PID-Fuzzy Control Method with Time Delay Compensation for Hybrid Active Power Filter with Injection Circuit

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ABSTRACT
Due to inherent time delays in the control system of Hybrid Active Power Filter with Injection Circuit (IHAPF) and the load harmonic currents changes rapidly and dramatically. In order to eliminate these harmonic currents, an IHAPF to be used must be able to respond quickly following variable of the harmonic currents. So, this paper proposes a PID-fuzzy control method with time-delay compensation for IHAPF. It is composed of PID-fuzzy controller and π-Smith predictor. The purpose of the fuzzy adjustor is to on-line update parameters of the PID controller, while π-Smith predictor is designed to time delay compensation and make a 180 degree delay between output current of IHAPF and load harmonic current. Compared to other IHAPF control methods, the proposed control method shows the advantages of shorter response time and higher precision. It is implemented in IHAPF model in laboratory. Simulation and experimental results demonstrated the feasibility and validity of the proposed control method.

Keywords
Hybrid Active Power Filter, fuzzy control, π-Smith predictor, PI control, time delay.

1. INTRODUCTION
In recent years, the increasing use of power electronics based loads connected to the grid is one of the causes of rising harmonics in power system. In order to solve harmonic problems, the passive power filter (PPF) [1], [2] is often used. Although, it has simple structure and is least expensive, the PPF inherits several disadvantages due to resonance, instability, mistuning, very difficult to improve total harmonic distortion and no capability online compensation, etc. From here, the Active Power Filter (APF) [3], [4] appears to be the solution for eliminating harmonic current and reactive power compensation; it is often parallel-connected with non-linear load, which has capability online compensation tracking harmonic current of nonlinear load. Nevertheless, it is limited by high cost, low-power capacity and is difficult to use in high-voltage grids. Another solution to cancel harmonic problem is to adopt a hybrid active power filter (HAPF) [5], [6]. The HAPF is the combination of active power filter and passive power filters. The aim of HAPF design is to reduce APF capacity. Beside, the HAPF inherits the advantages of both passive filter and active power filter. The IHAPF [7] is a novel HAPF with injection circuit; it has great promise in reducing harmonics with a relatively low capacity APF.

The control methods which have been used for IHAPF can be listed as follows: PI, hysteresis, fuzzy, neural network, adaptive network based fuzzy inference system (ANFIS) control methods, etc. The conventional PI control method has many advantages such as simple structure, easy use [8]. However, the K_P, K_I parameters are fixed during the whole control process. Therefore, with fast variable nonlinear loads, the dynamic response of the PI controller will not be good. The hysteresis control is characterized by its simplicity, fast response but its disadvantages depend on a widely varying switching frequency [9]. With the fuzzy logic control method then it is seen as conceptually easy to understand, flexible and can be combined with conventional control techniques [10], [11]. However, the input-output memberships are fixed and cannot be studied during the whole control process and its parameters depend on experience. If the controller uses neural network [12], the result is based on the training algorithm. The neural network controller can learn but the response is relatively slow and the transient time is large. The adaptive network based fuzzy inference system [13] uses techniques such as hybrid or back propagation learning rules to determine the input membership functions, following that the input membership functions after learning will give the desired results in output. Though ANFIS controller also has some drawbacks such as: much have a given training data sets, have a single output, namely the number of output membership functions must be equal to the number of rules, have unity weight for each rule. So, if the system only uses a single ANFIS controller then it is very difficult to achieve good results.

Another control method used for HAPF is the model predictive control (MPC) [14]-[17]. The basic of MPC is to calculate a sequence of future control signals in such a way that it minimizes a cost function defined over a prediction horizon. This control method is very suitable for nonlinear controls. However, the implementation of a practical system can be difficult and complex.

This paper presents a PID-fuzzy control method with time delay compensation for IHAPF. It is composed of PID-fuzzy controller and π-Smith predictor. Therefore, this control method has both online tuning and time-delay compensation ability.

This paper is organized as follows: section 1 gives the introduction of the former research on IHAPF. The topology and control strategy of the IHAPF are highlighted in section 2. Section 3 presents the proposed control method for IHAPF. Experimental and simulation results are presented in section 4. Finally, conclusions are drawn in section 5.

2. TOPOLOGY AND CONTROL STRATEGY OF IHAPF

2.1 Topology of IHAPF

Topology of IHAPF is presented as shown in Fig. 1.

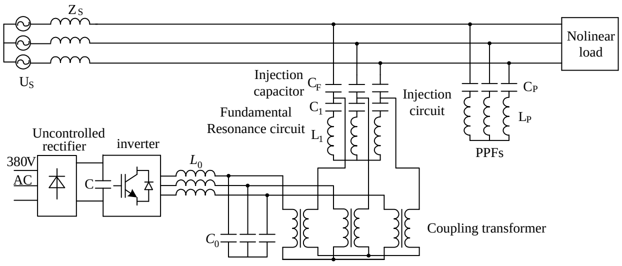


Fig 1: Topology of the IHAPF

where: U_s and Z_s are the supply voltage and equivalent impedance of the grid, respectively. $C_F, C_1, L_1, C_P, L_P, L_0$, C_0 are the injection capacitor, fundamental resonance capacitor, fundamental resonance inductor, the PPF_S capacitor and inductor, the output filter inductor and capacitor, respectively. APF consist of: uncontrolled rectifier, voltage source inverter, an output filter with capacitor C_0 and inductor L_0 to eliminate switching ripples, coupling transformer. To further decrease the rate of APF, a circuit $C_F - C_1 - L_1$ is added. C_1 and L_1 tune at the fundamental frequency and then compose with the injection branch C_F. Nonlinear load is the same as source generated harmonics. Most harmonics suppression and reactive power compensation are implemented by passive power filters (PPFs). The APF only compensates the residential harmonics. So, the power rating of APF is reduced.

2.2 Control Strategy of IHAPF

Single-phase equivalent circuit is shown in Fig. 2.

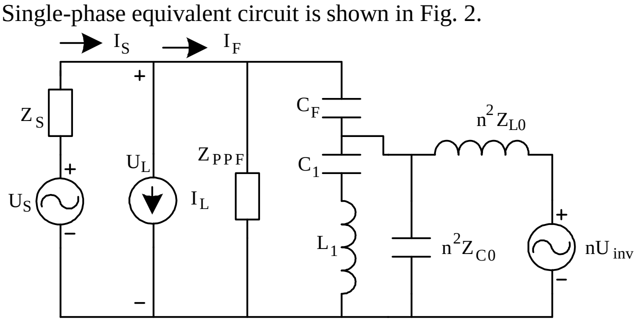


Fig 2: Single - phase equivalent circuit of IHAPF

where:

$$Z_{PPFs} = (Z_{C_{P1}} + Z_{L_{P1}}) // (Z_{C_{P2}} + Z_{L_{P2}})$$
(1)

Only considering the response of the controlled voltage source U_{inv}, the voltage source U_s and the load harmonic current I_L are both set to zero.

Single-phase equivalent circuit when only the controlled voltage source U_{inv} is considered as shown in Fig. 3.

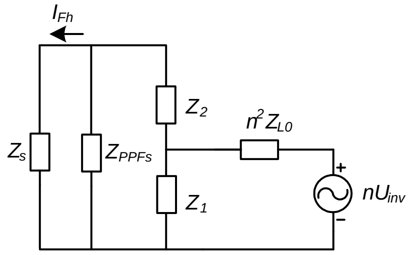


Fig 3: Single-phase equivalent circuit when only the U_{inv} is considered.

where:

$$\begin{cases} Z_s = R_s + L_s s; Z_2 = \dfrac{1}{C_F s}; \ Z_{L0} = R_0 + L_0 s \\ Z_1 = Z_{L_1C_1} // n^2 Z_{C0} = \left(R_1 + L_1 s + \dfrac{1}{C_1 s}\right) // \dfrac{n^2}{C_0 s} \end{cases} \quad (2)$$

From Fig. 3, we can calculate harmonic current injection to the power grid by IHAPF:

$$I_{Fh} = \\ = \frac{nU_{inv}.Z_1.Z_{PPFs}}{n^2 Z_{L0}[Z_{PPFs}(Z_1+Z_2)+Z_s(Z_1+Z_2+Z_{PPFs})]+Z_1(Z_2Z_s+Z_2Z_{PPFs}+Z_{PPFs}Z_s)} \quad (3)$$

Equation (3) indicates that, compensation harmonic current is determined by the controlled voltage source and response of the output circuit.

Supposing the transfer function of compensation harmonic current I_{Fh} to inverter output voltage U_{inv} is $G_{out}(s)$.

$$G_{out}(s) = \frac{I_{Fh}}{U_{inv}} = \\ = \frac{n.Z_1.Z_{PPFs}}{n^2 Z_{L0}[Z_{PPFs}(Z_1+Z_2)+Z_s(Z_1+Z_2+Z_{PPFs})]+Z_1(Z_2Z_s+Z_2Z_{PPFs}+Z_{PPFs}Z_s)} \quad (4)$$

The parameters of the output circuit are fixed during the whole control process. The voltage source inverter (VSI) in IHAPF is controlled as a voltage source. Following this, the two proposed control strategies for IHAPF are: control strategy based on load harmonic current detection and control strategy based on source current detection. In this paper, the control strategy based on load harmonic detection is selected. Single-phase equivalent circuit with the effect of a harmonic source is shown in Fig. 4.

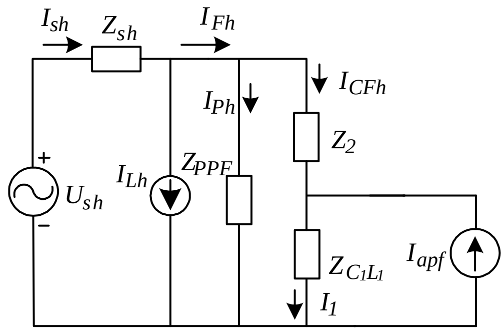


Fig 4: Single-phase equivalent circuit with the effect of a harmonic source

Where: Z_{C1L1} is impedance of the fundamental resonance circuit and APF is considered a controlled current source I_{apf}.

From Fig. 4 we can see that: if we can achieve the control goal $I_{Fh}(s) = -I_{Lh}(s)$ then the following goal can be obtained $I_{sh}(s) = 0$.

where: $I_{apf} = KI_{Lh}$ from Fig. 4 we can se that

$$\begin{cases} I_{sh} = I_{Lh} + I_{Fh} \\ I_1 = I_{apf} + I_{CFh} \\ I_{Fh} = I_{Ph} + I_{CFh} \\ I_{sh}Z_{sh} + I_{Ph}Z_{PPF} = U_{sh} \\ I_{CFh}Z_2 + I_1 Z_{C1L1} = I_{Ph}Z_{PPF} \end{cases} \quad (5)$$

From (5), I_{sh} can be calculated as

$$I_{sh} = \frac{(Z_2 + Z_{C1L1} - KZ_{C1L1})Z_{PPF}\, I_{Lh}}{(Z_2 + Z_{C1L1})(Z_{PPF} + Z_{sh}) + Z_{PPF}\, Z_{sh}} \quad (6)$$

Equation (6) indicates that it is possible to eliminate the influence of the load harmonic current and supply harmonic current as low as possible if K is large enough. K is controlled gain and it depends on the chosen control method.

Based on the detected harmonic current in load, the APF can compensate harmonics by making the inverter generate harmonics whose magnitude is equal to I_{Lh} but the phase is the opposite of it. The VSI in turn will generate desired compensation harmonic currents. Control strategy based on load harmonic current detection is shown in Fig. 5.

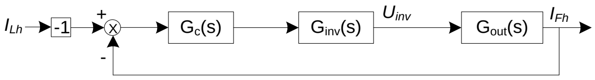


Fig 5: Control strategy based on load harmonic current detection

where: $G_c(s)$, $G_{inv}(s)$ and $G_{out}(s)$ are the transfer functions of the controller, voltage source inverter and output circuit, respectively.

3. PROPOSED CONTROL METHOD FOR IHAPF

Proposed control method for IHAPF is shown in Fig. 6

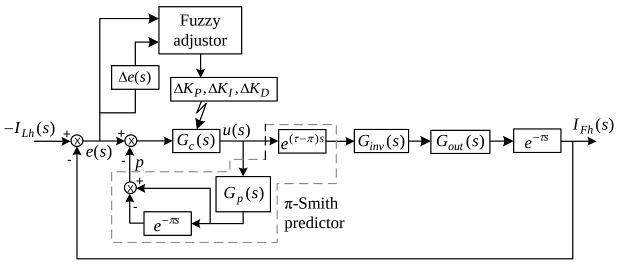


Fig 6: Proposed control method for IHAPF

3.1 π-Smith predictor for IHAPF

The purpose of using π-Smith predictor is to time delay compensation and making a 180 degree delay between output current of IHAPF and load harmonic current. From the proposed control strategy in Fig. 5, we can see that the output current of IHAPF into grid is through the voltage source inverter, passive filter, output filter and coupling transformer. Moreover, the control methods for voltage source inverter also have time delay. All of which will result in a time delay in IHAPF output. Time delay in IHAPF output can be expressed by a pure delay element $e^{-\tau s}$ and *τ(s)* represents the total time delay of IHAPF.

As a first step, suppose that we only consider $G_{inv}(s)$ and $G_{out}(s)$ without time delay and design a controller $G_c(s)$ with a closed loop transfer function as follows

$$G_{closed} = \frac{G_c(s).G_{inv}(s).G_{out}(s)}{1 + G_c(s).G_{inv}(s).G_{out}(s)} \quad (7)$$

Next, our purpose is to design a controller $G_c^*(s)$ for $G_{inv}(s)$ and $G_{out}(s)$ with time delay $e^{-\tau s}$ so that the closed loop transfer function

$$G_{closed}^*(s) = G_{closed}(s).e^{-\tau s} \quad (8)$$

Solving

$$\frac{G_c^*(s).G_{inv}(s).G_{out}(s).e^{-\tau s}}{1 + G_c^*(s).G_{inv}(s).G_{out}(s).e^{-\tau s}} = \frac{G_c(s).G_{inv}(s).G_{out}(s)}{1 + G_c(s).G_{inv}(s).G_{out}(s)} e^{-\tau s}$$

we obtain

$$G_c^*(s) = \frac{G_c(s)}{1 + G_c(s).G_{inv}(s).G_{out}(s)(1 - e^{-\tau s})} = \frac{G_c(s)}{1 + G_c(s).G_p(s)(1 - e^{-\tau s})} \quad (9)$$

where $G_p(s) = G_{inv}(s).G_{out}(s)$

G_c^* is the transfer function of the regulated controller.

According to the previous analysis, then the polarity of I_{Lh} and I_{Fh} should be opposite, the phase difference between them is π. It also means that $G_p(s)e^{-\tau s}$ should be $G_p(s)e^{-\pi s}$ through π-Smith predictor.

$$G_p(s)e^{-\pi s} = G_p(s)e^{-\tau s}.e^{(\tau - \pi)s} \quad (10)$$

And $G_c^*(s)$ becomes $G_c^*(s) = \dfrac{G_c(s)}{1 + G_c(s).G_p(s)(1 - e^{-\pi s})}$

According to Fig. 6, the following equations can be established

$$\begin{cases} e(s) = -I_{Lh}(s) - I_{Fh}(s) \\ u(s).G_p(s).(1 - e^{-\pi s}) = p \\ (e(s) - p).G_c^*(s) = u(s) \\ u(s).G_{inv}(s).G_{out}(s).e^{(\tau - \pi)s}.e^{-\tau s} = I_{Fh}(s) \end{cases} \quad (11)$$

The transfer function of closed loop system can be expressed as

$$G_{closed} = \frac{I_{Fh}(s)}{I_{Lh}(s)} = \frac{G_c^*(s).G_{inv}(s).G_{out}(s).e^{-\pi s}}{1 + G_c^*(s).G_{inv}(s).G_{out}(s)} \quad (12)$$

From (12), it is obvious that transfer function of closed loop system have no time delay item, which eliminates the influence of time delay on IHAPF system, and partial numerator $e^{-\pi s}$ of equation shows that the phase of I_{Fh} lags behind I_{Lh} *by π*. That shows the control goal $I_{Fh}(s) = -I_{Lh}(s)$ is achieved.

3.2 PID-Fuzzy Controller for IHAPF

The fuzzy adjustor is used to adjust the parameters of K_P, K_I, K_D based on the error *e(s)* and the change of error *Δe(s)*.

$$\begin{cases} K_P = K_P^* + \Delta K_P \\ K_I = K_I^* + \Delta K_I \\ K_D = K_D^* + \Delta K_D \end{cases} \quad (13)$$

where K_P^*, K_I^*, K_D^* are reference values of the conventional PI controller. In the paper, K_P^*, K_I^*, K_D^* are calculated offline based on the Ziegler-Nichols method. $\Delta K_P, \Delta K_I, \Delta K_D$ are adjusted by a fuzzy logic controller.

Structure of a fuzzy logic controller can be shown as Fig.7.

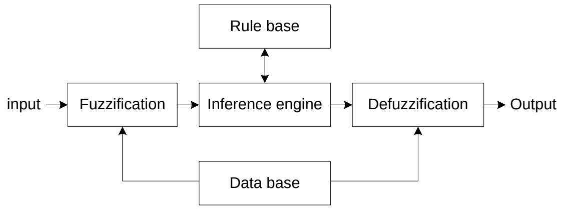


Fig 7: Structure of a fuzzy logic controller

Where: *e(s), Δe(s)* are the inputs of the fuzzy logic controller and we can be written as:

$$e(s)=-I_{Lh}(s)-I_{Fh}(s)$$
$$\Delta e(s)=e(s)-e(s-1)$$

The *e(s)* and *Δe(s)* are variable values from real system. To convert these variable values into linguistic variables, the following seven fuzzy sets are chosen as shown in Fig. 8: Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (ZO), Negative Small (NS), Negative Medium (NM) and Negative Big (NB).

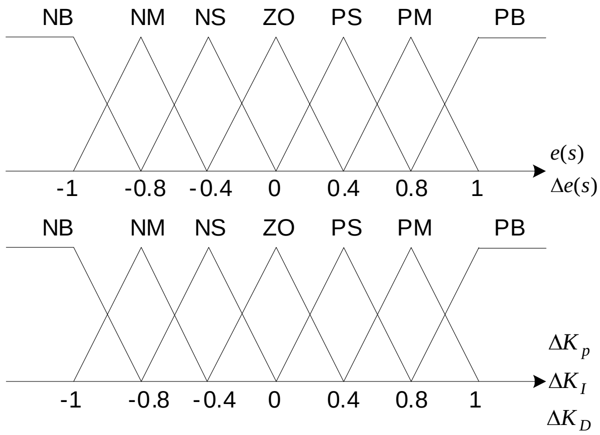


Fig. 8: Membership functions of the fuzzy variable

Membership functions are stored in the database. The fuzzy control rule is core of fuzzy control and it can be obtained as table 1, table 2 and table 3.

Table 1. Fuzzy control rule for ΔK_P

ΔK_P		$\Delta e(s)$						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
e(s)	**NB**	PB	PB	PM	PM	PS	PS	ZO
	NM	PB	PB	PM	PM	PS	ZO	ZO
	NS	PM	PM	PS	PS	ZO	NS	NS
	ZO	PM	PS	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NS	NS	NM	NM
	PM	PS	ZO	NS	NM	NM	NM	NB
	PB	ZO	NS	NM	NM	NM	NB	NB

Table 2. Fuzzy control rule for ΔK_I

ΔK_I		$\Delta e(s)$						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
e(s)	**NB**	NB	NB	NM	NS	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NM	NM	NS	NS	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PS	PM	PB	PB

Table 3. Fuzzy control rule for ΔK_D

ΔK_D		$\Delta e(s)$						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
e(s)	**NB**	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NM	NM	NS	ZO
	NS	ZO	NS	NM	NM	NS	NS	ZO
	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PM	ZO	PS	PS	PS	PS	PM
	PB	PB	PM	PM	PM	PS	PS	PB

This paper uses the *min–max* inference method to obtain the corresponding fuzzy set. The center of gravity method is used to defuzzification the fuzzy variable into physical domain. The inference method gives a resulting membership function $\mu_j(e,\Delta e)$ for the output fuzzy variable ΔK . The final membership function is obtained by combining all the membership functions and this method generates one output value ΔK which is the abscissa of the gravity center of the resulting membership function area, given by equation 14:

$$\begin{cases} K_P = K_P^* + \dfrac{\sum_{j=1}^{n} \mu_j(e,\Delta e)\Delta K_{Pj}}{\sum_{j=1}^{n} \mu_j(e,\Delta e)} \\ K_I = K_I^* + \dfrac{\sum_{j=1}^{n} \mu_j(e,\Delta e)\Delta K_{Ij}}{\sum_{j=1}^{n} \mu_j(e,\Delta e)} \\ K_D = K_D^* + \dfrac{\sum_{j=1}^{n} \mu_j(e,\Delta e)\Delta K_{Dj}}{\sum_{j=1}^{n} \mu_j(e,\Delta e)} \end{cases} \quad (14)$$

4. SIMULATION AND EXPERIMENTAL RESULTS

4.1 Simulation results

Simulation results of a 10kV system have been carried out with software MATLAB. The system parameters are listed in table 4. The nonlinear load is established by four harmonic current sources 5^{th}, 7^{th}, 11^{th} and 13^{th}. The dc-side voltage is 600V.

I_L, I_S, I_{Lh}, I_{Fh} and *error* represent the load current, supply current, load harmonic current, compensation harmonic current into grid by PPF and APF and error of compensation, respectively. Before compensation, the load current and supply current are the same. Simulation results are shown in Fig. 9, Fig. 10 and Fig. 11

Fig. 9 shows the dynamic response of IHAPF when different control methods are adopted. At t=0.3s system is connected by PPFs and APF. When the conventional PI control method (without time delay compensation) is used, the THD reduces to 5.18% from 16.80%, the error can be reduced to ±20A in 0.05s.

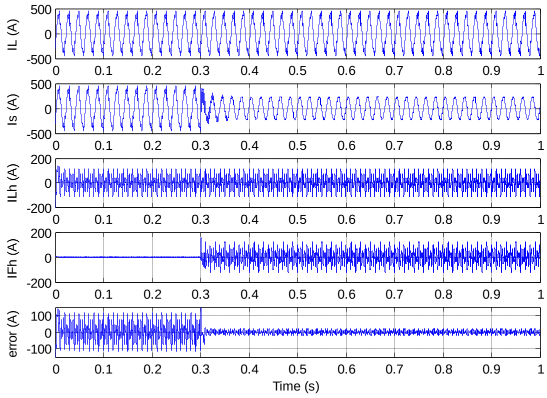
Table 4. Parameters of IHAPF

	L(mH)	C(μF)	Q
Output filter	0.2	60	
11th turned filter	1.77	49.75	50
13th turned filter	1.37	44.76	50
Fundamental resonance circuit	14.75	690	
Injection circuit		19.65	

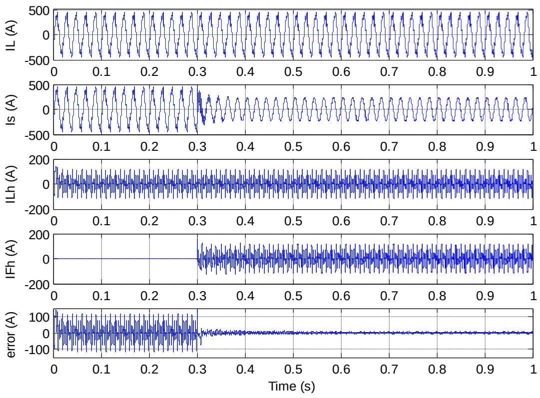
When the PID-fuzzy control method (without time delay compensation) is used, THD reduces to 1.08% from 16.80%, the error can be reduces to ±5A in 0.3s. When the proposed control method is used, the THD reduces to 1.08% from 16.80%, the error can be reduced to ±5A in 0.2s. It is obvious that the adjusting time of applying the proposed method is shorter than conventional PI and PID-fuzzy control method.

Fig. 10 shows the steady-state performance of the IHAPF when different control methods are used. When the conventional PI control method runs, the current total harmonic distortion reduces to 5.18% from 16.80% and the power factor increases to 0.9496 from 0.65. When the proposed control method runs, the current total harmonic distortion reduces to 1.08% from 16.80% and the power factor increases to 0.9512 from 0.65. It is obvious that the proposed control method has a better steady-state performance than conventional PI control method.

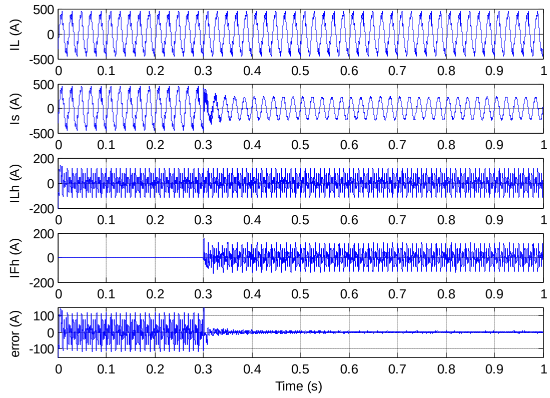
Fig. 11 shows the frequency spectrum of supply current when different control methods are used.



(a)

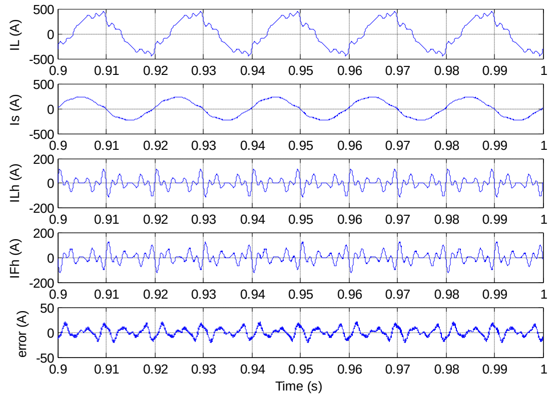


(b)

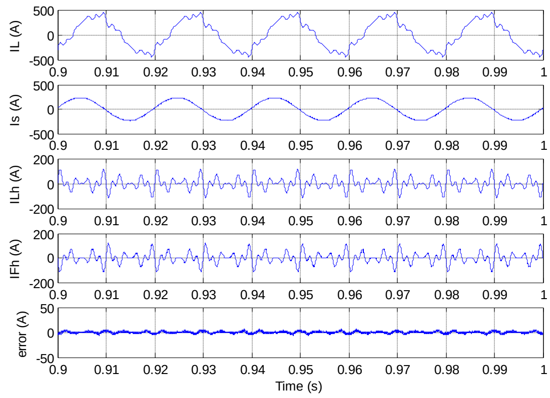


(c)

Fig. 9: Simulation results of the dynamic performance.
(a) Simulation results with the conventional PI controller.
(b) Simulation results with the PID-fuzzy controller.
(c) Simulation results with the proposed controller.

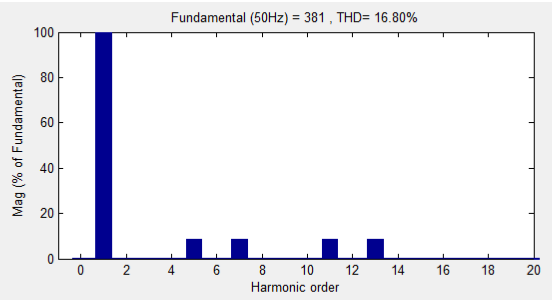


(a)

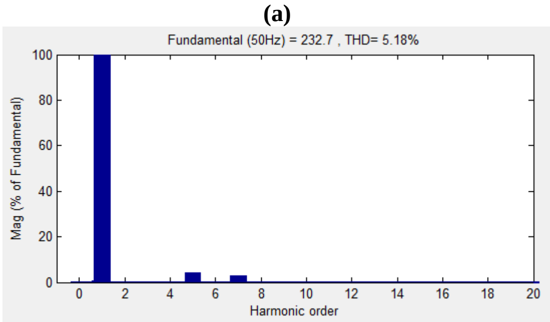


(b)

Fig. 10: Simulation results of steady-state compensation
(a) Simulation results with the conventional PI controller
(b) Simulation results with the proposed controller



(a)



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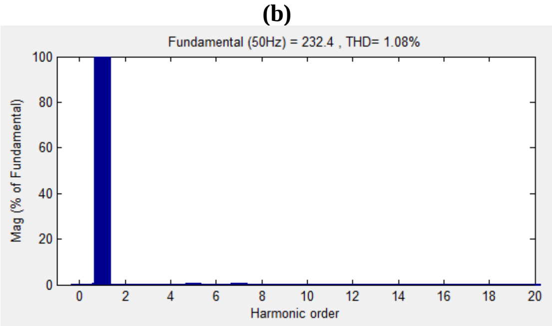


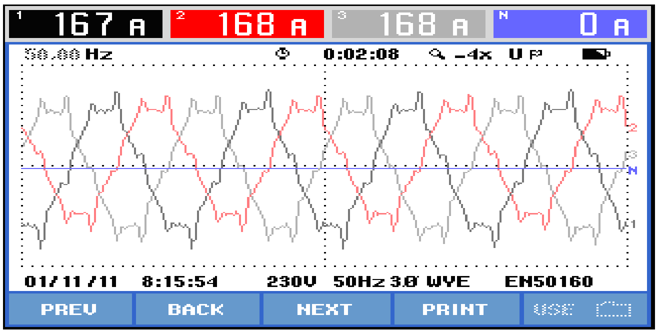
(c)

Fig. 11: Frequency spectrum of supply current (a) Frequency spectrum of supply current before compensation. (b) Frequency spectrum of supply current after compensation with conventional PI controller. (c) Supply current after compensation with proposed controller

4.2 Experimental results

In order to demonstrate the control method proposed in this paper better than conventional PI control method, experiments have been implemented on the prototype of IHAPF in the laboratory. The digital controller of IHAPF adopts DSP2812M as main processor and experimental results are shown in Fig.12. Experimental results demonstrate that with control method proposed the supply current turns to be a nearly sinusoidal wave from the distortion wave and the reactive power of the grid was compensated effectively.

(a)



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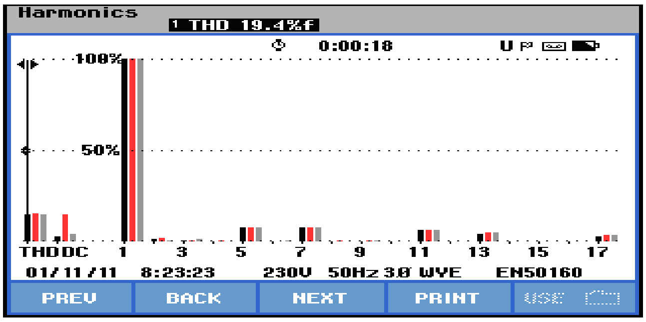

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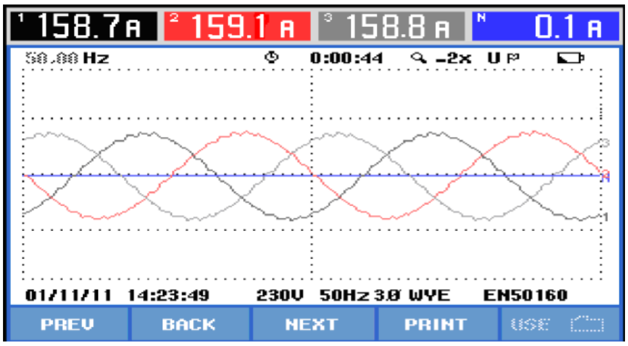
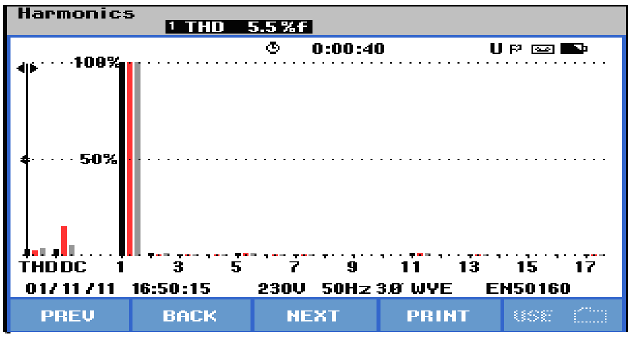
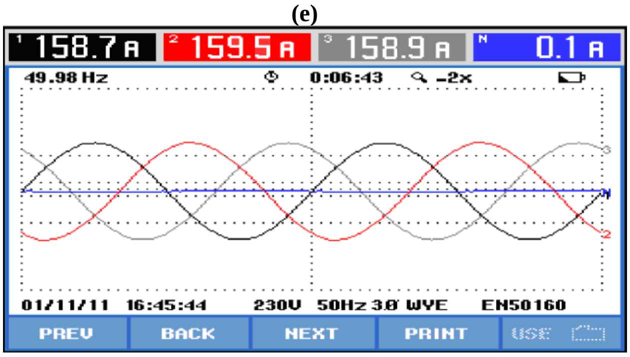


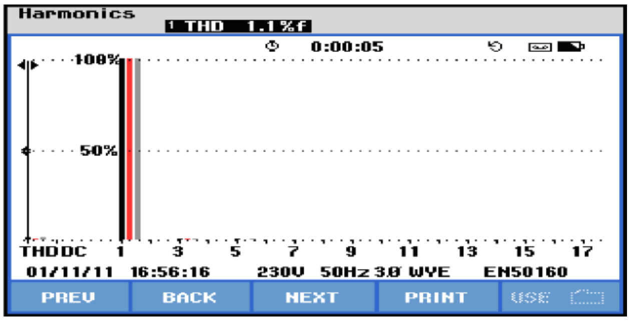
(d)



(e)



(f)



(g)

Fig. 12: Experimental results

(a) Local equipment of IHAPF. (b) Supply current before compensation. (c) Frequency spectrum of supply current before compensation. (d) Supply current after compensation with conventional PI controller. (e) Frequency spectrum of supply current after compensation with conventional PI controller. (f) Supply current after compensation with proposed controller. (g) Frequency spectrum of supply current after compensation with proposed controller

5. CONCLUSION

A PID- fuzzy control method with time-delay compensation for Hybrid Active Power Filter with Injection Circuit was proposed. Proposed control method is composed of PID-fuzzy and π-Smith predictor. Therefore, it has the capability to eliminate the influence of delay time on IHAPF system and adjust the parameters of conventional PID controller effectively. It is implemented in an IHAPF model in laboratory. Simulation results demonstrated the feasibility and validity of the proposed control method.

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