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GENERALIZED CURRENT DELAY COMPENSATION ON HYBRID ACTIVE POWER FILTER

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Abstract. *The structure of the Hybrid Active Power Filter (HAPF) consists of many parts such as rectifier, inverter, transformer, passive power filter and output filter. All the above components will make a delay in the output circuit of the HAPF, and the result will have an error between the compensation and reference signals. So, this paper proposes a control method with generalized current delay compensation for HAPF. The purpose of this method is to compensate the current delay and make 180 degrees between the compensation current and load harmonic current. Compared to the control method without generalized current delay compensation using conventional PI controller, the simulation results show that the proposed control method has not error between the compensation and reference signals, has total harmonic distortion of the supply current and compensation error in steady-state being smaller, and with a value of power factor approaching 1.*
Keywords: Generalized current delay, PI controller, Passive power filter, Hybrid active power filter

1. **Introduction.** As we know, Hybrid Active Power Filter (HAPF) is a combination of passive power filter and active power filter, so it inherits the advantages of both passive power filter and active power filter [1-3]. HAPF is very effective in reducing harmonics and reactive power compensation.

However, the effectiveness of HAPF depends on many factors, such as design parameters, controller, circuit structure, control strategy. The parameters of the circuit are usually calculated according to the fixed load and it is fixed during the control process. The controllers often used for HAPF are the traditional PI controller and the hysteresis controller. The traditional PI controller is characterized by simplicity, easy to perform experiments [4-6]. However, the disadvantage of PI controller is that the parameters K_p, K_i are fixed, if we choose a value of K_p too large, the response is faster but it very easily leads to instability and vice versa. The hysteresis controller has a simple structure, quick response, but the disadvantage is being dependent on the switching frequency, and the error in steady-state is large [7,8]. Several studies have used fuzzy or neural controller to control HAPF. The advantages of using the single-fuzzy logic controller are easy to define, high flexibility and acceptable result. However, we rarely used only a single-fuzzy logic controller alone to control because its input-output membership functions are fixed during the control process; therefore it is very difficult to achieve a result minimum steady-state error, so the process of controlling this controller is usually combined with conventional controller [9-11] to improve its working capacity. If the controller uses neural network [12-15] then the result gives dynamic response is relatively slow or transient time is large, because the achieved result depends on the training process and the input and output relations are very difficult to express.

In short, previous studies have only studied on the control system of HAPF with the goal of minimizing errors in steady-state, reducing dynamic response time and adapting to the load. However, the structure of HAPF consists of several elements in series, such as rectifier, inverter, transformer, passive power filter and output filter. So, it will lead to an error between the compensation signal and the reference signal, which results in a poor performance of the HAPF and causes instability in the system. And the previous studies had not yet to review the phase-shifting in the process of operation of HAPF. Therefore, this paper proposes a control method with phase-shifting compensation for HAPF, which is called the generalized current delay in this paper. The purpose of this control is to generate compensation current, which is equal to the load harmonic current but opposite in sign. The simulation results have demonstrated that the proposed control method has not error between the compensation and reference signals, has total harmonic distortion of the supply current and compensation error in steady-state is smaller, and with a value of power factor approaching 1.

The structure of the paper is divided into five parts. Part 1 provides an overview and urgency of issues to study. The ideal control model for HAPF is given in Part 2. The method for generalized current delay compensation for HAPF is proposed in Part 3. Part 4 shows the results of the simulation and discussion, and the conclusions are presented in Part 5.

2. **Ideal Control Model of the HAPF.** The structure of HAPF is expressed as in Figure 1. U_s and Z_s are the source voltage and the resistance of the source. C_1 and L_1 are capacitance and inductance at the fundamental frequency. C_F is the added capacitance to filter harmonics and reactive power compensation, the transformer has ratio $n:1$ to protect, insulate between the source and the VSI. L_0, C_0 are the output filter of the VSI.

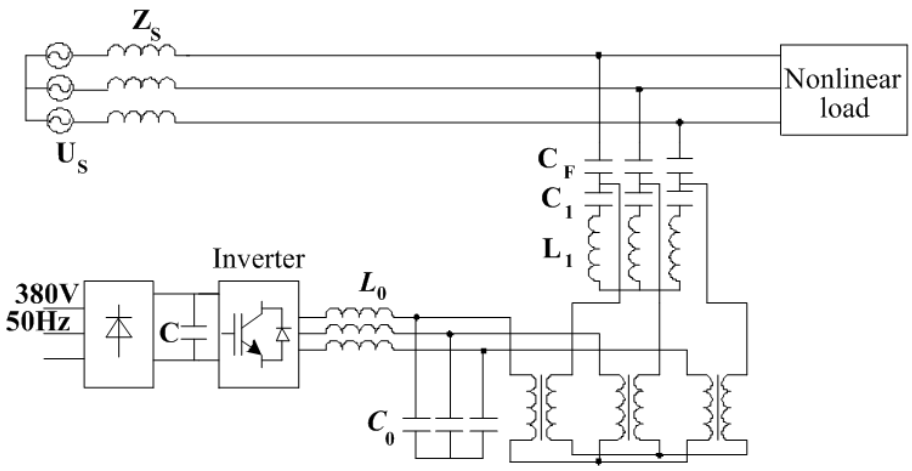


Figure 1. Structure of HAPF

The single-phase equivalent circuit of HAPF is represented in Figure 2.

In Figure 2, $Z_s = R_s + L_s s$; $Z_1 = 1/C_F s$; $Z_2 = \frac{n^2}{C_0 s} // \left(R_1 + L_1 s + \frac{1}{C_1 s}\right)$; $Z_{L0} = R_0 + L_0 s$; $Z_0 = n^2 Z_{L0}$.

According to [1], the ideal control diagram of the HAPF is shown in Figure 3.

In Figure 3, $G_{out}(s)$ is the transfer function of the output circuit

$$G_{out}(s) = \frac{I_{Fh}}{U_{inv}} = \frac{nZ_2}{Z_2(Z_1 + Z_s) + n^2 Z_{L0}(Z_2 + Z_1 + Z_s)} \tag{1}$$

$G_{inv}(s) = K_{inv}/(T_s + 1)$ is the transfer function of the inverter. $G_c(s)$ is the transfer function of the PI controller.

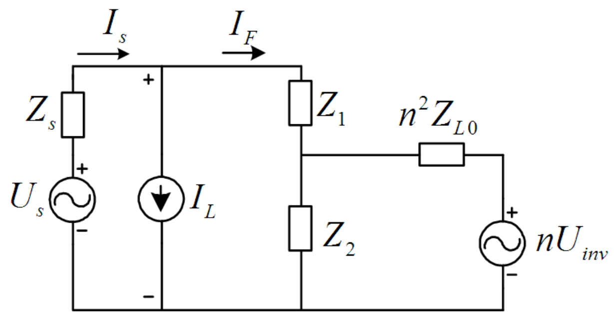


FIGURE 2. Single-phase equivalent circuit of HAPF

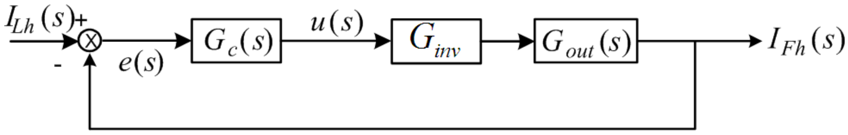


FIGURE 3. Ideal control diagram of the HAPF

3. **Control Method with Generalized Current Delay Compensation for HAPF.** From the structure of HAPF in Figure 1, we can see that the output current of the inverter flows into the grid through the passive power filters, output filter and coupling transformer, all of which will result in a delay in the output circuit. Its delay length varies with the corresponding frequency, which is called the generalized current delay in this paper. The delay is identified as $e^{-\tau s}$ and $\tau(s)$ expresses the total time delay. The control method with generalized current delay compensation for HAPF is represented as Figure 4.

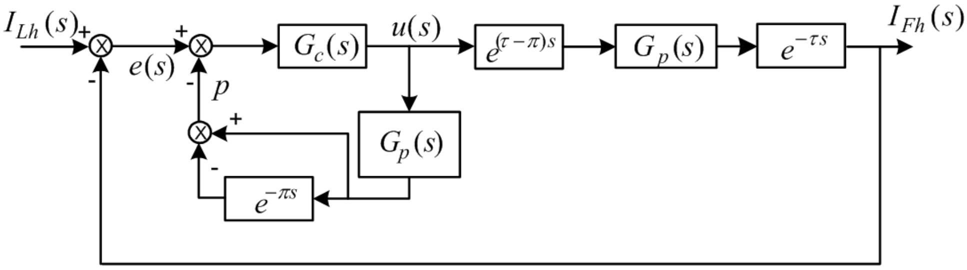


FIGURE 4. Control method with generalized current delay compensation for HAPF

First, the assumption that system has no delay, hence the transfer function of closed-loop control system is:

$$G_{closed} = \frac{G_c(s).G_{inv}(s).G_{out}(s)}{1 + G_c(s).G_{inv}(s).G_{out}(s)} \tag{2}$$

Next is the design of a controller $G_c^*(s)$ for $G_{inv}(s)$ and $G_{out}(s)$ with time delay $e^{-\tau s}$. Closed-loop transfer function is:

$$G^*_{closed}(s) = G_{closed}(s).e^{-\tau s} \tag{3}$$

Solve the equation

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

We obtained the transfer function of the adjusted controller as

$$G_c^*(s) = \frac{G_c(s)}{1 + G_c(s).G_p(s)(1 - e^{-\tau s})} \tag{4}$$

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

According to the above analysis, the pole of the I_{Lh} and I_{Fh} must be opposite, that means $G_p(s)e^{-\tau s}$ through the regulator will be $G_p(s)e^{-\pi s}$.

$$G_p(s)e^{-\pi s} = G_p(s)e^{-\tau s}.e^{(\tau-\pi)s} \quad (5)$$

And $G_c^*(s)$ becomes

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

According to Figure 4, the transfer function of the closed-loop system can be represented as

$$G_{closed} = \frac{I_{Fh}(s)}{I_{Lh}(s)} = \frac{G_c^*(s).G_{inv}(s).G_{out}(s).e^{-\pi s}}{1 + G_c^*(s).G_{inv}(s).G_{out}(s)} \quad (6)$$

From (6), we see that the closed-loop control system without time delay and the numerator only contains $e^{-\pi s}$. That proves that I_{Fh} is late versus I_{Lh} an angular π. So, the purpose of this control is achieved.

4. **Simulation and Discussion.** To compare the performance of without phase-shifting and with phase-shifting compensation control method, the simulation results are made on a system of HAPF 380V-50Hz. The parameters of HAPF system are for the following: C_F = 100μF, C_1 = 338μF, L_1 = 29.77mH, L_0 = 0.5mH, C_0 = 60μF, L_s = 0, 2mH, R_s = 0.01Ω, V_{DC} = 600V, $n = 1$. The non-linear load is built by a three-phase uncontrolled rectifier with load R = 3Ω, $THDi_L\%$ = 25.7%.

4.1. **Without generalized current delay compensation.** The error between the compensation signal and reference signal is shown in Figure 5.

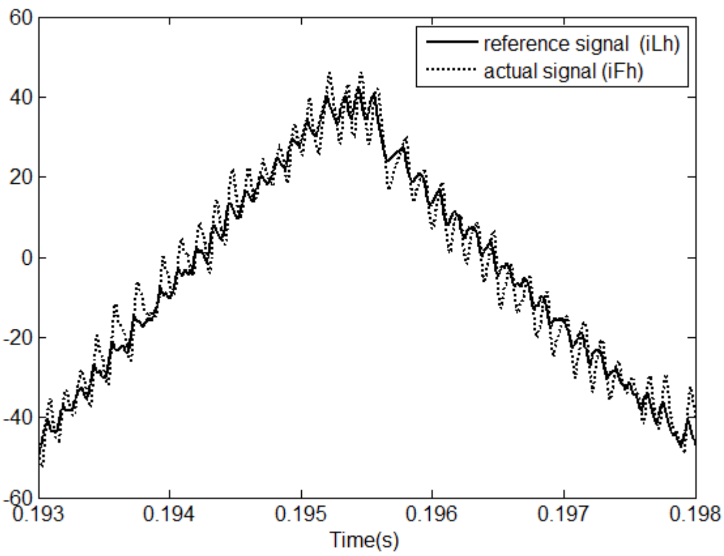
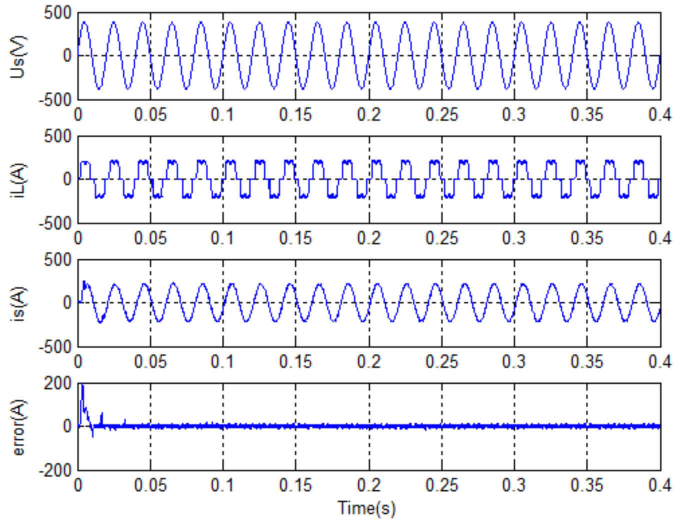


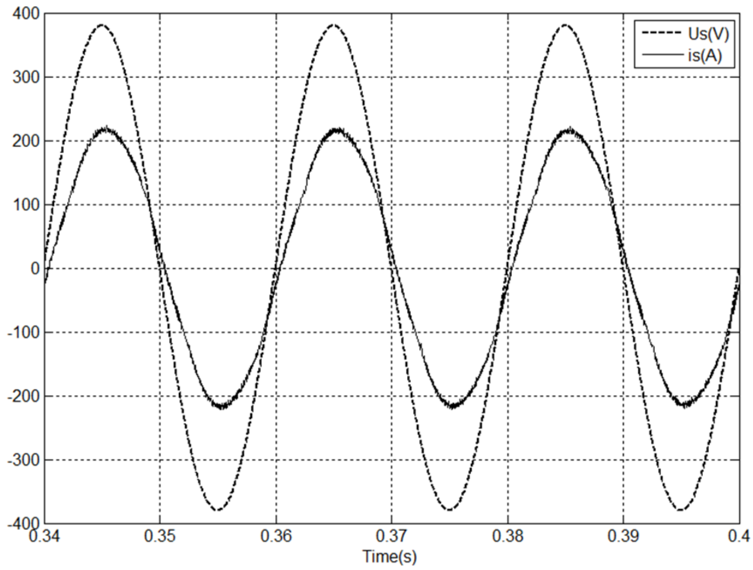
FIGURE 5. Error between the reference signal and compensation signal

From Figure 5, we can see that the error between compensation signal and reference signal is quite large. This error is larger when τ is larger. In this case, the supply current will have a large total harmonic distortion, the load current also distorted from the original. In summary, with τ as above, the HAPF system will not work well, even the HAPF system can become unstable if τ has a greater value.

Response of HAPF and phase-shifting between the supply voltage and supply current without generalized current delay compensation is shown as in Figure 6. Total Harmonic Distortion (THD) of i_s is 2.68%. The error between the reference and compensation



(a) Response of the HAPF



(b) Phase-shifting between the u_s and i_s

FIGURE 6. Response of HAPF and phase-shifting between the u_s and i_s

signals is ±10A. The supply current i_s is phase lag with the supply voltage U_s an angular of approximate 17 degrees, leading to $\cos\varphi$ will be 0.956.

4.2. **With generalized current delay compensation.** The error between the compensation signal and reference signal is shown in Figure 7.

From Figure 7, we can see that the error between the compensation signal and the reference signal is very small. The dynamic response of the HAPF and phase-shifting between the u_s and i_s with generalized current delay compensation is shown as in Figure 8.

From Figure 8, we can see that: the supply current becomes almost the ideal sine with frequency 50Hz, leading to that $\cos\varphi$ will approach 1, the error between the reference signal and the compensation signal is ±4A. Total Harmonic Distortion (THD) of i_s is 0.6%.

5. **Conclusions.** This paper proposed a control method with generalized current delay compensation for HAPF. Therefore, it has ability to cancel the influence of current delay

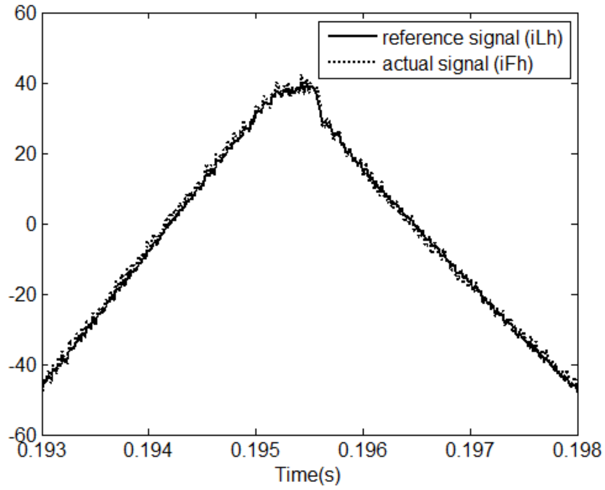
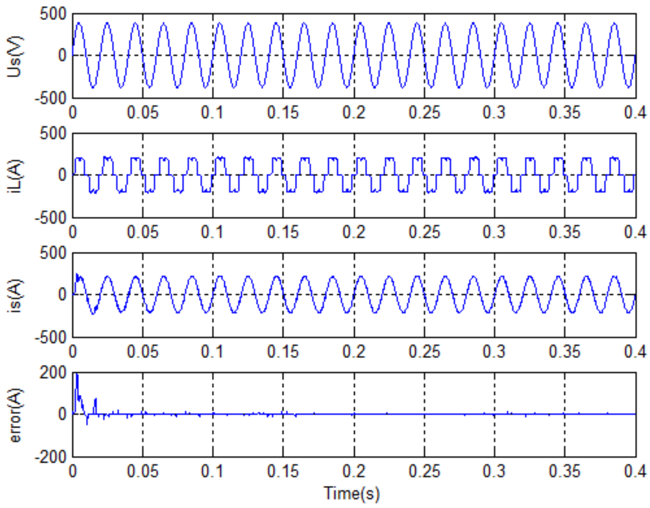
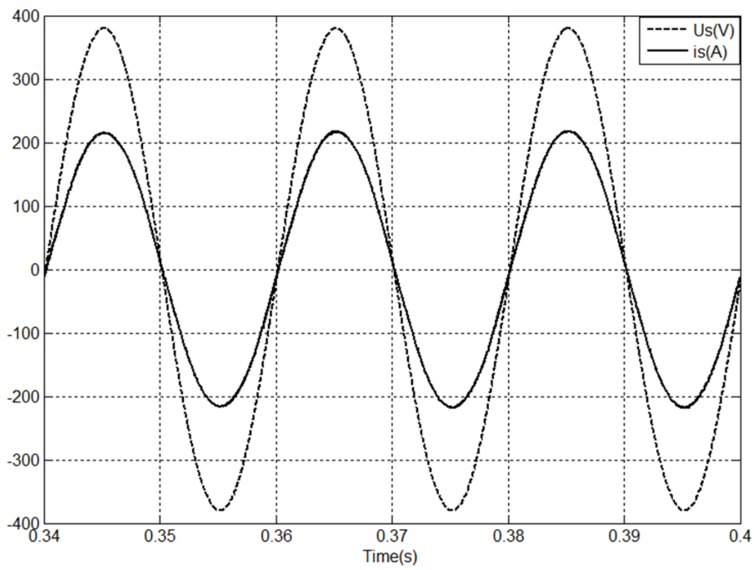


FIGURE 7. Error between the reference signal and compensation signal



(a) Dynamic response of the HAPF



(b) Phase-shifting between the u_s and i_s

FIGURE 8. Response of HAPF and phase-shifting between the u_s and i_s

on HAPF system. Compared to the control method without current delay compensation, the simulation results have demonstrated the effectiveness of the proposed control method in filtering harmonics and improved power factor. This method will be applied to industrial HAPF models, because these models are very susceptible to instability due to the delay of the control system. This study is also a solution to overcoming delays in fuzzy or neural controllers.

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