Experimental Validation of Modified Adaptive Fuzzy Control for Power Quality Improvement

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ABSTRACT
This study aims to present a modified adaptive fuzzy control (MAFC) for power quality improvement, whereby adaptive fuzzy control with parameter adaptive capability is employed to emulate optimal control. Different from conventional fuzzy control-based current control method without analytical tools to guarantee basic performance criteria, high-performance control system can be realized using Lyapunov-based adaptive fuzzy control. Also, in order to compensate the fuzzy approximation error (FAE) in conventional fuzzy control, a modified adaptive fuzzy control with adaptive compensator is developed. Unlike the existing approaches, adaptive compensator can estimate the optimal value of FAE with no need of upper bound of FAE. Simulation and experimental results verify that proposed control strategies reveal superior performance under different conditions.

INDEX TERMS
Power quality, adaptive fuzzy control, adaptive estimation, active power filter.

I. INTRODUCTION
In recent years, power electrical devices have drawn more and more attention [1], [2]. Since the harmonics, produced by increasing power electrical devices, cause additional loss of motors and damage electrical equipments, harmonic filter plays a critical role in power systems [3], [4]. By removing harmonic currents from the grid, passive power filters play a pivotal role as conventional solutions. However, with the disadvantages of fixed compensation, it will lead to over-compensation and under-compensation. In addition, reactive power and harmonic current cannot be compensated at the same time, especially for nonlinear loads with large fluctuation. Furthermore, with the increasing requirements of satisfactory power quality, the development of active power filter (APF) becomes a general concern [5]–[7]. APFs present clear advantages such as increased frequency range, accelerated dynamic response, etc. Since performance of APF mainly depends on the current control loop, there are various current control techniques present in literature, e.g., PI control, repetitive control [8], model predictive control [9], sliding mode control [10], etc. However, the challenge for these control methods is highlighted when APF is adopted to eliminate harmonics caused by dynamic loads, where it was found that the deterioration of power quality is more serious during the variations, which leads to the parameter fluctuations and even unstable steady state compensation. Therefore, significant improvements are being foreseen to carry out control schemes that could result in enhanced robust control over harmonics from the perspective of dynamic loads [11], [12].

In the past decades, fuzzy logical control for various classes of nonlinear systems have received sustained attention due to the capabilities like robustness, model-free, and universal approximation theorem, and the novel design schemes have been reported, for example [13]–[17]. In [18], [19], fuzzy control is utilized to further develop effective control strategies during steady/dynamic states. However, the majority of these control implementations suffer from the lack of a rigorous theoretical analysis to obtain basic performance criteria [20]. Fuzzy control becomes a more powerful tool for adaptive robust application owing to universal approximation theorem [21]. Moreover, as discussed in [20], the problem of optimal fuzzy approximation error (FAE) also cannot be neglected. By assuming that the optimal FAE is square integrability, Wang added an auxiliary control term to guarantee
closed-loop stability. Nevertheless, it is not easy to obtain the supremum of nonlinear functions in auxiliary control term and above assumption also cannot be validated. In order to tackle this problem, a variable structure control term is designed to compensate the approximate error. The strategy needs to know the upper bound of the optimal FAE, but it is difficult to get the upper bound of the optimal FAE. In addition, it will inevitably lead to high gain and chattering. To solve this problem, Sun et al. [22] used the adaptive law to estimate the optimal value of the optimal FAE. This is also the most common method for dealing with optimal FAE [23]–[26].

As discussed above, to design a controller for APF, we have the following problems.

1) The dynamics of APF in practical applications are uncertain, while in most existing works, only some parametric uncertainties are considered, the effects of dynamic loads have not been investigated fully.

2) Fuzzy logic has been widely applied to enhance control performance for active power filter [27]–[31]. However, the majority of these proposals are designed without rigorous theory analysis to ensure basic performance criteria, especially systematic stability. As we know, the rigorous stability analysis is the first condition for reliable operation of control system.

3) The problem of optimal fuzzy approximation error (FAE) in adaptive fuzzy control structure has not been considered in the existing literature addressing APF control strategies.

Motivated by the above issues, in this study, a modified adaptive fuzzy control with adaptive estimation technique is presented for APF.

The major contributions of the study are listed as follows:

1) From the perspective of dynamic loads and parameter fluctuations, these uncertain factors during the operation process will reduce the reliability and efficiency of APF even leading to unstable steady state compensation. Thus, it is essential to design the APF control system that provides the superior robustness. Due to the property of adaptive fuzzy control that is robustness and model-free, an adaptive fuzzy control scheme for APF is designed to improve the current tracking and harmonic-suppress performance.

2) Adaptive compensator is designed to avoid the high gain and chattering problem caused by the compensation items in 23]. Moreover, the assumptions that the fuzzy approximation error is square integrable in [21] are relaxed, and asymptotic property of tracking error is guaranteed in the proposed control strategy. The fuzzy parameters are adjusted online by the adaptive laws derived from the Lyapunov stability analysis to assure the closed-loop stability.

3) This study solves the problem of modeling and control for APF by using modified adaptive fuzzy control, which not only develops fuzzy control theory, but also has some theoretical guidance significance for intelligent control in power electronic dominated nonlinear system. Simulation and experimental results also verify the effectiveness of the proposed MAFC.

The rest of the paper is listed as follows. Section II gives the dynamic model of current control system for APF with the lumped uncertainties. The proposed MAFC for APF is presented in Section III. Detailed simulation and experimental results demonstrate the accurate and robust control abilities of MAFC in Section IV and Section V. Finally, Section VI shows the conclusions.

II. PROBLEM FORMULATION

In this section, we consider a single-phase active power filter, as shown in Fig. 1. The mathematical model for APF inner current loop can be performed as [32], [33]

\[ i_c = f(i_c) + U + H \]  \hspace{1cm} (1)

where \( f(i_c) = -\frac{R_1}{L_1}i_c + \frac{U}{L_1} \), \( U = -\frac{U_{dc}}{L_1}u \). \( H \) represent the lumped uncertainties.

The tracking error is defined as:

\[ e = i_c - i_{c}^* \]  \hspace{1cm} (2)

And the derivative of \( e \) is:

\[ \dot{e} = i_c - i_{c}^* \]  \hspace{1cm} (3)

Then the optimal controller is designed as:

\[ U^* = -f(i_c) + i_{c}^* - D\text{sgn}(e) \]  \hspace{1cm} (4)

Assumption 1: The uncertainties \( H \) are bounded to satisfy

\[ |H| \leq H_M \]  \hspace{1cm} (5)

where \( H_M \) is a positive constant.
**Proof:** Choose a Lyapunov function as

\[ V_1 = \frac{1}{2} e^2 \]  

(6)

Differentiating (6) with respect to time, one can obtain:

\[ \dot{V}_1 = e \dot{e} = e[f(i_c) + U + H - \hat{\theta}^*] \]  

(7)

Substituting (4) into (7) leads to

\[ \dot{V}_1 = e[H - D \text{sgn}(e)] \leq -D|e| + |e|HM \leq |e|(HM - D) \]  

(8)

The above inequality meets \( \dot{V}_1 < 0 \) if we properly choose \( D \) as \( D > HM \). According to Barbalat lemma, \( e(t) \) will asymptotically converge to zero, \( \lim_{t \to \infty} e(t) = 0 \).

However, the optimal controller depends on the dynamic of APF, which is uncertain in industry oriented control object. So the controller (4) need to be further modified. To relieve the defects, a modified adaptive fuzzy control is developed in the next part.

**III. MODIFIED ADAPTIVE FUZZY CONTROL (MAFC)**

In the previous discussion, we need know the dynamics of APF to achieve the optimal controller. On the other hand, there exists chattering phenomenon if a larger \( D \) is selected. Therefore, in order to increase the tracking capability, relax the restrictions using optimal controller, and reduce chattering, the proposed modified adaptive fuzzy control with adaptive compensator in this section.

**Assumption 2:** the optimal approximation error \( \omega \) is bounded such that there exists a constant to satisfy \( |\omega| \leq \omega_{\text{max}} \), and \( \dot{\omega} = 0 \).

Using adaptive fuzzy control technique [34], following controller is designed as:

\[ U_1 = uD(i_c | \theta) - u_c \]  

(9)

\[ u_c = \omega_{\text{max}} \text{sgn}(e) \]  

(10)

\[ \dot{\theta} = -\gamma e \xi(i_c) \]  

(11)

where \( uD(i_c | \theta) = \sum_{i} \theta_i \xi(i_c) = \theta^T \xi(i_c) \), \( \xi(i_c) \) is fuzzy basis function, \( u_c \) is compensation control term, which is utilized to overcome the defects of FAE, \( \text{sgn}(\cdot) \) is sign function.

**Proof:** Choose a Lyapunov function as

\[ V_2 = \frac{1}{2} e^2 + \frac{1}{2\gamma} \hat{\theta}^T \hat{\theta} \]  

(12)

where \( \gamma \) is a designed positive constant, \( \hat{\theta} = \theta - \theta^* \).

Based on (4), \( f(i_c) \) can be defined as

\[ f(i_c) = i_c^* - D \text{sgn}(e) - U^* \]  

(13)

Using (13), (1) can be rewritten as

\[ \dot{i}_c = i_c^* - D \text{sgn}(e) - U^* + U + H \]  

(14)

Then we can obtain

\[ \dot{e} = -U^* + uD(i_c | \theta) - u_c + H - D \text{sgn}(e) \]  

(15)

Optimal parameter vector can be defined as

\[ \theta^* = \arg \min_{\theta \in \mathbb{R}^n_{i_c \in \mathbb{R}}} \sup_{i \in \mathbb{R}} |u^* - uD(i_c | \theta)| \]  

(16)

Optimal fuzzy approximation error can be given as

\[ \omega = uD(i_c | \theta^*) - u^* \]  

(17)

Then (15) can be rewritten as

\[ \dot{e} = \omega - uD(i_c | \theta^*) + uD(i_c | \theta) - u_c + H - D \text{sgn}(e) \]  

(18)

Differentiating (12) with respect to time gives

\[ \dot{V}_2 = \frac{1}{\gamma} \hat{\theta}^T [\gamma e \xi(i_c) + \hat{\theta}] - eu_c + e\omega + e[H - D \text{sgn}(e)] \]  

(19)

Using (10) and (11), (19) can be rewritten as

\[ \dot{V}_2 \leq |e|(|\omega| - \omega_{\text{max}}) + e[H - D \text{sgn}(e)] \leq |e|H - |e|HM \leq |e|HM - D \]  

(20)

The above inequality meets \( \dot{V}_2 < 0 \) if we properly choose \( D \) as \( D > HM \). The fact that \( \dot{V} \) is negative definite ensures that \( V_2, e, \hat{\theta} \) are all bounded. \( \dot{e} \) is also bounded. The inequality (20) implies that \( e \) is integrable as \( \int_{0}^{t} |e|d\tau \leq \frac{\sqrt{\dot{V}(0)} - \sqrt{\dot{V}(t)}}{HM - D} \). Since \( V_2(0) \) is bounded and \( V_2(t) \) is nonincreasing and bounded, it can be concluded that \( \lim_{t \to \infty} \int_{0}^{t} |e|d\tau \) is bounded. Since \( \lim_{t \to \infty} \int_{0}^{t} |e|d\tau \) is bounded and \( \dot{e} \) is also bounded, according to Barbalat lemma, \( e(t) \) will asymptotically converge to zero, \( \lim_{t \to \infty} e(t) = 0 \).

However, it is difficult to get \( \omega_{\text{max}} \) in practical applications. Though \( \omega_{\text{max}} \) can be selected by trial-and-error method, too large \( \omega_{\text{max}} \) leads to the increasing of the chattering phenomena caused by the term \( \omega_{\text{max}} \text{sgn}(e) \) in (10). Hence, to overcome these drawbacks, a modified adaptive fuzzy control with adaptive compensator, shown in Fig.2, is designed in the following section. The key idea of MAFC is to use adaptive estimation technology to identify approximation error to ensure excellent control performance with closed-loop system stability.

Using adaptive estimation technique, (10) can be rewritten as

\[ \dot{u}_c = \hat{\omega} \]  

(21)

\[ \dot{\hat{\omega}} = \gamma e \hat{e} \]  

(22)

\[ \dot{\theta} = -\gamma_1 e \xi(i_c) \]  

(23)

**Proof:** Choose a Lyapunov function as

\[ V_3 = \frac{1}{2} e^2 + \frac{1}{2\gamma} \hat{\theta}^T \hat{\theta} + \frac{1}{\gamma_2} \hat{\omega}^T \hat{\omega} \]  

(24)
where $\gamma_1, \gamma_2$ is given positive constants, $\tilde{\phi} = \theta - \theta^*$, $\tilde{\omega} = \hat{\omega} - \omega$, $\hat{\omega}$ is the estimate of fuzzy approximation error.

Then (15) can be rewritten as

$$\dot{e} = (\theta - \theta^*)^T \xi(i_c) + \hat{\omega} + \omega + H - Dsgn(e)$$

(25)

Differentiating (24) with respect to time gives

$$\dot{V}_3 = \frac{1}{\gamma} \tilde{\phi}^T [ye\xi(i_c) + \tilde{\phi}] - e\dot{\omega} + \frac{1}{\gamma_2} \tilde{\omega} \dot{\tilde{\omega}} + e[H - Dsgn(e)]$$

(26)

Using (21)-(23), we can rewrite (26) as

$$\dot{V}_3 \leq e[H - Dsgn(e)]$$

$$\leq -D|e| + |e|HM$$

$$\leq |e| (HM - D)$$

(27)

The above inequality meets $\dot{V}_3 < 0$ if we properly choose $D$ as $D > HM$. The fact that $\dot{V}_3$ is negative definite ensures that $V_3, e, \hat{\theta}, \tilde{\omega}$ are all bounded. $\dot{e}$ is also bounded. $e(t)$ will asymptotically converge to zero.

Remark 1: The proposed MAFC as (9) is based on the direct adaptive fuzzy control framework in [34]. Optimal parameter vector and optimal fuzzy approximation error also are designed in the same form as [34], $u_c$ as (21), $\tilde{\omega}$ as (22), and $\theta$ as (23) is selected to achieve $\dot{V}_3 < 0$ leading to the closed-loop stability in the framework of Lyapunov analysis.

IV. SIMULATION RESULTS

In this section, detailed simulation studies are carried out using Matlab/Simulink to show the validity of the proposed MAFC for APF. The details of simulation parameters are listed in Table 1. The performance of control scheme has been tested in the following aspects: 1) steady-state compensation; 2) dynamic response to load fluctuation.

In Fig. 3, membership functions of fuzzy controller are chosen as

$$\mu = \exp(-(x + 15 - (i - 1)7.5)/3.75), \ i = 1, \ldots, 5.$$
Compared with GSMC, fuzzy neural control with structural adjustment is utilized to estimate uncertain function for SOGSMC in [33]. As can be seen from Table 2, THD of the proposed MAFC is lower than GSMC, but a little higher than SOGSMC. However, the design of fuzzy neural estimator with structural adjustment for SOGSMC is computationally expensive. Therefore, the proposed MAFC can realize a tradeoff between filter performance and computational burden.

V. EXPERIMENTAL RESULTS

In this section, the experimental results of MAFC for APF are presented. A single-phase APF prototype is built based on DSP TMS320F28335 shown in Fig. 7, whose main parameters have been listed in Table 3. Sampling frequency of TMS320F28335 floating point digital signal processor is set as 20kHz. The steady-state experimental waveforms are presented in Figs. 8 and 9. Fig. 8 presents the steady-state waveforms of grid side voltage, load current, compensation current and grid side current. It is seen that there exists high-frequency oscillation in the load current with a high THD of 26.04%. Using APF with the proposed MAFC, the grid side current becomes purely sinusoidal and the THD is kept at a very low level of 4.14% which is fully compatible with IEEE standards. The dynamic experimental results when nonlinear loads add or lessen are presented in Fig. 10. One can see that grid side currents still remain sinusoidal waves even with
FIGURE 5. Dynamic simulation results. (a) Load current. (b) Source current. (c) Compensation current and reference current. (d) Tracking error. (e) DC voltage.
FIGURE 6. Harmonic spectra of load current and source current. (a) load current at 0.2s. (b) source current at 0.2s. (c) load current at 0.4s. (d) source current at 0.4s. (e) load current at 0.7s. (f) source current at 0.7s. (g) load current at 1.1s. (h) source current at 1.1s.
TABLE 3. System parameters for experiment.

| Parameter                              | Value                              |
|----------------------------------------|------------------------------------|
| Grid voltage                           | $V_s = 240 V, f = 50Hz$            |
| Nonlinear loads                        | $R = 15 \Omega, C = 1mF$           |
| Active power filter parameters         | $I_o = 10mA, R = 0.1\Omega, C = 2200\mu F, v_{ref} = 50V$ |
| Switching frequency                    | $f_s = 20KHz$                      |
| Power IGBTs                            | SKM75GB12T4, SEMIKON               |
| IGBT drivers                           | SKYPER 32_R, SEMIKON               |
| Voltage sensors                        | CHY-255, Beijing SENSOR            |
| Current sensors                        | CSM01A, CHIFUL                     |
| Auxiliary power supply                 | DPF31, RIGOL                       |

Remark 2: The advantages of MAFC for APF can be summarized as follows: (1) a modified adaptive fuzzy control is developed for APF enhancing robust control performance over harmonics from the perspective of dynamic loads; (2) the online learning algorithms of fuzzy control are derived from the Lyapunov stability analysis to guarantee tracking performance and stability of the closed-loop system; (3) adaptive estimation technology is used to identify fuzzy approximation error to remove the assumptions that the fuzzy approximation error is square integrable in [21].

Remark 3: It should be noteworthy that the state signals and control input signals are restricted into certain regions owing to the specific system structure for practical applications generally [35]. In the experimental results, the compensation current and control input signals are limited to the following region: $-15A < i_c < 15A$ and $0V \leq U \leq 3V$. Due to the given constraints, the assumptions of $|H| \leq H_M$ and $|\omega| \leq \omega_{max}$ are reasonable. $H_M$ and $\omega_{max}$ also can be designed conservatively without the detailed system dynamic. In addition, the values of $H_M$ and $\omega_{max}$ both are not used in the proposed MAFC.

Remark 4: The detailed membership function selection criteria are listed as follows. Firstly, Gaussian membership function is determined due to its high-efficiency. Then, the range of membership functions should be set based on the region of compensation current: $-15A < i_c < 15A$. Finally, the number of membership functions should be properly chosen. It is noteworthy that more membership functions imply heavier computational complexity, but higher precision control. Thus, a tradeoff between the membership functions and the accurate...
fuzzy controller for APF due to its better control performance than traditional fuzzy control [36]–[38].

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