures that s,φ_f, φ_h and $\tilde{\omega}$ are all bounded. $\dot{s}$ is also bounded. The inequality (27) implies that s is integrable as $\int_0^t |s|d\tau \leq \frac{V(0)-V(t)}{H_M-D}$. Since $V(0)$ is bounded and $V(t)$ is nonincreasing and bounded, it can be concluded that $\lim_{t\to\infty}\int_0^t |s|d\tau < \infty$. Since $\lim_{t\to\infty}\int_0^t |s|d\tau$ is bounded and $\dot{s}$ is also bounded, according to Barbalat lemma, s will asymptotically converge to zero, $\lim_{t\to\infty} s = 0$, and $\lim_{t\to\infty} e(t) = 0$.

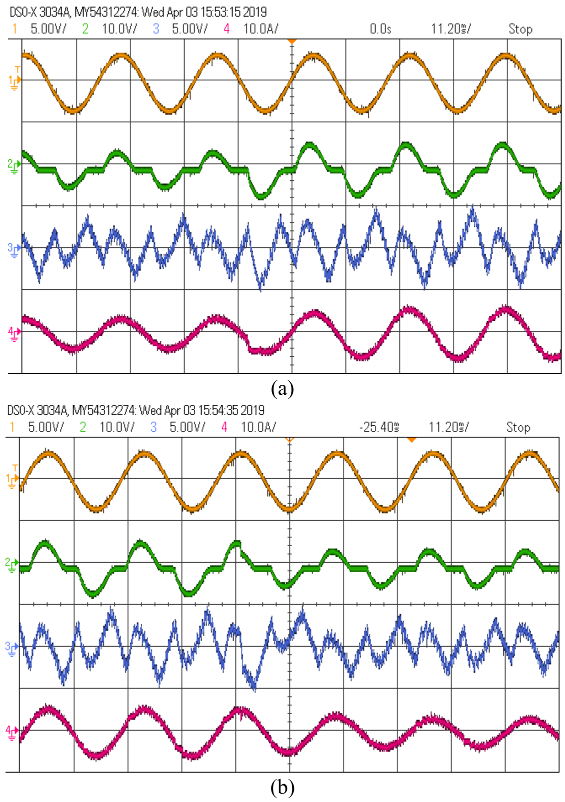


FIGURE 6. Dynamic experimental results: (a) loads increase, (b) loads decrease. From top to bottom: Grid voltage, load current, compensation current, and source current.

IV. EXPERIMENTAL RESULTS

A photograph of a reduced scale experimental prototype of single-phase APF is shown in Fig.4. Nominal values of system parameters and components are collected in Table 1. The control algorithm is implemented on a dSPACE 1104 with a sampling frequency of 20 kHz. Voltage boosting circuit is designed to convert PWM signal to meet the standards for input voltage of IGBT driver. Test results are recorded using Agilent DSO X3034A and power quality analysis module DSOX3PWR in the oscilloscope.

In the AFGSMC, $C = 100$,$r_1 = 10000$, $r_2 = 1000$, $r_3 = 10$.

It is worth mentioning here that the choice of all aforementioned design parameters may affect the tracking performances in terms of settling time and tracking accuracy. Their values are tuned during a trial-and-error process for which the outcome is a set of parameters that lead to optimal tracking performances.

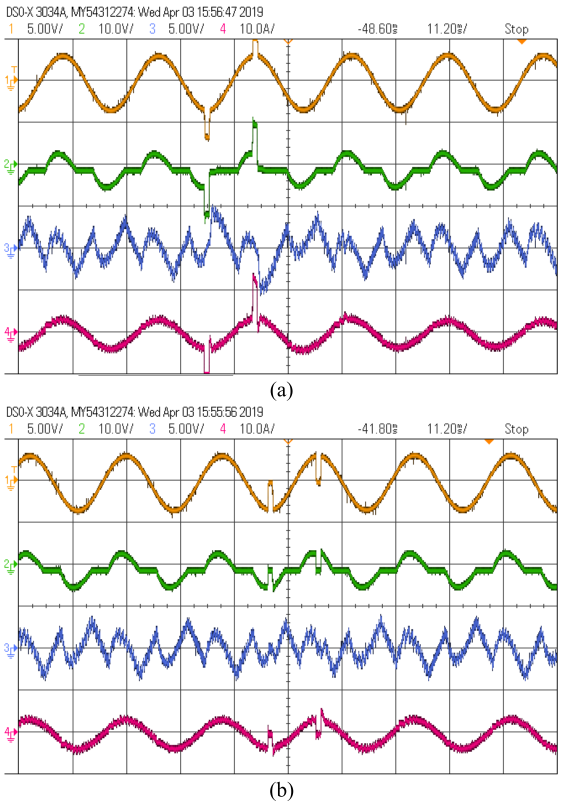


FIGURE 7. Experimental results under abnormal grid-voltage: (a) voltage swell,(b)voltage sag. From top to bottom: Grid voltage, load current, compensation current, and source current.

The performance of proposed control algorithm for APF has been tested in the following conditions:

1) steady-state performance
2) dynamic performance to load variations
3) compensation performance under abnormal grid voltage
4) compensation performance with parameter variations
5) control methods comparison

A. STEADY-STATE PERFORMANCE

Figs.4 and 5 show the steady-state performance of APF under nonlinear load. Fig.4 depicts the waveforms of grid voltage, load current, compensation current and source current. It should be noted that there is no upper convexities and lower concavities in the source current, revealing stable control performance of proposed AFGSMC. Fig.5 shows that the harmonic currents are efficiently compensated and source current is almost sinusoidal a small THD around 3.82% whereas the load current is highly distorted with a THD around 30.24%. So the effectiveness of the proposed control method is verified achieve a THD below of the standard requirement.

B. DYNAMIC PERFORMANCE TO LOAD VARIATIONS

To evaluate the dynamic response performance of the proposed control strategy with load variations, the following two cases are set up: (1) loads increase, (2) loads decrease.

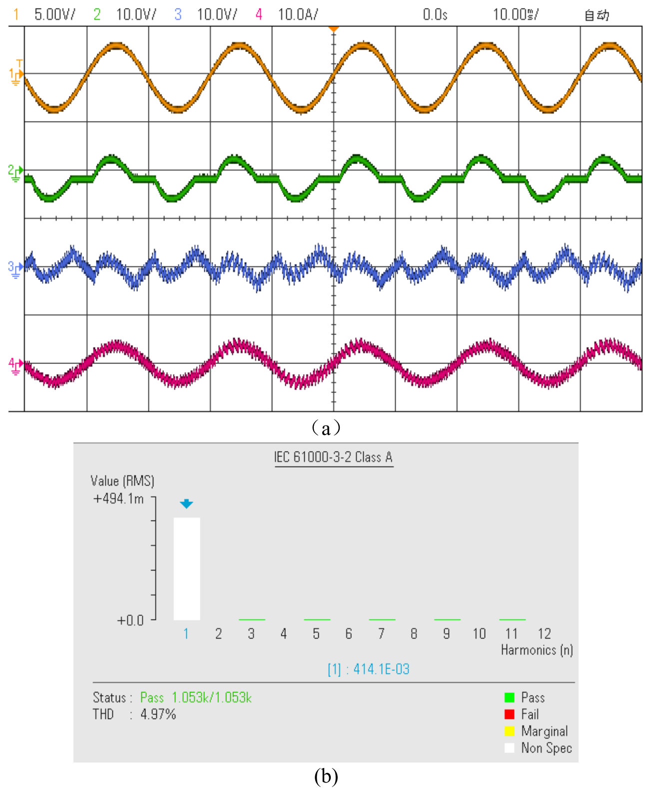


FIGURE 8. Experimental results using AFSC. From top to bottom: Grid voltage, load current, compensation current, and source current.

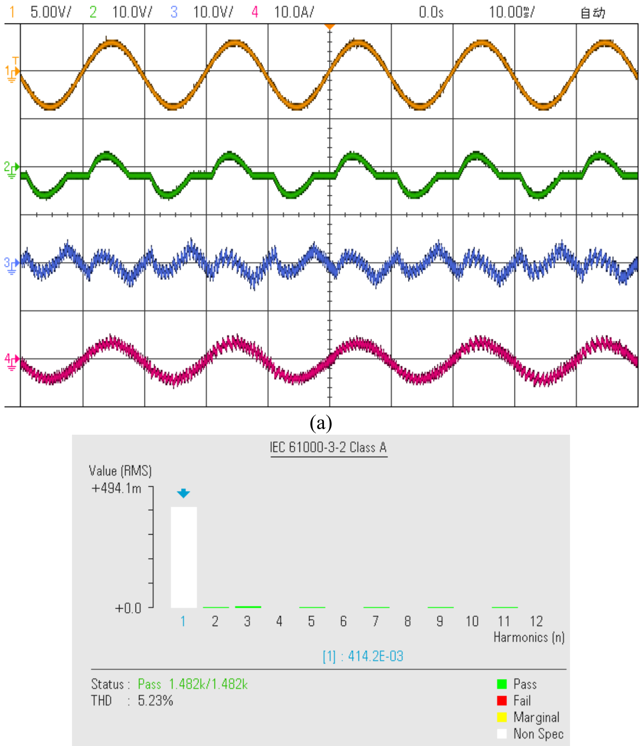
TABLE 2. The effect of parameter variations.

AC inductance(mH)	DC capacitor(μF)	THD
10	2200	3.82%
8	2200	4.13%
6	2200	4.84%
10	1100	4.01%
10	733	4.18%

Fig.6 shows the response of the system when the load suddenly increases and decreases. The waveform is grid voltage, load current, compensation current and source current, respectively. As shown in Fig.6, the compensation current quickly responds to changes to achieve efficient harmonic suppression no matter the load suddenly increase or decrease. Thus it is verified through experiments that APF with AFGSMC has good steady-state performances as well as good dynamic responses.

C. APF PERFORMANCES UNDER ABNORMAL GRID VOLTAGE

Compensation performances under abnormal grid voltage are shown in Fig.7. The main purpose of this test is to study the following two aspects:(a)voltage swell, (b) voltage sag. The waveform is grid voltage, load current, compensation current and source current, respectively. In each case, the APF maintains a sinusoidal source current. Therefore, the performance of proposed current control method for APF is satisfactory with abnormal grid voltage.



(a)

(b)

FIGURE 9. **Experimental results using AFBC. From top to bottom: Grid voltage, load current, compensation current, and source current.**

D. APF PERFORMANCES UNDER PARAMETER VARIATIONS

In order to demonstrate that AFGSMC has strong robustness in the presence of parameter variation, an APF with the parameter variation is testified. As shown in Table 2, the THD is still in the normal range with the parameter variation. It can be concluded that AFGSMC has good robustness to the parameter uncertainties.

E. CONTROL STRATEGIES COMPARISON

The effectiveness of proposed AFGSMC can be further verified by comparison experiments. Experimental results with adaptive fuzzy backstepping control (AFBC) [13] and adaptive fuzzy sliding control (AFSC) [19] presented are shown in Fig.8 and Fig.9. It is worth noted that these two control strategies both are effective for APF to eliminate the harmonics. According to THD, proposed AFGSMC scheme has over 24% and 28% harmonic suppression improvements than AFSC and AFBC, respectively.

V. CONCLUSION

In this paper, an adaptive fuzzy global sliding mode control is proposed for single-phase active power filter. To further enhance the global robust performance of APF, global sliding mode controller is designed to provide good global robustness against unknown disturbances and parameter perturbations. In order to cope with sensor fault and eliminate chattering, fuzzy system is utilized to estimate unknown parameters and switching term. Moreover, a compensation control item is designed by using fuzzy approximation error adaptive estimation technique. The parameters of AFGSMC can be adaptively updated based on the Lyapunov analysis and the stability of the closed-loop system can be guaranteed with the proposed control strategy. The performances of the proposed controller are analyzed and compared with other intelligent control strategies. It has been shown that APF using proposed AFGSMC has good performance in both steady-state and dynamic operations under normal and abnormal grid voltage even with parameter variations.

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