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A NEW CONTROLLER FOR HYBRID ACTIVE POWER FILTER

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Abstract. *This paper aims to design a new controller for the Hybrid Active Power Filter. This controller is established based on the traditional Generalized Proportional Integral controller and the lookup table method. Although the Generalized Proportional Integral controller has the advantage of minimizing the error in the steady-state, it also has disadvantages such as large transient time and large simulation time. To improve these disadvantages, a transition from the frequency domain to the time domain of Generalized Integral controller is performed, and then the lookup table method is used to adjust the parameters of the Generalized Proportional Integral controller. Compared to the traditional Generalized Proportional Integral controller, the simulation results have demonstrated that the proposed controller has a smaller compensation error in steady-state, smaller current total harmonic distortion and shorter transient time.*
Keywords: Hybrid Active Power Filter, Generalized PI controller, Lookup table, 2-D lookup table

1. **Introduction.** To solve harmonic problems in power systems, Passive Power Filters (PPFs) are often used to connect at the Point of Common Coupling (PCC) [1]. However, the PPF has the disadvantage that it is easy to resonate with the system impedance. Since then, Active Power Filter (APF) was born to solve the shortcomings of PPF [2]. However, APF also has disadvantages that are low power, high cost and difficult to apply to medium and high voltage systems. From the shortcomings of the APF and PPF, the Hybrid Active Power Filter (HAPF) was born [3,4]. HAPF is a combination of APF and PPF so it has all the advantages of both APF and PPF.

The controllers used for HAPF can be listed as follows. The traditional Proportional Integral (PI) controller [5,6] is the simplest and most commonly used controller. However, the K_P and K_I parameters are fixed during the control, so it is not suitable for controls with load changes. The hysteresis controller [7] is characterized by a fast response, but compensation error in steady-state is large. Single fuzzy controller [8,9] has the advantage of being easy to define, and can be used for situations where there is no need for a mathematical model. However, its response is very slow and it is difficult to apply in practice. The neural network controller [10,11] has the advantage of being self-learning, so it is suitable for adaptive controls, but it has disadvantages that are difficult to use and respond very slowly. Fuzzy-PI controller or neural-PI controller [12-14] uses the advantages of fuzzy and neural controllers to improve the performance of the traditional PI controller, i.e., using fuzzy, neural controllers to adjust K_P and K_I parameters of PI controller. However, due to the slow response of the fuzzy and neural controllers, the compensation error is still large. A relatively modern controller is a fuzzy neural controller [15,16]. This controller has the advantage that it has ability to online control very good,

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but the shortcoming is slow response, large simulation time and difficult to apply in real time.

In summary, the controllers above listed give a large compensation error in steady-state. Since then, the Generalized Proportional Integral (Generalized PI) controller has been born [17,18]. This controller has the advantage of minimizing the compensation error in steady-state. However, it has the disadvantage that the transient time is too large, the response is slow because this controller contains too many integral stages. Therefore, this paper proposes a new controller for HAPF. This controller is based on the Generalized PI controller to get a compensation error in steady-state approximately zero, while the K_P and K_I parameters of the Generalized PI controller will be adjusted through the data table by the table lookup method. Therefore, the proposed controller has a very fast response, short simulation time, short transient time and minimum compensation error in steady-state and suitable for real-time applications.

The paper structure is divided into five parts: Part 1 provides an overview of the problem to be studied, Part 2 is the control block diagram of HAPF, the proposed controller for HAPF is proposed in Part 3, Part 4 is the simulation results and discussion and Part 5 is the conclusion.

2. **Control Block Diagram of Hybrid Active Power Filter.** Let us consider a typical HAPF topology as shown in Figure 1.

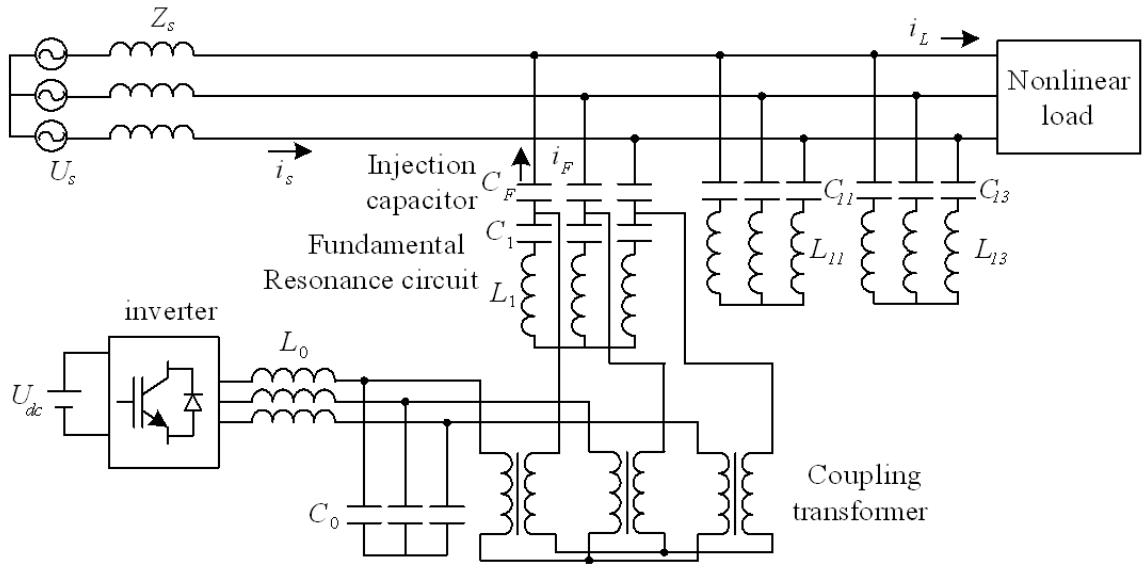

Figure 1. Topology of the Hybrid Active Power Filter

The topology of an HAPF consists of: the nonlinear load model, the passive power filters are turned at the 11th and 13th, injection capacitor C_F, fundamental resonance circuit C_1-L_1, output filter circuit L_0-C_0 and voltage source inverter.

From Figure 1 and according to [15], we can derive the control block diagram for HAPF as shown in Figure 2.

In Figure 2, i_{Lh} is the harmonic component of the load current i_L, and i_{Fh} is the harmonic component of the compensation current i_F.

The error $e(s)$ between the load harmonic current i_{Lh} and the compensation current i_{Fh} will go through the controller, the Pulse Width Modulation (PWM) to create pulse and control the inverter to generate the signal through the output circuit (the circuit part from the inverter output to PCC point). The signal at the output of the output circuit i_F will pass the harmonic detection circuit to produce a feedback signal.

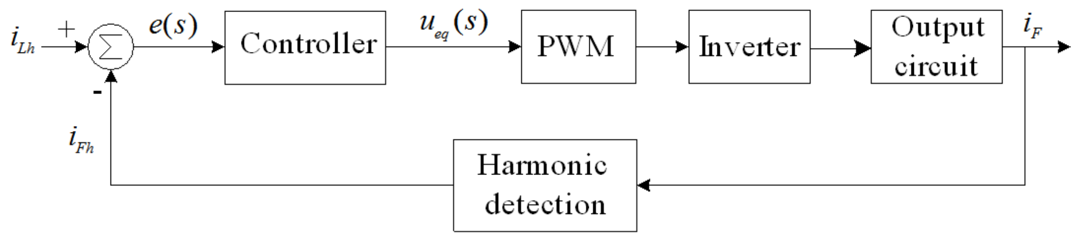

FIGURE 2. Control block diagram for HAPF

3. **Proposed Controller for Hybrid Active Power Filter.** From Figure 2, for only the controller itself, according to [17,18], we have a transfer function of the Generalized Integral controller for ω_n as follows.

$$G_n(s) = \frac{2s}{s^2 + \omega_n^2} \tag{1}$$

where ω_n is the angular frequency at n order harmonic.

Similar to the conventional PI controller, the transfer function of the Generalized PI controller can be expressed as

$$u_{eq}(s) = e(s)\left(K_P + \sum_{n \subseteq N} \frac{2K_{In}s}{s^2 + (n\omega_s)^2}\right) \tag{2}$$

$$N \subseteq \{2, 3, 5, 7, 9, 11, 13, 17, 19, 23\}$$

where $e(s)$ is the error of current reference signal and the feedback current signal; N denotes the harmonic orders that need to be considered; ω_s is the fundamental angular frequency; K_P is the proportional coefficient; K_{In} is the integral coefficient for the nth-order harmonic.

However, we can see that Equation (2) contains many integral layers, so the calculation time will be very large, leading to the difference between the reference signal and the actual signal into the APF grid. This is not suitable for applications in real time. To improve this drawback, let us move the transfer function of the Generalized Integral controller from the frequency domain to the time domain [18]. Assuming the generalized integrator for the nth-order harmonic current is

$$u_{In}(s) = e(s)\frac{2K_{In}s}{s^2 + (n\omega_s)^2} \tag{3}$$

Then

$$s^2 u_{In}(s) + (n\omega_s)^2 u_{In}(s) = 2K_{In} s e(s) \tag{4}$$

So in time domain, (4) can be expressed as

$$\frac{d^2 u_{In}(t)}{d^2(t)} + (n\omega_s)^2 u_{In}(t) = 2K_{In}\frac{de(s)}{dt} \tag{5}$$

So the controller law of generalized integrator for the nth order harmonic current is

$$u_{In}(k) = \frac{2K_{In}[e(k) - e(k-1)] + 2u_{In}(k-1) - u_{In}(k-2)}{1 + (n\omega_s)^2} \tag{6}$$

From (6), we can be see that according to the control quantity of previous two-control cycle and the error of the last control cycle $u_{In}(k)$ can be calculated easily.

So the Generalized PI controller law of the HAPF control system can be expressed as

$$u_{eq}(k) = K_P e(k) + \sum_{m \subseteq N} u_{In}(k) \tag{7}$$

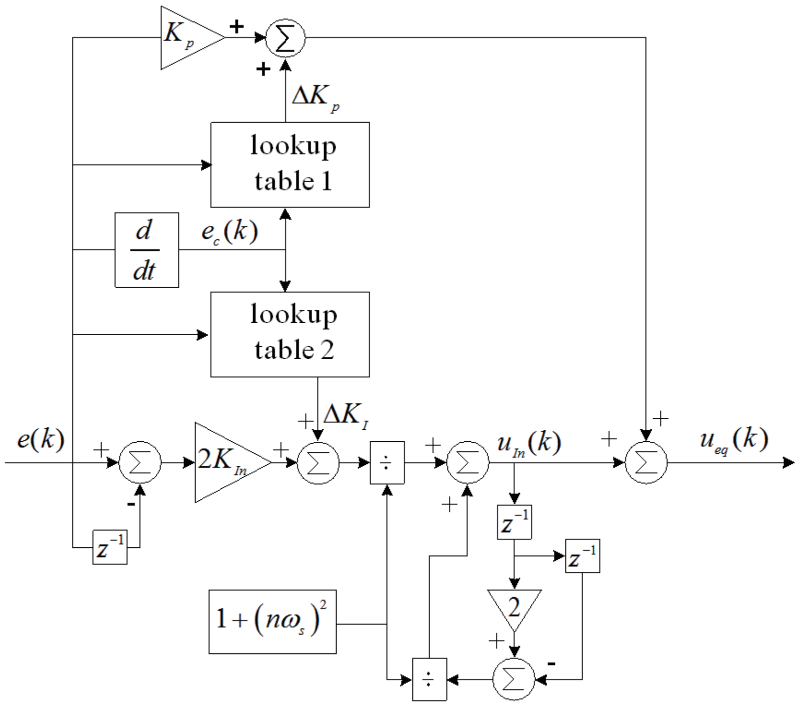

FIGURE 3. Generalized PI-lookup table controller for Hybrid Active Power Filter

To adjust the K_P and K_{In} coefficients of the Generalized PI controller, the lookup table method is used. From (6) and (7), we proposed the Generalized PI-lookup table controller as shown in Figure 3.

The task of lookup table 1 is to control ΔK_P and the task of lookup table 2 is to control ΔK_I. The tables here use the form of a table with two inputs and one output, which is a 2-D lookup table form. The first input is $e(k)$ and the second input is $e_c(k)$. Outputs are ΔK_P and ΔK_I. The search methods used in this table include: Interpolation, Extrapolation and Diagnostics for out-of-range input methods.

The parameters of lookup table 1 and lookup table 2 are built on the following principles.

- When $|e(k)|$ is large, it needs a large ΔK_P value and $\Delta K_I = 0$, and when $|e(k)|$ is small, it needs a small ΔK_P value.
- When $e(k) \times e_c(k) > 0$ requires a large ΔK_P value and when $e(k) \times e_c(k) < 0$, a small ΔK_P value is needed.
- When $|e(k)|$ is small, then ΔK_I is effective and ΔK_I is large when $|e(k)|$ is smaller.

4. **Simulation Results and Discussion.** To demonstrate the efficiency of the proposed controller compared to traditional Generalized PI controller, the simulation results are performed on an HAPF 10kV-50Hz model. HAPF system parameters are given in Table 1.

TABLE 1. HAPF system parameters

C_F (µF)	C_1 (µF)	L_1 (mH)	L_0 (mH)	C_0 (µF)	C_{11} (µF)	L_{11} (mH)	C_{13} (µF)	L_{13} (mH)	U_{dc} (V)
30.65	690	14.75	0.2	60	49.75	1.77	44.76	1.37	535

In the period from 0s to 0.1s, the PPFs and APF have not been connected to the system. Hence the supply current is equal to the load current. At $t = 0.1$s the PPF and APF are connected to the system. The Total Harmonic Distortion (THD) of the load current is 18.37%.

When the Generalized PI controller is used, the error reduces to ±5A at 0.7s, and the dynamic response time is 0.6s. In the steady-state, the THD of i_s decreased from 18.37% to 0.98% and the power factor increases to 0.98 from 0.64. Figure 4 shows the dynamic response of HAPF when the Generalized PI controller is used.

With the proposed controller, the parameters of lookup table 1 and lookup table 2 are given in Table 2 and Table 3. Figure 5 shows the dynamic response of HAPF when the proposed controller is used. When the proposed controller is used, the error can be reduced to ±3A at 0.4s, the dynamic response time is 0.3s. In the steady-state, the THD of i_s decreased from 18.37% to 0.72% and the power factor increases to 0.98 from 0.64.

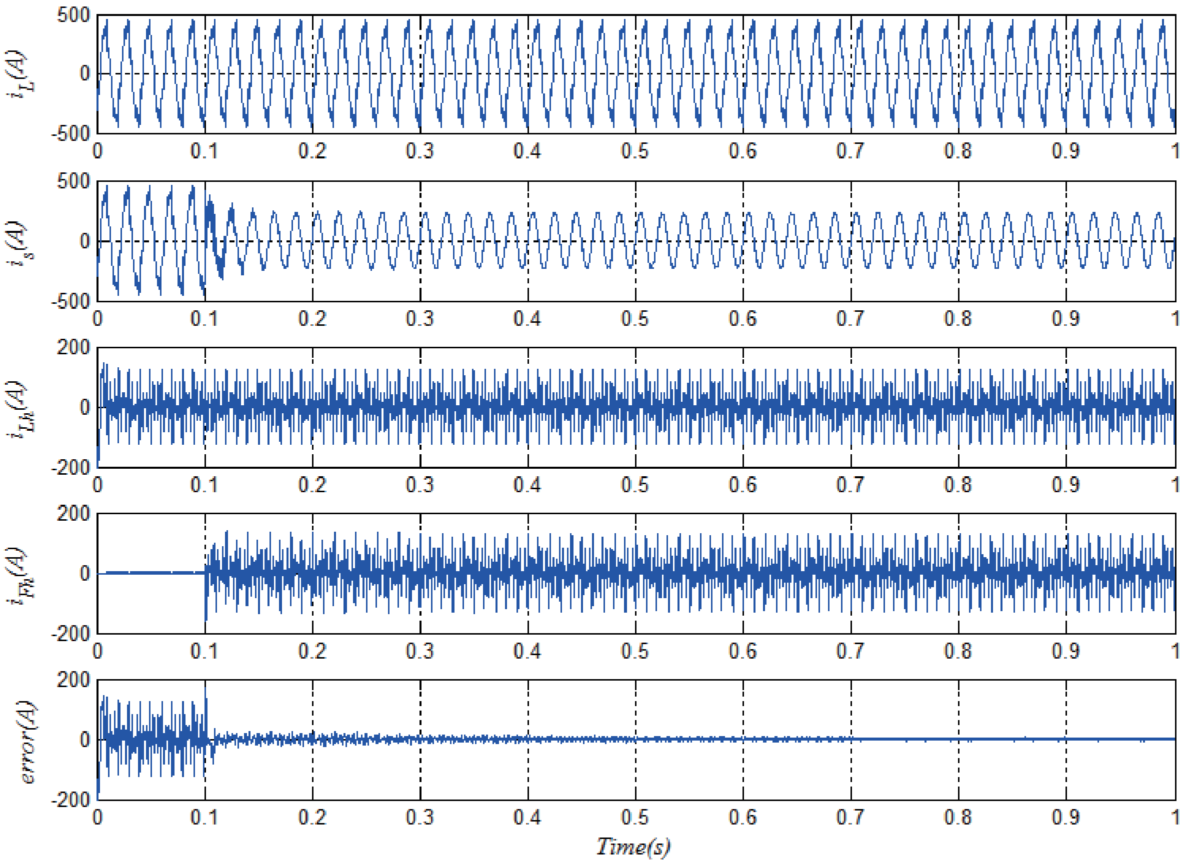

FIGURE 4. Dynamic response of HAPF with the Generalized PI controller

TABLE 2. Parameters of the lookup table 1

ΔK_P		$e_c(k)$										
		−10	−8	−6	−4	−2	0	2	4	6	8	10
$e(k)$	−10	−20	−18	−16	−12	−10	−8	−7	−6	−4	−2	0
	−8	−18	−16	−14	−10	−8	−6	−5	−4	−2	0	2
	−6	−16	−14	−10	−8	−6	−4	−3	−2	0	1	4
	−4	−14	−10	−8	−6	−4	−2	−1	0	1	2	6
	−2	−12	−8	−6	−4	−2	−1	0	1	2	4	8
	0	−10	−6	−4	−2	−1	0	1	2	4	6	10
	2	−8	−4	−2	−1	0	1	2	4	6	8	12
	4	−6	−2	−1	0	1	2	4	6	8	10	14
	6	−4	−1	0	2	3	4	6	8	10	14	16
	8	−2	0	2	4	5	6	8	10	14	16	18
	10	0	2	4	6	7	8	10	12	16	18	20

TABLE 3. Parameters of the lookup table 2

ΔK_I		$e_c(k)$										
		-10	-8	-6	-4	-2	0	2	4	6	8	10
	-10	0	0	0	0	0	0	0	0	0	0	0
	-8	0	0	0	0	0	0	0	0	0	0	0
	-6	0	0	0	0	0	0	0	0	0	0	0
	-4	0	0	0	-1	-1	1	1	1	0	0	0
	-2	0	0	0	-2	-1	1	2	2	0	0	0
$e(k)$	0	0	0	0	-2	-1	1	2	2	0	0	0
	2	0	0	0	-2	-1	1	2	2	0	0	0
	4	0	0	0	-1	-1	1	1	1	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0	0	0

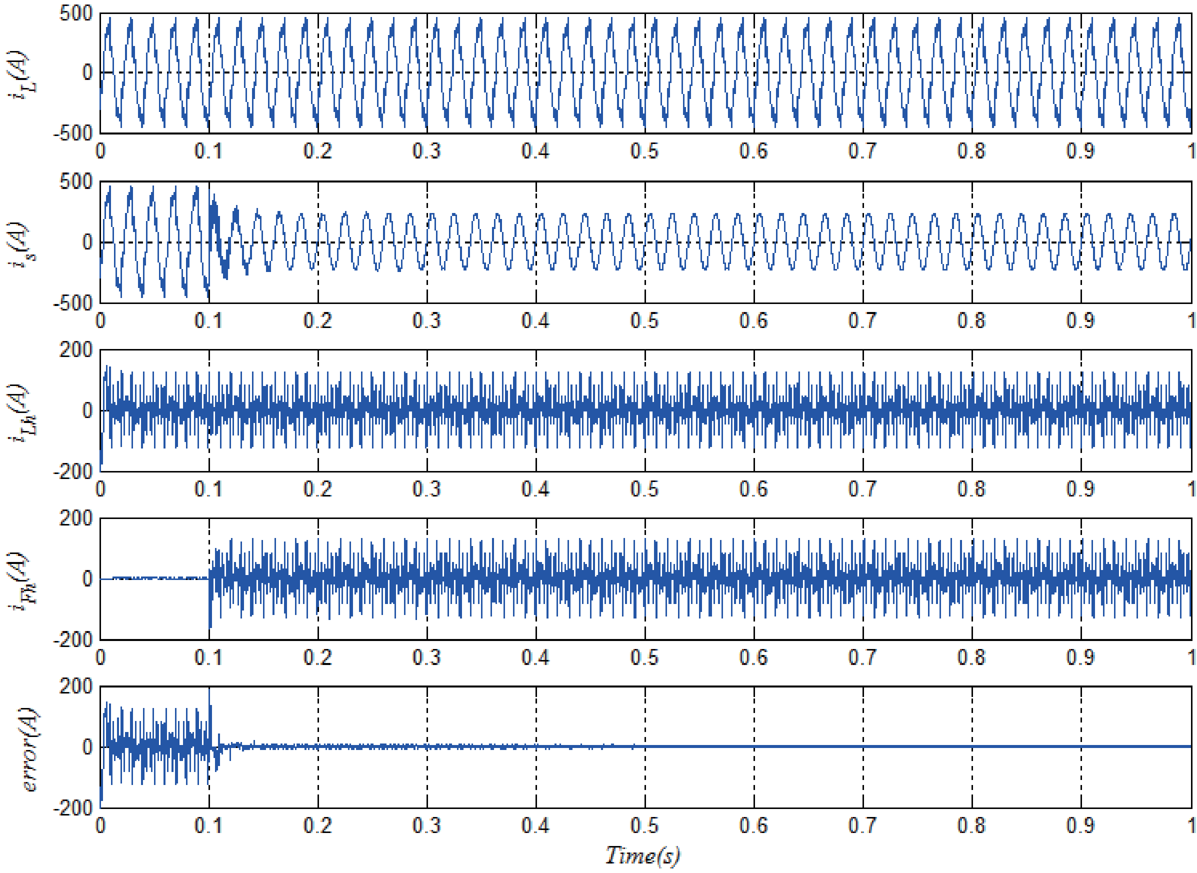

FIGURE 5. Dynamic response of HAPF with the proposed controller

THD of i_s in steady-state with the Generalized PI is shown in Figure 6 and THD of i_s in steady-state with the proposed controller is shown in Figure 7.

From the simulation results, we can conclude that: the proposed controller has a better dynamic response time and smaller supply current total harmonic distortion than the traditional Generalized PI controller.

5. **Conclusion.** This paper has provided a new controller for HAPF. This controller is a combination of a Generalized PI controller with a 2-D lookup table. The advantage of this controller is the ability to respond quickly, the short transient time and the minimum

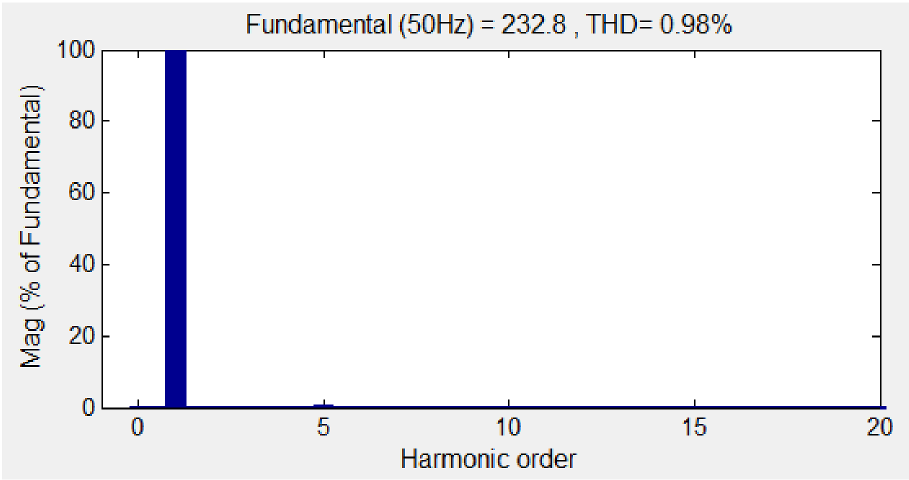

Figure 6. THD of i_s in steady-state with the Generalized PI controller

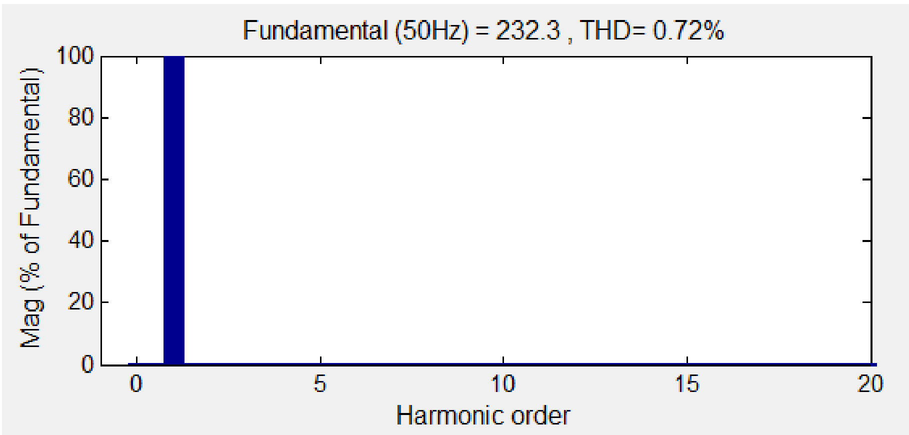

Figure 7. THD of i_s in steady-state with the proposed controller

compensation error in steady-state. This controller is also useful and applicable to any other active power filters. Moreover, in the future this controller will be applied in industrial HAPF models and it will be used for control design of all different HAPF forms. The research result has practical implications in HAPF real-time control.

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