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Stable Self-Adjustment Control Method for Hybrid Active Power Filter

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Abstract

Hybrid Active Power Filter (HAPF) has high efficiency in improving power quality in the power system. However, the structure of the HAPF consists of many parts such as the rectifier, inverter, transformer, passive power filter and output filter. All above components will make a time delay in the output circuit of the HAPF, and the result will have an error between the compensation and reference signals. So, this paper aims to analysis the stability of HAPF in considering time delay. The mathematical model of the HAPF with time delay was established and analyzed. On that basis, the stable condition of the HAPF was determined based on the Routh stability criterion. A stable self-adjustment method for the HAPF is proposed, this method aims to maintain stability of the HAPF through adjusting of the controlled gain when there is a variation of time delay. To demonstrate the correctness of the proposed control method, simulation results were performed in two cases: controlled gain is fixed and adjusted. The simulation results proved that the delay time has a great influence on operation of the HAPF system and it is inversely proportional to controlled gain. This research has practical signification in the design and control of HAPF.

Keywords: Hybrid Active Power Filter, fuzzy controller, PI controller, Routh criterion.

INTRODUCTION

Currently, there are many power electronic devices are connected to the electrical system. It is the cause of harmonics and reduction of power factor in the power system. Accordingly, in order to solve harmonics of the grid, the passive power filter (PPF) is often used. The passive power filters are simple, low cost, ability to compensate reactive power with harmonic filtering [1-3]. However, they are many disadvantages such as resonance with impedance of the system, no flexibility in harmonic filtering also reactive power compensation, instability in power system.

A new harmonic filter method based on power electronic is active power filter (APF). The APF is connected parallel with nonlinear loads. However, APF is limited by high cost, small capacity, less life of power electronic devices and difficult connection with high voltage network [4-5]. To solve these problems, hybrid active power filter (HAPF) is studied. HAPF is a topology that is combined by the passive power filters and active power filter. Hence the HAPF inherits the advantages of both passive power filter and active power filter. HAPF has the ability to eliminate harmonic, avoid resonance with the impedance of system, connect with high voltage network [6-10]. Moreover, the power rating of APF is reduced greatly. Therefore, studying about the hybrid active power filter is a necessary role to contribute energy saving, especially save energy at business, office, school, factory, etc. Also improve power quality in power system.

When research on the HAPF, there have been many authors studied in different aspects, such as: research on the determination of parameters [11], the control methods [12-18], stablity of the HAPF system [19] and stability of DC bus voltage [20]. However, none of the authors studied the stability of the HAPF system considering the time delay. Because in a HAPF system, from the load harmonic current signal to the compensation current into the grid must through many elements such as capacitors, inductors, transformer, and output filter, etc. All these elements will create a time delay at the output circuit. This delay time will affect the efficiency and stability of the HAPF system.. Therefore, in this paper, the mathematical model of HAPF is established with considering the time delay of the system. Since then, an analysis of the stability of the HAPF system has been done to find a stable domain of HAPF system. On that basis, a stable self-adjustment control method for HAPF is proposed, this method aims to maintain stability for the HAPF when time delay change.

The structure of this paper consists of six parts: part 1 overview of issues should do, part 2 is to build a mathematical model of HAPF with time delay, analysis of stability for HAPF by considering of time delay is presented in part 3, the stable self-adjustment technique for HAPF is given in part 4, part 5 is the simulation results and discussion, section 6 is the conclusions of the paper.

MATHEMATICAL MODEL OF HAPF WITH TIME DELAY

The topology of HAPF is shown in Fig 1. In Figure 1, U_s and Z_s are supply voltage and equivalent impedance of the grid. 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 capacitor and inductor of the passive power filters, the capacitor and inductor of the output filter. Control block diagram of HAPF with time delay is shown as in Figure 2. Where $G_c(s)$ and $G_{inv}(s)$ are transfer functions of the controller and voltage source inverter

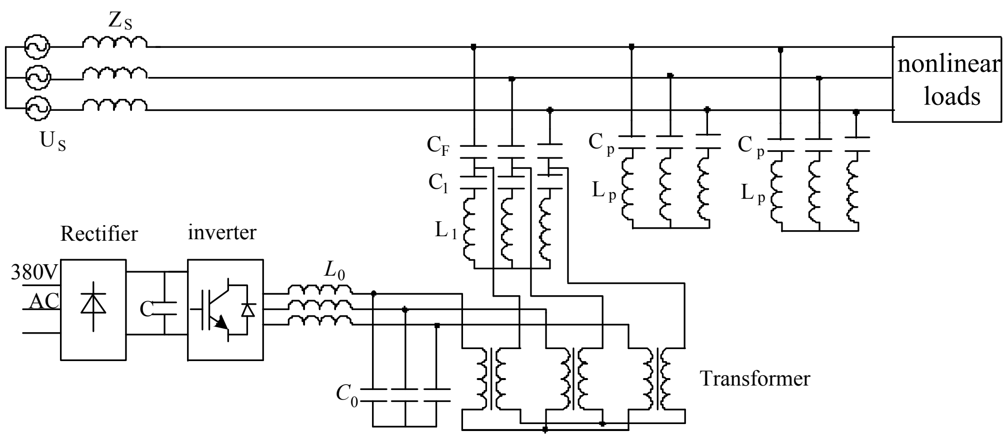

Figure 1: Topology of HAPF

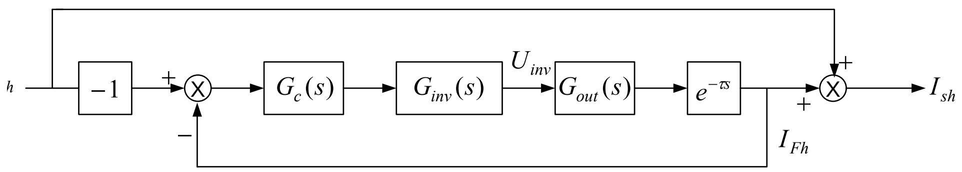

Figure 2: Control block diagram of HAPF with time delay

The transfer function of the controller used in here is conventional PI controller:

$$G_c(s) = K\left(1 + \frac{1}{T_i s}\right) \tag{1}$$

Where K is the proportional gain constant and T_i is the integral time.

The transfer function of VSI is expressed:

$$G_{inv}(s) = \frac{K_{inv}}{T_{inv}s + 1} \tag{2}$$

Where K_{inv} is amplification factor of the voltage source inverter (VSI) and T_{inv} is time delay of the VSI.

$G_{out}(s)$ is the transfer function of compensation harmonic current I_{Fh} along the controlled voltage source U_{inv} and determinated as in Figure 3.

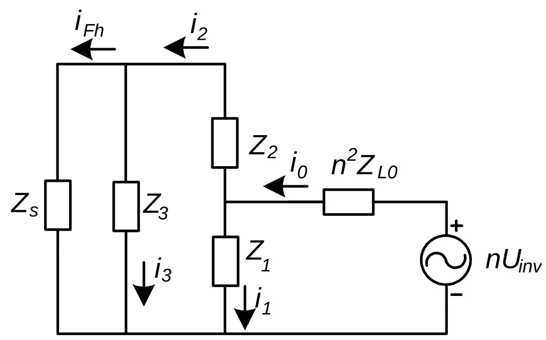

Figure 3: Single phase equivalent circuit when only considering VSI

Where:

$$Z_2 = \frac{1}{C_F s};\ Z_3 = Z_{PPFs};\ \ Z_{L0} = R_0 + L_0 s;\ Z_s = R_s + L_s s$$

$$Z_1 = Z_{L1}C_1 \,//\, n^2 Z_{C0}$$

From Fig.3 $G_{out}(s)$ is calculated:

$$G_{out}(s)=\frac{i_{Fh}}{U_{inv}}= \tag{3}$$

$$\frac{n.Z_1.Z_3}{n^2 Z_{L0}\left[Z_3(Z_1+Z_2)+Z_s(Z_1+Z_2+Z_3)\right]+Z_1(Z_2Z_s+Z_2Z_3+Z_3Z_s)}$$

The time delay of HAPF is τ and can be represented by function $e^{-\tau s}$.

According to [14], the time delay length varies with the corresponding frequency, which is called the generalized current delay in this paper. What generates the generalized current delay is named the phase-shifting impedance. The phase-shifting impedance which can be derived with the HAPF with Injection Circuit component parameters is expressed as

$$Z_n = R_n + jX_n \tag{4}$$

where R_n and X_n are constants and determined by the n-multiple fundamental angular frequency of nω.

The generalized shifting phase θ_n of i_{Fh} caused by Z_n can be calculated as:

$$\theta_n = \arctan\left|X_n / R_n\right| \tag{5}$$

The generalized current time delay τ_n of the current component at the angular frequency nω can be expressed as:

$$\tau_n = \frac{\theta_n}{n\omega} \tag{6}$$

where ω is the fundamental angular frequency and n is the order of harmonic.

From (5) and (6) we can see that: θ_n and τ_n will change whenever there is a change in load.

According to control block diagram of HAPF in Figure 2, the control transfer function with load current input signal I_{Lh} and current output signal I_{sh} of HAPF system with time delay $e^{-\tau s}$ is calculated :

$$G(s)=\frac{I_{sh}}{I_{Lh}}=\frac{1}{1+G_c(s).G_{inv}(s).G_{out}(s).e^{-\tau s}} \tag{7}$$

STABILITY ANALYSIS OF HAPF WITH TIME DELAY

There are many criteria used to assess the stability of a system of such: Routh criterion, Hurwitz criterion, the root locus, Bode plots, Nyquist plots… In this paper, Routh criterion used to stable analysis for the HAPF. From (7), the characteristic equation of the control transfer function of HAPF system is determined

$$D(s)=a_0s^{11}+a_1s^{10}+a_2s^9+a_3s^8+a_4s^7 \tag{8}$$
$$+a_5s^6+a_6s^5++a_7s^4+a_8s^3+a_9s^2+a_{10}s^1+a_{11}s^0$$

Where: $a_0 \ldots a_{11}$ are coefficients of the characteristic equation (8) with the 11th degree, that is the highest degree of the equation.

Setting $K_c = K_{inv} \times K$; n is the ratio of the transformer .

From the coefficients of the characteristic equation (8) can be established Routh table to survey of stability of HAPF system as in table 1. To demonstrate the HAPF system is stable, then the all of elements at first column are positive.

Table 1: Routh table of closed loop system

s^{11}	a_0	a_2	a_4	a_6	a_8	a_{10}
s^{10}	a_1	a_3	a_5	a_7	a_9	a_{11}
s^9	b_0	b_2	b_4	b_6	b_8	b_{10}
s^8	b_1	b_3	b_5	b_7	b_9	b_{11}
s^7	c_0	c_2	c_4	c_6	c_8	
s^6	c_1	c_3	c_5	c_7	c_9	
s^5	d_0	d_2	d_4	d_6		
s^4	d_1	d_1	d_3	d_5		
s^3	e_0	e_2	e_4			
s^2	e_1	e_3				
s^1	f_0	f_2				
s^0	f_1					

STABLE SELF-ADJUSTMENT TECHNIQUE FOR HAPF

The purpose of this technique is to online control of controlled gain K_C so that the system remains stability when there is a change of the time delay. Let's consider a HAPF system has parameters listed as follows:

R_1=0.01Ω; L_1=29.77mH; C_1=349.2µF; C_F=80 µF; R_{13}=0.01Ω; L_{13}=1.35mH; C_{13}=44.76µF; R_{11}=0.01Ω; L_{11}=1.72mH; C_{11}=49.18µF; L_0=0.8mH; C_0=690µF; n=1:1.

With T_{inv}=0.01ms; K_{inv}=1 and T_i=0.1 are determinated by experimental research [16].

From the parameters of HAPF system and stable condition of (8), we obtain the relationship between K_{Cmax} and τ as in Table 2.

Based on table 2, when τ is large then K_{Cmax} must be decreased and vice versa. Due to K_{inv} is fixed, so K_{Cmax} is depends on K. So, we can control the controlled gain K_c of the APF through the parameter K of the PI controller.

Table 2: Relationship between K_{Cmax} and τ

τ(μs)	K_{Cmax}
10	22.12
20	19.35
30	14.75
50	10.12
100	8.52

Otherwise, according to (6) then τ vary with harmonic current ingredients goes through it, this components are generated by non-linear loads and is calculated based on the p-q theory method. The p-q theory method can be shortly summarized in Figure. 4.

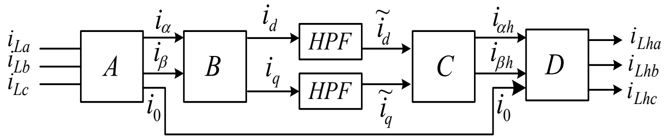

Figure 4: Synchronous reference frame method

Where:

$$A=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}\quad B=\begin{bmatrix}\cos(\omega t) & \sin(\omega t)\\ -\sin(\omega t) & \cos(\omega t)\end{bmatrix};$$

$$C=\begin{bmatrix}\cos(\omega t) & -\sin(\omega t)\\ \sin(\omega t) & \cos(\omega t)\end{bmatrix}\quad D=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0 & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\end{bmatrix}$$

ω is the fundamental angular frequency of the system, HPF is High Pass Filter

So, when the load change, the magnitude of the harmonic components also are changed, leading to time delay τ also changed. The parameters of the system is designed with a load is fixed, when the load changes, the design parameters will be not fitted because the hardware parameters (R, L, C) are not changed during the process of work, and we can only change the parameters of the controller. In summary, when the load changes, the system can instability and poor work performance. Therefore, this paper proposes a stable self-adjustment technique for HAPF when there is a changing of the load (i.e. when τ is changed). The stable self-adjustment technique for HAPF described as in Figure 5.

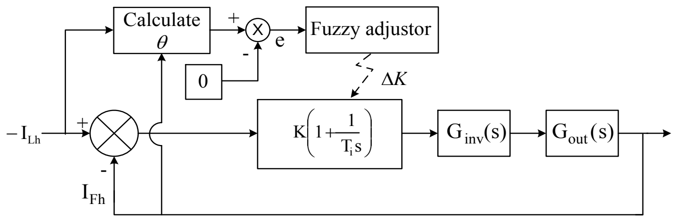

Figure 5: Stable self-adjustment technique for HAPF

The actual signal i_{Fh} form the output of APF will be compared with the reference signal i_{Lh} to pass PI controller through inverter, output circuit and used to calculate θ. The value θ will be compared with zero to provide for fuzzy adjustor. The input of the fuzzy adjustor is *e* and output is *ΔK*. To convert these numerical variables into linguistic variables, we use seven memberships following as: NB (negative big), NM (Negative medium), NS (Negative small), ZO (zero), PS (positive small), PM (positive medium) and PB (positive big). The membership functions of input-output variables are presented in Figure 6.

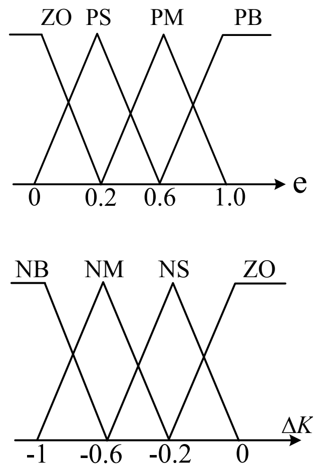

Figure 6: Membership functions of the fuzzy variable

According to the results of table 2, fuzzy rules are shown as follows:

- If *e* is *ZO*, then *ΔK* is *ZO*
- If *e* is *PB*, then *ΔK* is *NB*
- If *e* is *PM*, then *ΔK* is *NM*
- If *e* is *PS*, then *ΔK* is *NS*

Select fuzzy reasoning method is max-min and the center of gravity method is used to defuzzify the fuzzy variable.

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SIMULATION RESULTS AND DISCUSSION

To prove the correctness of the above analysis, simulations were made for a three-phase 380V/50 Hz HAPF system with parameters listed as in section 4. Where: i_{La}, i_{Lha}, i_{sa} and error represent the load current, load harmonic current, supply current and error compensation of phase A. The simulation is done in two cases: K_{Cmax} is fixed and K_{Cmax} is adjusted.

Originally, the system was assumed to have a time delay of 0.0 µs, we set the coefficient of K_{Cmax} = 30. The simulation results in the case of K_{Cmax} is fixed are represented as Figure 7. Figure 8 shows simulation results in case K_{Cmax} is adjusted. The frequency spectrum of the load current and supply current of phase A is represented as in Figure 9 and Figure 10.

From the simulation results we can see that: in period t = (0.0 s ÷ 0.2 s), the system is stability. At time t = 0.2s we let load change, in the case of K_{Cmax} is fixed, the system is instability, in case K_{Cmax} is adjusted, the system is stable self-adjustment in approximately 0.08 s.

In steady-state, THD of the i_L before change is 28.75%, i_s before the load change is 3.09%, compensation error is ± 20A. THD of the i_L after load change is 31.75%, i_s after the load change is 3.26%, compensation error is ± 25A.

From the simulation results we noticed that: the proposed method is able to maintain system stability whenever there is a change in load.

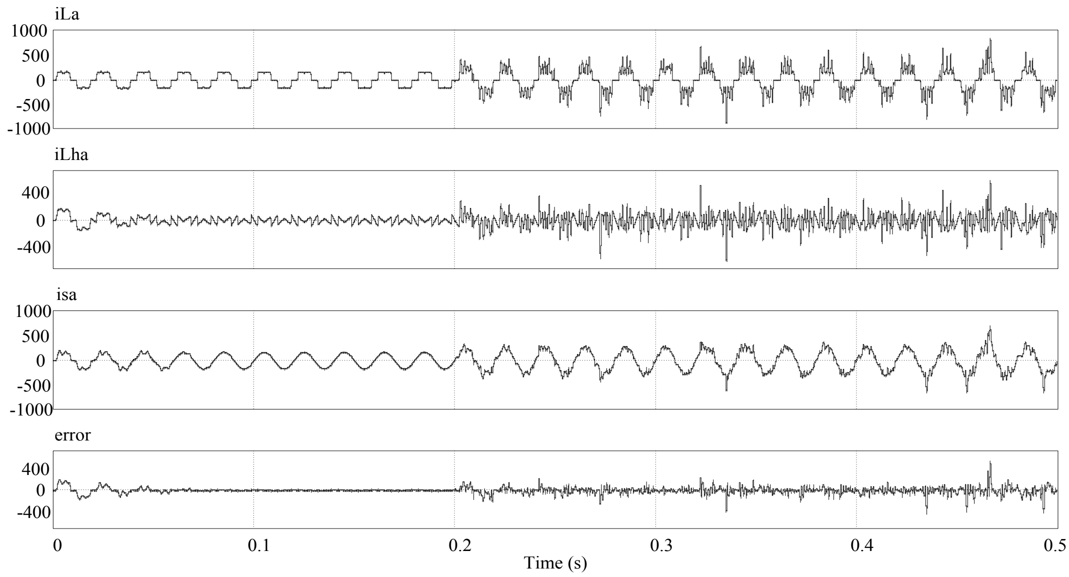

Figure 7: Simulation results in the case K_{Cmax} is fixed

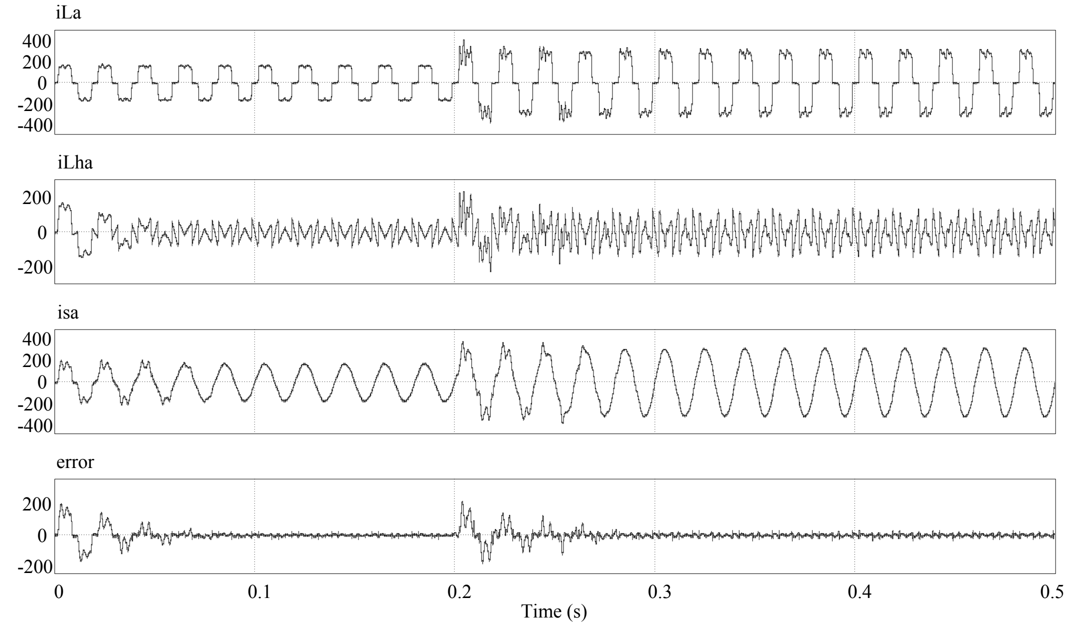

Figure 8: Simulation results in case K_{Cmax} is adjusted

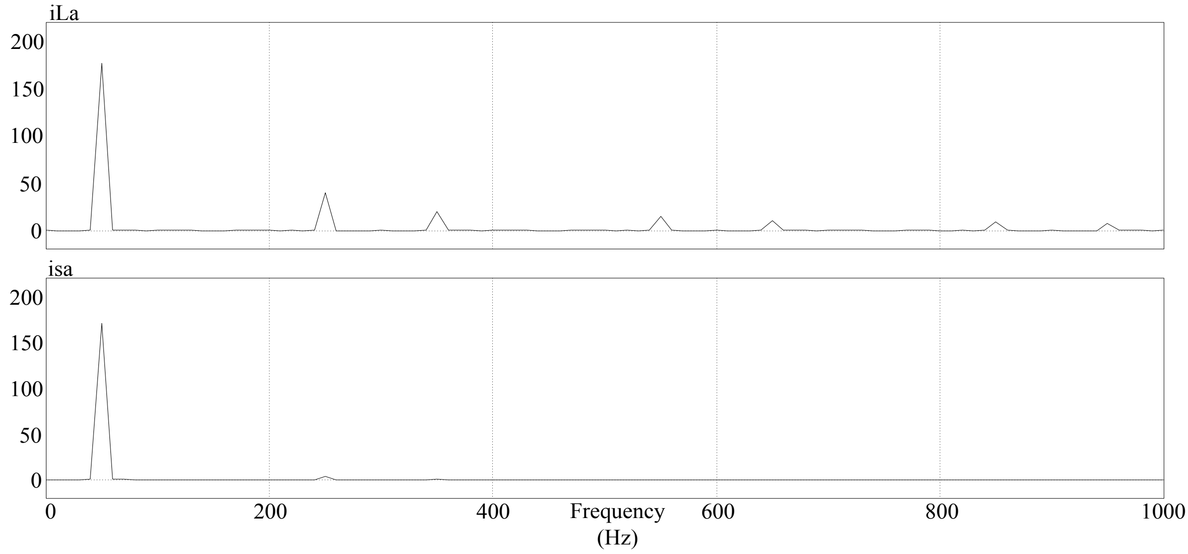

Figure 9: Frequency spectrum of the i_{La} and i_{sa} before the load is changed in case K_{Cmax} is adjusted

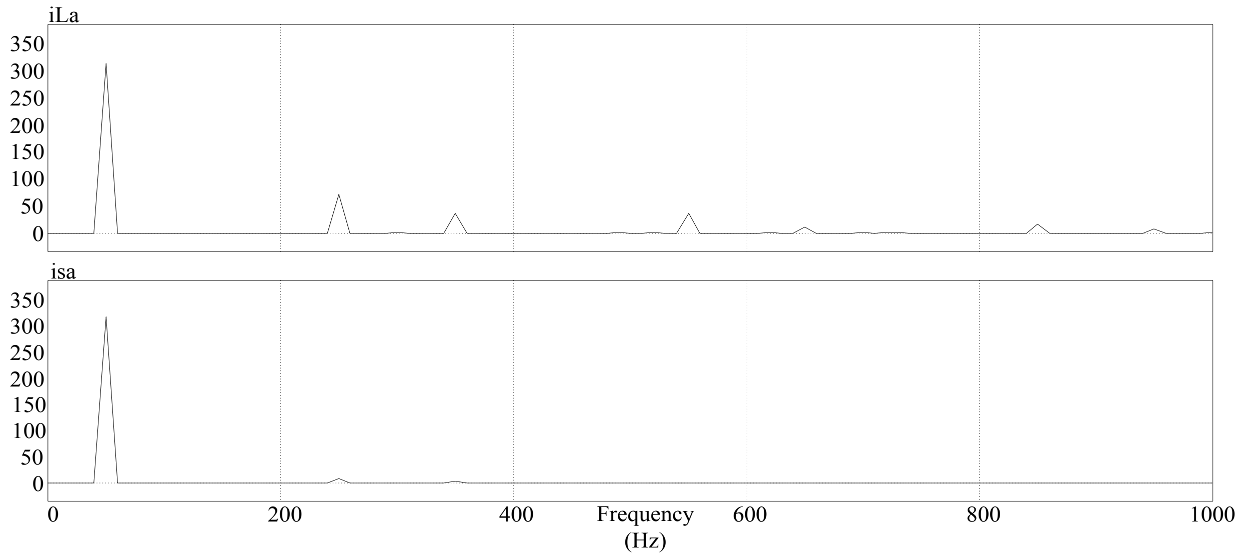

Figure 10: Frequency spectrum of the i_{La} and i_{sa} after the load is changed in case K_{Cmax} is adjusted

CONCLUSION

This paper has built a mathematical model for HAPF have considering the time delay. On the basis that a stable analysis for HAPF use Routh's standard to find out stable condition of HAPF. A stable self-adjustment method for HAPF use the fuzzy regulator was proposed. In this method, through the adjustment coefficients of the PI controller, we can adjust the controlled gain of active power filter to maintain stability of HAPF system. The simulation results have proven the effectiveness of proposed stable self-adjustment method. These results of this study as a basis for choice parameters of HAPF in considering time delay, and also ensure stability and more efficient operation of HAPF system.

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