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.

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], stability 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

![Topology of HAPF](image)

### Figure 2: Control block diagram of HAPF with time delay

![Control block diagram of HAPF with time delay](image)

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

\[
G_c(s) = K \left(1 + \frac{1}{T_1 s}\right)
\]

(1)

Where \( K \) is the proportional gain constant and \( T_1 \) is the integral time.

The transfer function of VSI is expressed:

\[
G_{inv}(s) = \frac{K_{inv}}{T_{inv}s + 1}
\]

(2)

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

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

### Figure 3: Single phase equivalent circuit when only considering VSI

![Single phase equivalent circuit when only considering VSI](image)

Where:

\[
Z_2 = \frac{1}{C_p s} ; Z_3 = Z_{PPF} ; Z_{L0} = R_0 + L_0 s ; Z_s = R_s + L_s s
\]

\[
Z_4 = Z_{L3} C_i // n^2 Z_{C0}
\]
From Fig.3 G_{out}(s) is calculated:

\[ G_{out}(s) = \frac{I_{nh}}{U_{inv}} \]  

}\hspace{1cm} (3) \hspace{1cm} n^2Z_{1n}[Z_1(Z_1+Z_1)+Z_2(Z_2+Z_2)]+Z_3(Z_4+Z_4+Z_4+Z_4). \]

The time delay of HAPF is \( \tau \) 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 control transfer function of HAPF system is

\[ Z_n = R_n + jX_n \]  

}\hspace{1cm} (4) \hspace{1cm} \text{where } R_n \text{ and } X_n \text{ are constants and determined by the } n^-\text{multiple fundamental angular frequency of } \Omega_0. \]

The generalized shifting phase \( \Theta_n \) of \( i_{nh} \) caused by \( Z_n \) can be calculated as:

\[ \Theta_n = \arctan\left|\frac{X_n}{R_n}\right| \]  

}\hspace{1cm} (5) \hspace{1cm} \text{The generalized current time delay } \tau_n \text{ of the current component at the angular frequency } \Omega_0 \text{ can be expressed as:} \]

\[ \tau_n = \frac{\Theta_n}{n\Omega} \]  

}\hspace{1cm} (6) \hspace{1cm} \text{where } \Omega_0 \text{ is the fundamental angular frequency and } n \text{ is the order of harmonic.} \]

From (5) and (6) we can see that: \( \Theta_n \) and \( \tau_n \) 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 \( I_{nh} \) of HAPF system with time delay \( e^{-\tau s} \) is calculated:

\[ G(s) = \frac{I_{nh}}{I_{lh}} = \frac{1}{1 + G_c(s)G_{inv}(s)G_{out}(s)e^{-\tau s}} \]  

}\hspace{1cm} (7) \hspace{1cm} \text{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

\[ D(s) = a_0s^{11} + a_1s^{10} + a_2s^9 + a_3s^8 + a_4s^7 \]

\[ + a_5s^6 + a_6s^5 + a_7s^4 + a_8s^3 + a_9s^2 + a_{10}s + a_{11}s^0 \]  

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

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.

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

\[ \text{Table 1: Routh table of closed loop system} \]

\[ \text{STABLE SELF-ADJUSTMENT TECHNIQUE FOR HAPF} \]

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:

\[ R_1=0.01\Omega; L_1=29.77mH; C_1=349.2\mu F; C_5=80 \mu F; R_{13}=0.01\Omega; \]

\[ L_{13}=1.35mH; C_{13}=44.76\mu F; R_{11}=0.01\Omega; L_{11}=1.72mH; \]

\[ C_{11}=49.18\mu F; L_0=0.8mH; C_0=690\mu F; n=1:1. \]

With \( T_{inv}=0.01ms; K_{inv}=1 \) and \( T_{i}=0.1 \) are determined by experimental research [16].

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

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

\[ A = \begin{bmatrix} \frac{2}{\sqrt{3}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \quad B = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix}, \quad C = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix}, \quad D = \begin{bmatrix} \frac{2}{\sqrt{3}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix}. \]

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.

The actual signal \( i_{lh} \) form the output of APF will be compared with the reference signal \( i_{lb} \) 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 \( \Delta K \). 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.

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

- If \( e \) is ZO, then \( \Delta K \) is ZO
- If \( e \) is PB, then \( \Delta K \) is NB
- If \( e \) is PM, then \( \Delta K \) is NM
- If \( e \) is PS, then \( \Delta K \) is NS

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

Table 2: Relationship between \( K_{C_{max}} \) and τ

<table>
<thead>
<tr>
<th>τ(µs)</th>
<th>( K_{C_{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>22.12</td>
</tr>
<tr>
<td>20</td>
<td>19.35</td>
</tr>
<tr>
<td>30</td>
<td>14.75</td>
</tr>
<tr>
<td>50</td>
<td>10.12</td>
</tr>
<tr>
<td>100</td>
<td>8.52</td>
</tr>
</tbody>
</table>

Figure 5: Stable self-adjustment technique for HAPF

Figure 6: Membership functions of the fuzzy variable
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: \( K_{C_{max}} \) is fixed and \( K_{C_{max}} \) is adjusted.

Originally, the system was assumed to have a time delay of 0.0 µs, we set the coefficient of \( K_{C_{max}} \) = 30. The simulation results in the case of \( K_{C_{max}} \) is fixed are represented as Figure 7. Figure 8 shows simulation results in case \( K_{C_{max}} \) 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 \( t = (0.0 \ s \div 0.2 \ s) \), the system is stability. At time \( t = 0.2s \) we let load change, in the case of \( K_{C_{max}} \) is fixed, the system is instability, in case \( K_{C_{max}} \) 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.

![Simulation results in the case \( K_{C_{max}} \) is fixed](image7.png)

![Simulation results in case \( K_{C_{max}} \) is adjusted](image8.png)
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.

REFERENCES


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