ANALYZE THE EFFECT OF TIME DELAY ON THE STABILITY OF HYBRID ACTIVE POWER FILTER

CHAU MINH THUYEN
Faculty of Electrical Engineering & Technology, Industrial University of Ho Chi Minh City; chauminhthuyen@iuh.edu.vn

Abstract. Hybrid Active Power Filter (HAPF) has highly effective in improving the power quality of power system. In this paper, a stable analysis of HAPF considering the time delay was made. The mathematical model of HAPF with time delay has been established. Based on that, the stable domain of the HAPF parameters was determined based on the Routh's stability standard. Simulation results based on Matlab software have shown that: time delay has a marked impact on the stability of the HAPF system. This research has practical significance in the design and control of HAPF in real system.
Keywords. Passive power filter, hybrid active power filter, stability analysis, time delay.

1 INTRODUCTION

Nowadays, the power electronic devices are very popular, such as motor drives, converters in renewable, electric arc furnace, uninterruptible Power Supply, etc. All of these devices are nonlinear loads. The nonlinear loads are the sources of the harmonic distortion; it affect directly to grid and reduces power quality of the power system. There are many ways to solve this problem such as using a passive power filter (PPF), active power filter (APF) and hybrid active power filter (HAPF). The passive power filters are simple, low cost, ability to compensate reactive power and harmonic filter [1-3]. However, they are many disadvantages such as resonance with supply system, no flexibility in harmonic filtering also reactive power compensation, instability in power system.

A new harmonic filter method based on power electronic devices is an active power filter (APF). The APF is connected parallel with nonlinear loads and harmonic elimination more flexibility than PPF. 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 is studied. HAPF is a topology that is combined by passive power filter (PPF) and active power filter (APF). Hence the HAPF inherits the advantages of both passive power filter (PPF) and active power filter (APF). Hybrid active power filter (HAPF) flexibly eliminated harmonic, greatly reduced power rating of APF, avoided resonance with the supply system, connected with high voltage network [6-10]. 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.

Determination of the exact parameters of the hybrid active power filter will decide its performance. So far these parameters of hybrid active power filter are most determined based on experience but not considering stable system. Moreover, researches [11-16] are not considering time delay. In HAPF system, from harmonic current signal of load to compensation of current into the grid must through many elements such as capacitors, coils, transformer, output filter, voltage source inverter, controller, etc. All these elements created time delay at output. The time delay affected the efficiency and stability of HAPF. In this paper, the mathematical model of HAPF is established with considering time delay of system. Since then, an analysis of the stability of the HAPF system is established to find a stable domain for parameters of HAPF. This has practical significance for improving work efficiency of HAPF in the real system conditions.

2 TOPOLOGY AND OPERTING PRINCIPLE OF HAPF

The topology of HAPF is shown in Figure 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. A branch with C_F - C_1 - L_1 is injected to reduce capacity of APF. C_1 and L_1 resonate at the fundamental frequency and connect in series with additional branch C_F. Nonlinear loads are considered as sources of harmonics. Most high order harmonics will be reduced by the passive filter PPF. In this paper, the passive filters eliminate the 11^{th}

and 13th order harmonics. Moreover, the APF also rejects some remaining low order harmonics. Thus the capacity of PPF is reduced significantly.

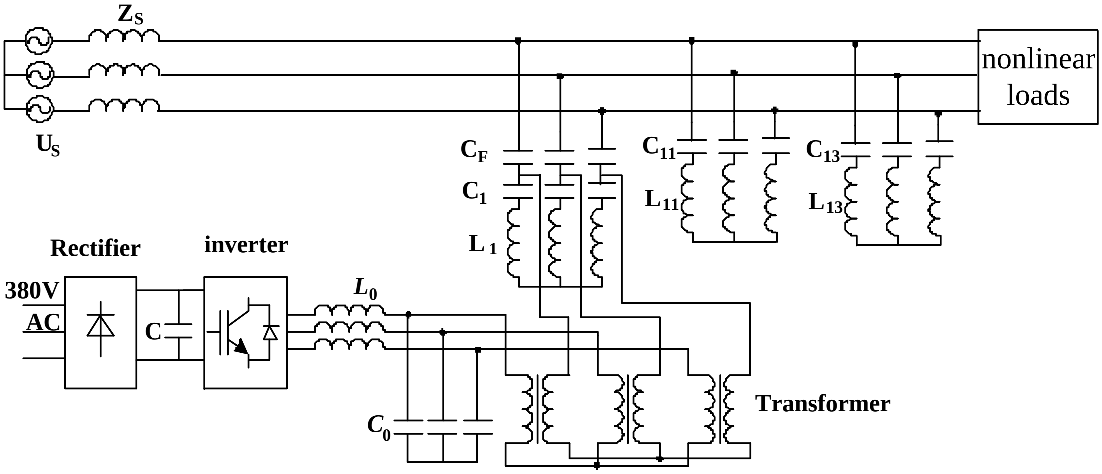

Figure 1: Topology of HAPF.

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

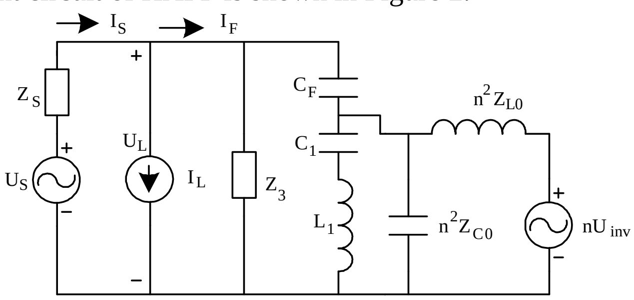

Figure 2: Single phase equivalent circuit of HAPF.

Where:

The impedance of resonance at fundamental frequency branch $Z_{C_1L_1} = Z_{C1} + Z_{L1}$

The impedance of additional branch $Z_2 = Z_{CF}$

The impedance of the PPFs is Z_3. Where $R_{11} - C_{11} - L_{11}$ branch and $R_{13} - C_{13} - L_{13}$ branch are inner resistance of inductor, capacitor and inductor that tuned at the 11th and 13th harmonics. In each passive filter branch, the impedance is

$$\begin{cases} Z_{11} = Z_{R_{11}} + Z_{C_{11}} + Z_{L_{11}} \\ Z_{13} = Z_{R_{13}} + Z_{C_{13}} + Z_{L_{13}} \end{cases}$$

The single phase equivalent circuit with the effect of harmonic source is shown in Figure 3 with output current of APF is i_{apf} .

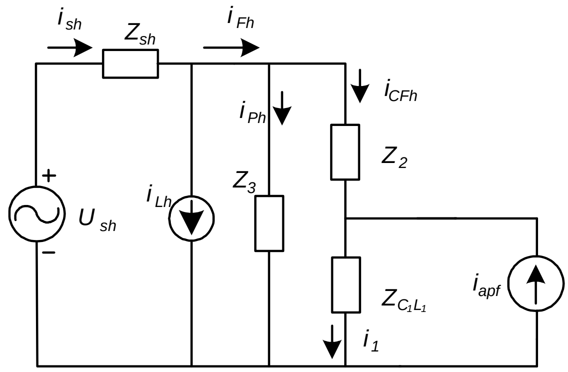

Figure 3: Single phase equivalent circuit with the effect of harmonic source.

According to Figure 3, if we control to achieve the purpose $I_{Fh} = -I_{Lh}$ then we will obtain $I_{sh} = 0$.

With control strategy $I_{apf} = KI_{Lh}$ is output current of APF. According to Figure 3, equations are established:

$$\begin{cases} I_{sh} = I_{Lh} + I_{Fh} \\ I_1 = I_{apf} + I_{CFh} \\ I_{Fh} = I_{Ph} + I_{CFh} \\ I_{sh}Z_{sh} + I_{Ph}Z_3 = U_{sh} \\ I_{CFh}Z_2 + I_1 Z_{C1L1} = I_{Ph}Z_3 \end{cases} \quad (1)$$

From (1), I_{sh} is calculated as

$$I_{sh} = \frac{(Z_2 + Z_{C1L1} - KZ_{C1L1})Z_3 I_{Lh}}{(Z_2 + Z_{C1L1})(Z_3 + Z_{sh}) + Z_3 Z_{sh}} \quad (2)$$

The equation (2) showed that if K is large enough, the harmonic current source components will gain a value of zero. K is the coefficient control and depends on many elements such as control strategy, parameters, topology…

If only considering the response of the voltage source inverter, U_s=0, i_L=0. The single phase equivalent circuit is shown in Figure 4.

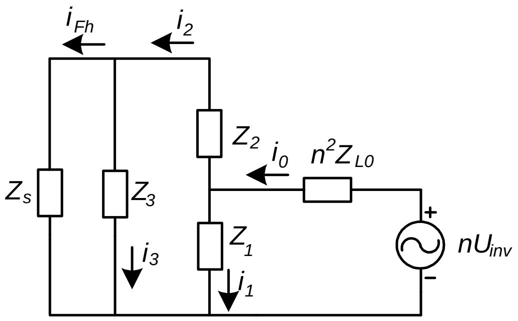

Figure 4: Single phase equivalent circuit when only considering VSI.

Where:

$$\begin{cases} Z_s = R_s + L_s s \\ Z_1 = Z_{L1}C_1 // n^2 Z_{C0} = \left(R_1 + L_1 s + \dfrac{1}{C_1 s}\right) // \dfrac{n^2}{C_0 s} = \dfrac{\dfrac{n^2}{C_0 s}\left(R_1 + L_1 s + \dfrac{1}{C_1 s}\right)}{\dfrac{n^2}{C_0 s} + R_1 + L_1 s + \dfrac{1}{C_1 s}} \\ Z_2 = \dfrac{1}{C_F s} \\ Z_{L0} = R_0 + L_0 s \end{cases} \quad (3)$$

According Figure 4, equations are established:

$$\begin{cases} I_2 = I_{Fh} + I_3 \\ I_{L0} = I_2 + I_1 \\ I_{Fh}Z_s = I_3 Z_3 \\ I_1 Z_1 + I_{L0} n^2 Z_{L0} = nU_{inv} \\ I_{Fh}Z_s + I_2 Z_2 + I_{L0} n^2 Z_{L0} = nU_{inv} \end{cases} \quad (4)$$

With I_{Fh} is compensation harmonic current that is controlled by VSI, VSI as a controlled voltage source. From (4), I_{Fh} can be calculated as (5)

$$I_{Fh} = \frac{nU_{inv}.Z_1.Z_3}{n^2 Z_{L0}\left[Z_3(Z_1 + Z_2) + Z_s(Z_1 + Z_2 + Z_3)\right] + Z_1(Z_2 Z_s + Z_2 Z_3 + Z_3 Z_s)} \quad (5)$$

The transfer function of compensation harmonic current I_{Fh} along the controlled voltage source U_{inv} is $G_{out}(s)$

$$G_{out}(s)=\frac{i_{Fh}}{U_{inv}}=\frac{n.Z_1.Z_3}{n^2 Z_{L0}\left[Z_3(Z_1+Z_2)+Z_s(Z_1+Z_2+Z_3)\right]+Z_1(Z_2Z_s+Z_2Z_3+Z_3Z_s)} \quad (6)$$

There are two control strategies for U_{inv} based on load harmonic current detection and source harmonic current detection. In this paper, the control strategy is based on load harmonic current detection. Here the load harmonic current detection is calculated based on i_p-i_q harmonic detection method [6], [10].

From the above analysis, we can see that the HAPF system has not time delay. With time delay is constituted by processes of the HAPF system, control block diagram of HAPF is shown in Figure 5. Where $G_c(s)$ and $G_{inv}(s)$ are transfer functions of the conventional PI controller and the VSI.

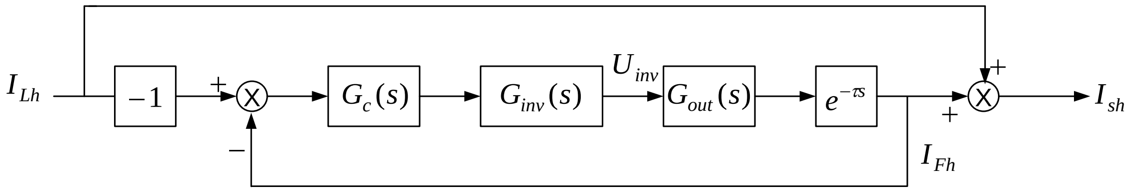

Figure 5: Control block diagram of HAPF.

The transfer function of the conventional PI controller:

$$G_c(s)=K_p\left(1+\frac{1}{T_i s}\right) \quad (7)$$

Where K_p is the proportional gain constant and T_i is the integral time.
The transfer function of VSI is expressed:

$$G_{inv}(s)=\frac{K_{inv}}{T_{inv}s+1} \quad (8)$$

Where K_{inv} is amplification factor of the VSI and T_{inv} is time delay of the VSI.
The time delay of the entire system of HAPF is τ and can be represented as $e^{-\tau s}$ function. To facilitate the analysis, may be simplified as follow

$$e^{-\tau s}=\frac{1}{e^{\tau s}}\sim\frac{1}{1+\tau s+\frac{(\tau s)^2}{2!}} \quad (9)$$

According to control block diagram of HAPF in Figure 5, the control transfer function with load current input signal I_{Lh} and source current output signal I_{sh} of HAPF system with time delay $e^{-\tau s}$ is calculated

$$G(s)=\frac{I_{sh}}{I_{Lh}}=\frac{1}{1+G_c(s).G_{inv}(s).G_{out}(s).e^{-\tau s}} \quad (10)$$

3 STABILITY ANALYSIS OF HAPF IN CONSIDERING 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, etc. In this paper, Routh criterion used stability analysis of HAPF. To consider the stability of the system according to Routh criterion, first establishing Routh table follows rules. The elements in row *i* column *j* of Routh table ($i \geq 3$) are calculated:

$$c_{ij}=c_{i-2,\,j+1}-\alpha_i.c_{i-1,\,j+1} \quad (11)$$

Where $\alpha=\frac{c_{i-2,1}}{c_{i-1,1}}$

From (10), the characteristic equation of the control transfer function of HAPF system is determined

$$D(s)=a_0s^{11}+a_1s^{10}+a_2s^9+a_3s^8+a_4s^7+a_5s^6+a_6s^5+a_7s^4+a_8s^3+a_9s^2+a_{10}s^1+a_{11}s^0 \quad (12)$$

Where the coefficients $a_0 \ldots a_{11}$ are coefficients of the characteristic equation (12) with the 11^{th} degree, that is the highest degree of the equation. The coefficients are calculated:

$a_0 = T_i\tau^2 A_1$; $a_1 = T_i(2\tau A_1 + \tau^2 A_2)$; $a_2 = T_i(2A_1 + 2\tau A_2 + \tau^2 A_3)$; $a_3 = T_i(2A_2 + 2\tau A_3 + \tau^2 A_4)$;

$a_4 = T_i(2A_3 + 2\tau A_4 + \tau^2 A_5 + 2nK_c C_F B_1)$; $a_5 = T_i(2A_4 + 2\tau A_5 + \tau^2 A_6 + 2nK_c C_F B_2)$;

$a_6 = T_i(2A_5 + 2\tau A_6 + \tau^2 A_7 + 2nK_c C_F B_3)$; $a_7 = T_i(2A_6 + 2\tau A_7 + \tau^2 A_8 + 2nK_c C_F B_4)$;

$a_8 = T_i(2A_7 + 2\tau A_8 + \tau^2 A_9 + 2nK_c C_F B_5)$; $a_9 = T_i(2A_8 + 2\tau A_9 + \tau^2 + 2nK_c C_F B_6)$;

$a_{10} = 2T_i(A_9 + \tau + \tau^2 + nK_c C_F B_7)$; $a_{11} = 2T_i(1 + nK_c C_F)$

Where:

$K_c = K_{inv} \times K_p$; n is the transfer ratio of the transformer and the expressions from A_1 to A_9 and B_1 to B_7 are determined by the Appendix.

From the coefficients of the characteristic equation (12) can be established Routh table to survey of stability of HAPF system. To determine the HAPF is stable, then the all of elements at first column are positive. Thus the stable domain of parameters of the HAPF system is determined as (13)

$$\begin{cases} c_{11} > 0 \\ c_{21} > 0 \\ c_{31} > 0 \\ c_{41} > 0 \\ c_{51} > 0 \\ c_{61} > 0 \\ c_{71} > 0 \\ c_{81} > 0 \\ c_{91} > 0 \\ c_{101} > 0 \\ c_{111} > 0 \\ c_{121} > 0 \end{cases} \quad (13)$$

Where the coefficients from c_{11} to c_{121} are calculated in Appendix

4 SIMULATION RESULTS AND DISCUSSION

To demonstrate the influence of time delay on the stability of the system HAPF, simulation results are implemented on a system HAPF 10kV-50Hz with parameters as in [5] and are listed as in Table 1. Nonlinear loads contain order harmonics such as such as 5th, 7th, 11th and 13th. The dc-side voltage is 600V.

Table 1: Parameters of system simulation.

Parameters	R (Ω)	L (mH)	C (μF)
11th turned filter	0.0157	1.77	49.75
13th turned filter	0.086	1.37	44.76
Fundamental resonance circuit	0.0168	14.75	690
Injection circuit	-	-	29.65
Output filter	-	0.2	-

When $\tau=10^{-8}$s, T_{inv}=0.01ms, K_{inv}=1, $T_i=10^{-6}$s, K_c=100 the elements in first column of Routh table c_{11}, c_{21}, c_{31}, c_{41}, c_{51}, c_{61}, c_{71}, c_{81}, c_{91}, c_{101}, c_{111} and c_{121} are determined in Table 2. All elements at first column are positive, that HAPF system is stable operation.

Now, we change time delay of the HAPF system: τ=0.0095s, T_{inv}=0.01ms, K_{inv}=1, $T_i=10^{-6}$s, K_c=100. Calculate the parameters of the Routh table we can see that the elements c_{51} and c_{111} at first column Table 3 change sign. According to Routh criterion, the HAPF system with these parameters won't be stabilize when it operate.

To demonstrate the above analysis, the simulation results done in MATLAB software, the HAPF system with the parameters in the stable domain is shown in Figure 6. The HAPF system will be stabilize after the transitional period 0.01s.

The grid current harmonic spectrum with the parameters in the stable domain is shown Figure 7. The total harmonic distortion THD of supply current in this case is 3.38%, satisfaction of IEEE Std 1547™ and IEEE 519-2014 Standard [17-18].

Table 2: The elements of the Routh table with $\tau=10^{-8}$s

s^{11}	c_{11}= 6.9612E-55	c_{12}= 1.4061E-38	c_{13}= 6.71E-28	c_{14}= 2.88E-20	c_{15}= 2.85E-13	c_{16}= 1.63E-07
s^{10}	c_{21}= 1.40E-46	c_{22}= 1.3941E-32	c_{23}= 6.52E-22	c_{24}= 1.81E-14	c_{25}= 1.22E-07	c_{26}= 1.19E-02
s^{9}	c_{31}= 1.40E-38	c_{32}= 6.68E-28	c_{33}= 2.87E-20	c_{34}= 2.84E-13	c_{35}= 1.63E-07	
s^{8}	c_{41}= 1.39E-32	c_{42}= 6.52E-22	c_{43}= 1.81E-14	c_{44}= 1.22E-07	c_{45}= 1.19E-02	
s^{7}	c_{51}= 1.32E-29	c_{52}= 1.05E-20	c_{53}= 1.61E-13	c_{54}= 1.51E-07		
s^{6}	c_{61}= 6.41E-22	c_{62}= 1.79E-14	c_{63}= 1.22E-07	c_{64}= 1.19E-02		
s^{5}	c_{71}= 1.01E-20	c_{72}= 1.59E-13	c_{73}= 1.51E-07			
s^{4}	c_{81}= 7.87E-15	c_{82}= 1.13E-07	c_{83}= 1.19E-02			
s^{3}	c_{91}= 1.38E-14	c_{92}= 1.36E-07				
s^{2}	c_{101}= 3.52E-08	c_{102}= 1.19E-02				
s^{1}	c_{111}= 1.31E-07					
s^{0}	c_{121}= 1.19E-02					

Table 3: The elements of the Routh table with τ=0.0095s.

s^{11}	c_{11}= 6.28252E-35	c_{12}= 2.4509E-27	c_{13}= 2.75E-20	c_{14}= 1.23E-13	c_{15}= 3.17E-08	c_{16}= 2.12E-03
s^{10}	c_{21}= 1.62E-31	c_{22}= 3.0786E-24	c_{23}= 3.57E-17	c_{24}= 1.19E-10	c_{25}= 1.30E-05	c_{26}= 2.00E-01
s^{9}	c_{31}= 1.26E-27	c_{32}= 1.37E-20	c_{33}= 7.68E-14	c_{34}= 2.66E-08	c_{35}= 2.04E-03	
s^{8}	c_{41}= 1.31E-24	c_{42}= 2.58E-17	c_{43}= 1.15E-10	c_{44}= 1.28E-05	c_{45}= 2.00E-01	
s^{7}	**c_{51}= -1.11E-20**	c_{52}= -3.38E-14	c_{53}= 1.43E-08	c_{54}= 1.85E-03		
s^{6}	c_{61}= 2.18E-17	c_{62}= 1.17E-10	c_{63}= 1.30E-05	c_{64}= 2.00E-01		
s^{5}	c_{71}= 2.56E-14	c_{72}= 2.09E-08	c_{73}= 1.95E-03			
s^{4}	c_{81}= 9.91E-11	c_{82}= 1.13E-05	c_{83}= 2.00E-01			
s^{3}	c_{91}= 1.80E-08	c_{92}= 1.90E-03				
s^{2}	c_{101}= 9.06E-07	c_{102}= 2.00E-01				
s^{1}	**c_{111}= -2.08E-03**					
s^{0}	c_{121}= 2.00E-01					

Simulation results of the HAPF system with the parameter τ changed is shown Figure 8. These parameters of HAPF are set outside of stable domain with time delay τ = 0.0095s, T_{inv} = 0.01ms, K_{inv}= 1, T_i = 0.1s, K_c

= 100. The HAPF system will be destabilized from 0.0095s to 0.2s. The supply current increases to 1600A and the current error is 1500A.

The supply current harmonic spectrum with the parameters outside of stable domain is shown Figure 9. The total harmonic distortion THD of supply current in this case is 379.21%. The individual harmonic components almost increase higher than in case the parameters of in the stable domain, not satisfying power quality standards in power system [17-18].

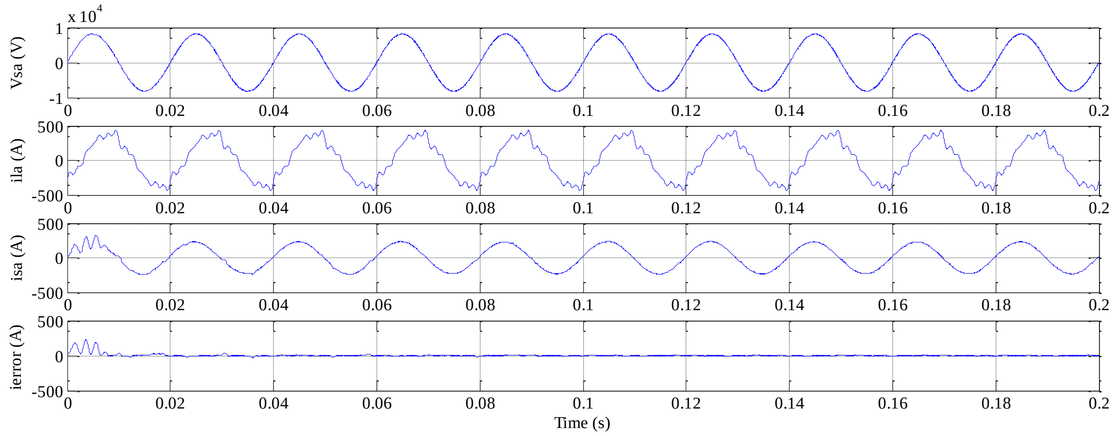

Figure 6: Response of HAPF with the parameters in the stable domain.

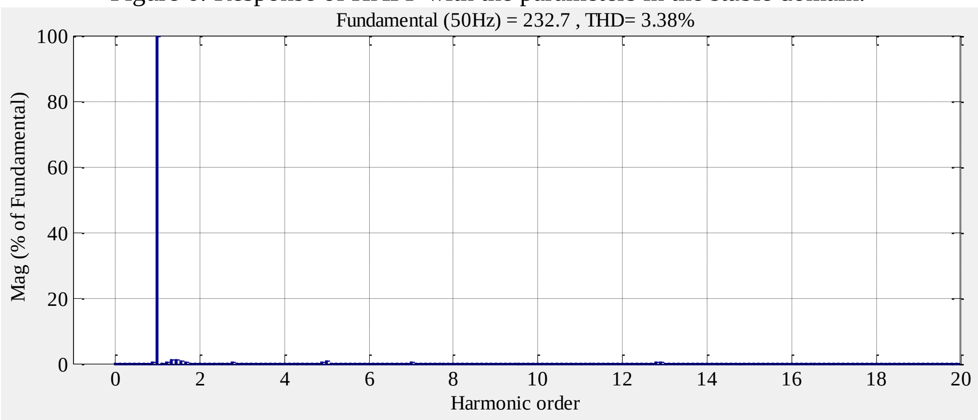

Figure 7: The supply current harmonic spectrum with the parameters in the stable domain.

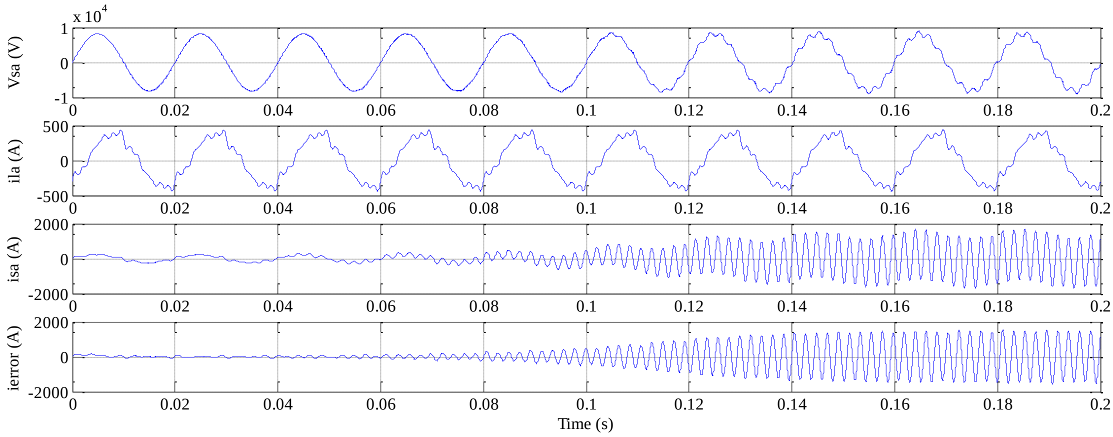

Figure 8: Response of HAPF with the parameters outside of stable domain.

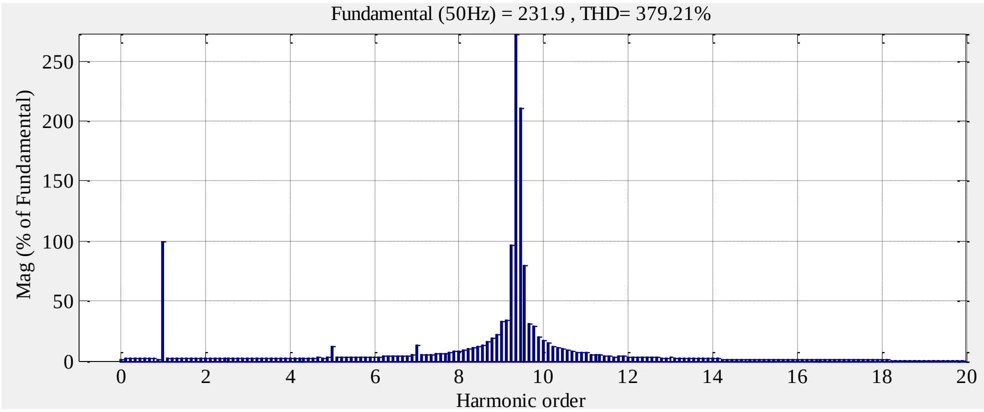

Figure 9: Grid current harmonic spectrum with the parameters outside of stable domain.

According to the obtained simulation results, in the case of parameters of HAPF outside of stable domains cannot be stabilized for the filtering as well as the power system network that the filtering is connected. In this case, the total harmonic distortion and individual harmonic will be raised much more than in the case of parameters in stable domain. Thus, with time delay highly increases will result in adverse impacts, loss of stability of HAPF. Power quality of the power system will become very poor and unachievable standards for connecting to the grid.

5 CONCLUSION

The paper has built the mathematical model of HAPF considering the time delay and analyzed the impact of the time delay on the stability of the system HAPF. When the time delay becomes smaller, the stability of HAPF is higher, and vice versa. The parameters of filtering outside of stable domain and longer time delay are unstable with HAPF system as well as power system that the filtering is connected. Thus power quality will not achieve international standards with requirements becoming more and more stringent. The results of this study can serve as a basis for choice parameters of HAPF in considering time delay, and also ensure stability and more efficient operation of HAPF system.

APPENDIX

$$c_{11} = T_i\tau^2 A_1\,;\; c_{12} = T_i(2A_1 + 2\tau A_2 + \tau^2 A_3)\;\; c_{13} = T_i(2A_3 + 2\tau A_4 + \tau^2 A_5 + 2nK_c C_F B_1)$$

$$c_{14} = T_i(2A_5 + 2\tau A_6 + \tau^2 A_7 + 2nK_c C_F B_3)\,;\;\; c_{15} = T_i(2A_7 + 2\tau A_8 + \tau^2 A_9 + 2nK_c C_F B_5)$$

$$c_{16} = 2T_i(A_9 + \tau + \tau^2 + nK_c C_F B_7)$$

$$c_{21} = T_i(2\tau A_1 + \tau^2 A_2)\,;\; c_{22} = T_i(2A_2 + 2\tau A_3 + \tau^2 A_4)\;\; c_{23} = T_i(2A_4 + 2\tau A_5 + \tau^2 A_6 + 2nK_c C_F B_2)$$

$$c_{24} = T_i(2A_6 + 2\tau A_7 + \tau^2 A_8 + 2nK_c C_F B_4)\,;\;\; c_{25} = T_i(2A_8 + 2\tau A_9 + \tau^2 + 2nK_c C_F B_6)\;\; c_{26} = 2T_i(1 + nK_c C_F)$$

$$c_{31} = \left[T_i(2A_1 + 2\tau A_2 + \tau^2 A_3) - \frac{T_i\tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_2 + 2\tau A_3 + \tau^2 A_4) \right]$$

$$c_{32} = T_i(2A_3 + 2\tau A_4 + \tau^2 A_5 + 2nK_c C_F B_1) - \\ - \frac{T_i\tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_4 + 2\tau A_5 + \tau^2 A_6 + 2nK_c C_F B_2)$$

$$c_{33} = T_i(2A_5 + 2\tau A_6 + \tau^2 A_7 + 2nK_c C_F B_3) - \\ - \frac{T_i\tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_6 + 2\tau A_7 + \tau^2 A_8 + 2nK_c C_F B_4)$$

$$c_{34} = T_i(2A_7 + 2\tau A_8 + \tau^2 A_9 + 2nK_c C_F B_5) - \\ - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_8 + 2\tau A_9 + \tau^2 + 2nK_c C_F B_6)$$

$$c_{35} = 2T_i(A_9 + \tau + \tau^2 + nK_c C_F B_7) - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} 2T_i(1 + nK_c C_F)$$

$$c_{41} = T_i(2A_2 + 2\tau A_3 + \tau^2 A_4) - \\ - \frac{T_i(2\tau A_1 + \tau^2 A_2)}{\left[T_i(2A_1 + 2\tau A_2 + \tau^2 A_3) - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_2 + 2\tau A_3 + \tau^2 A_4)\right]} \times c_{32}$$

$$c_{42} = T_i(2A_4 + 2\tau A_5 + \tau^2 A_6 + 2nK_c C_F B_2) - \\ - \frac{T_i(2\tau A_1 + \tau^2 A_2)}{\left[T_i(2A_1 + 2\tau A_2 + \tau^2 A_3) - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_2 + 2\tau A_3 + \tau^2 A_4)\right]} \times c_{33}$$

$$c_{43} = T_i(2A_6 + 2\tau A_7 + \tau^2 A_8 + 2nK_c C_F B_4) - \frac{T_i(2\tau A_1 + \tau^2 A_2)}{c_{31}} c_{34}$$

$$c_{44} = T_i(2A_8 + 2\tau A_9 + \tau^2 + 2nK_c C_F B_6) - \\ - \frac{T_i(2\tau A_1 + \tau^2 A_2)}{\left[T_i(2A_1 + 2\tau A_2 + \tau^2 A_3) - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_2 + 2\tau A_3 + \tau^2 A_4)\right]} c_{35}$$

$$c_{45} = 2T_i(1 + nK_c C_F);$$

$$c_{51} = T_i(2A_3 + 2\tau A_4 + \tau^2 A_5 + 2nK_c C_F B_1) - \\ - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_4 + 2\tau A_5 + \tau^2 A_6 + 2nK_c C_F B_2) - \frac{c_{31}}{c_{41}} c_{42}$$

$$c_{52} = T_i(2A_5 + 2\tau A_6 + \tau^2 A_7 + 2nK_c C_F B_3) - \\ - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_6 + 2\tau A_7 + \tau^2 A_8 + 2nK_c C_F B_4) - \frac{c_{31}}{c_{41}} c_{43}$$

$$c_{53} = T_i(2A_7 + 2\tau A_8 + \tau^2 A_9 + 2nK_c C_F B_5) - \\ - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} T_i(2A_8 + 2\tau A_9 + \tau^2 + 2nK_c C_F B_6) - \frac{c_{31}}{c_{41}} c_{44}$$

$$c_{54} = 2T_i(A_9 + \tau + \tau^2 + nK_c C_F B_7) - \frac{T_i \tau^2 A_1}{T_i(2\tau A_1 + \tau^2 A_2)} 2T_i(1 + nK_c C_F) - \frac{c_{31}}{c_{41}} c_{45}$$

$$c_{61} = c_{42} - \frac{c_{41}}{c_{51}} c_{52};\ c_{62} = c_{43} - \frac{c_{41}}{c_{51}} c_{53};\ c_{63} = c_{44} - \frac{c_{41}}{c_{51}} c_{54},\ c_{64} = c_{45};\ c_{71} = c_{52} - \frac{c_{51}}{c_{61}} c_{62};\ c_{72} = c_{53} - \frac{c_{51}}{c_{61}} c_{63};$$

$$c_{73} = c_{54} - \frac{c_{51}}{c_{61}} c_{64};\ c_{81} = c_{62} - \frac{c_{61}}{c_{71}} c_{72};\ c_{82} = c_{63} - \frac{c_{61}}{c_{71}} c_{73};\ c_{83} = c_{64}$$

$$c_{91} = c_{72} - \frac{c_{71}}{c_{81}} c_{82};\ c_{92} = c_{73} - \frac{c_{71}}{c_{81}} c_{83};\ c_{101} = c_{82} - \frac{c_{81}}{c_{91}} c_{92};\ c_{102} = c_{83};\ c_{111} = c_{92} - \frac{c_{91}}{c_{101}} c_{102};\ c_{121} = c_{102}$$

The expressions from A1 to A9 and B1 to B7 are expressed:

$A_1 = T_{inv}\left(f_1 + n^2 L_0 f_2\right)$

$A_2 = T_{inv} L_1 C_1 C_F f_3 + T_{inv} f_4 + T_{inv} n^2 L_0 f_5 + f_1 + n^2 L_0 f_2$

$A_3 = T_{inv} L_1 C_1 f_6 + T_{inv} R_1 C_1 C_F f_3 + T_{inv} L_{11} L_{13} C_{11} C_{13} L_s C_F + T_{inv} n^2 L_0 R_s f_7 + T_{inv} n^2 L_0 L_s f_8 +$
$+ T_{inv} n^2 L_0 C_F f_9 + L_1 C_1 C_F f_3 + f_4 + n^2 L_0 f_5$

$A_4 = T_{inv} L_1 C_1 f_{10} + T_{inv} R_1 C_1 f_6 + T_{inv} C_F f_3 + T_{inv} n^2 L_0 R_s f_8 + T_{inv} n^2 L_0 L_s f_{11} + T_{inv} n^2 L_0 C_F f_{12} +$
$+ L_1 C_1 f_6 + R_1 C_1 C_F f_3 + L_{11} L_{13} C_{11} C_{13} L_s C_F + n^2 L_0 R_s f_7 + n^2 L_0 L_s f_8 + n^2 L_0 C_F f_9$

$A_5 = T_{inv} L_1 C_1 f_{13} + T_{inv} R_1 C_1 f_{10} + T_{inv} f_6 + T_{inv} n^2 L_0 R_s f_{11} + T_{inv} n^2 L_0 L_s f_{14} + T_{inv} n^2 L_0 C_F f_{15} +$
$+ L_1 C_1 f_{10} + R_1 C_1 f_6 + C_F f_3 + n^2 L_0 R_s f_8 + n^2 L_0 L_s f_{11} + n^2 L_0 C_F f_{12}$

$A_6 = T_{inv} L_1 C_1 f_{16} + T_{inv} R_1 C_1 f_{13} + T_{inv} f_{10} + T_{inv} n^2 L_0 R_s f_{14} + T_{inv} n^2 L_0 C_F f_{17} + L_1 C_1 f_{13} +$
$+ R_1 C_1 f_{10} + f_6 + n^2 L_0 R_s f_{11} + n^2 L_0 L_s f_{14} + n^2 L_0 C_F f_{15}$

$A_7 = T_{inv} L_1 C_1 + T_{inv} R_1 C_1 f_{16} + T_{inv} f_{13} + T_{inv} n^2 L_0 f_{18} + L_1 C_1 f_{16} + R_1 C_1 f_{13} + f_{10} +$
$+ n^2 L_0 R_s f_{14} + n^2 L_0 C_F f_{17}$

$A_8 = T_{inv} f_{19} + L_1 C_1 + R_1 C_1 f_{16} + f_{13} + n^2 L_0 f_{18}$

$A_9 = T_{inv} + R_1 C_1 + R_s\left(C_{11} + C_{13}\right) + R_{11} C_{11} + R_{13} C_{13} + C_F R_s$

$B_1 = T_i L_1 C_1 L_{11} L_{13} C_{11} C_{13}$

$B_2 = T_i L_1 C_1 C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right) + T_i R_1 C_1 L_{11} L_{13} C_{11} C_{13} + L_1 C_1 L_{11} L_{13} C_{11} C_{13}$

$B_3 = T_i L_1 C_1\left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right) + T_i R_1 C_1 C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right) +$
$+ T_i L_{11} L_{13} C_{11} C_{13} + L_1 C_1 C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right) + R_1 C_1 L_{11} L_{13} C_{11} C_{13}$

$B_4 = T_i L_1 C_1\left(R_{11} C_{11} + R_{13} C_{13}\right) + T_i R_1 C_1\left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right) +$
$+ T_i C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right) + L_1 C_1\left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right) +$
$+ R_1 C_1 C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right) + L_{11} L_{13} C_{11} C_{13}$

$B_5 = T_i L_1 C_1 + T_i R_1 C_1\left(R_{11} C_{11} + R_{13} C_{13}\right) + T_i\left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right) +$
$+ L_1 C_1\left(R_{11} C_{11} + R_{13} C_{13}\right) + R_1 C_1\left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right) + C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right)$

$B_6 = T_i R_1 C_1 + T_i\left(R_{11} C_{11} + R_{13} C_{13}\right) + L_1 C_1 + R_1 C_1\left(R_{11} C_{11} + R_{13} C_{13}\right) +$
$+ \left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right)$

$B_7 = T_i + R_1 C_1 + \left(R_{11} C_{11} + R_{13} C_{13}\right)$

Where:

$f_1 = L_{11} L_{13} C_{11} C_{13} L_s C_F L_1 C_1$

$f_2 = L_s C_F L_1 C_1\left(L_{11} + L_{13}\right) C_{11} C_{13} + L_s C_1 C_F L_{11} L_{13} C_{11} C_{13} + C_F L_1 C_1 L_{11} L_{13} C_{11} C_{13}$

$f_3 = L_{11} L_{13} C_{11} C_{13} R_s + \left(R_{11} L_{13} + R_{13} L_{11}\right) C_{11} C_{13} L_s$

$f_4 = R_1 C_1 L_{11} L_{13} C_{11} C_{13} L_s C_F$

$f_5 = R_s C_F L_1 C_1\left(L_{11} + L_{13}\right) C_{11} C_{13} + R_s C_1 C_F L_{11} L_{13} C_{11} C_{13} + L_s C_F L_1 C_1\left(R_{11} + R_{13}\right) C_{11} C_{13} +$
$+ L_s C_F L_1 C_1\left(L_{11} + L_{13}\right) C_{11} C_{13} + L_s C_1 C_F\left(R_{11} L_{13} + R_{13} L_{11}\right) C_{11} C_{13} + C_F R_1 L_{11} L_{13} C_{11} C_{13} +$
$+ C_F L_1 C_1 C_{11} C_{13}\left(R_{11} L_{13} + R_{13} L_{11}\right)$

$f_6 = \left(L_{11} + L_{13}\right) C_{11} C_{13} L_s + L_{11} L_{13} C_{11} C_{13} + C_F\left(R_{11} L_{13} + R_{13} L_{11}\right) C_{11} C_{13} R_s +$
$+ C_F\left(R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}\right) L_s$

$f_7 = C_F L_1 C_1\left(R_{11} + R_{13}\right) C_{11} C_{13} + C_F R_1 C_1\left(L_{11} + L_{13}\right) C_{11} C_{13} + C_1 C_F\left(R_{11} L_{13} + R_{13} L_{11}\right) C_{11} C_{13}$

$$f_8 = C_F L_1 C_1 (C_{11} + C_{13}) + C_F R_1 C_1 (R_{11} + R_{13}) C_{11} C_{13} + (C_F + C_1)(L_{11} + L_{13}) C_{11} C_{13} + C_1 C_F (R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11})$$

$$f_9 = L_{11} L_{13} C_{11} C_{13} \left(1 + \frac{C_1}{C_F}\right) + C_{11} C_{13} (R_{11} L_{13} + R_{13} L_{11}) R_1 C_1 + (R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}) L_1 C_1$$

$$f_{10} = (L_{11} + L_{13}) C_{11} C_{13} R_s + L_s (R_{11} + R_{13}) C_{11} C_{13} + (R_{11} L_{13} + R_{13} L_{11}) C_{11} C_{13} + C_F (R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}) R_s + C_F (R_{11} C_{11} + R_{13} C_{13}) L_s$$

$$f_{11} = C_F R_1 C_1 (C_{11} + C_{13}) + (C_F + C_1)(R_{11} + R_{13}) C_{11} C_{13} + C_1 C_F (R_{11} C_{11} + R_{13} C_{13})$$

$$f_{12} = C_{11} C_{13} (R_{11} L_{13} + R_{13} L_{11}) \left(1 + \frac{C_1}{C_F}\right) + (R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}) R_1 C_1 + (R_{11} C_{11} + R_{13} C_{13}) L_1 C_1$$

$$f_{13} = R_s (R_{11} + R_{13}) C_{11} C_{13} + L_s (C_{11} + C_{13}) + R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11} + C_F (R_{11} C_{11} + R_{13} C_{13}) R_s + C_F L_s$$

$$f_{14} = (C_F + C_1)(C_{11} + C_{13}) + C_1 C_F$$

$$f_{15} = (R_{11} R_{13} C_{11} C_{13} + L_{13} C_{13} + L_{11} C_{11}) \left(1 + \frac{C_1}{C_F}\right) + (R_{11} C_{11} + R_{13} C_{13}) R_1 C_1 + L_1 C_1$$

$$f_{16} = R_s (L_{13} + C_{13}) + R_{11} C_{11} + R_{13} C_{13} + C_F R_s$$

$$f_{17} = (R_{11} C_{11} + R_{13} C_{13}) \left(1 + \frac{C_1}{C_F}\right) + R_1 C_1$$

$$f_{18} = C_F \left(1 + \frac{C_1}{C_F}\right)$$

$$f_{19} = R_1 C_1 + R_s (C_{11} + C_{13}) + R_{11} C_{11} + R_{13} C_{13} + C_F R_s$$

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PHÂN TÍCH ẢNH HƯỞNG CỦA THỜI GIAN TRỄ ĐẾN SỰ ỔN ĐỊNH CỦA MẠCH LỌC TÍCH CỰC DẠNG LAI GHÉP

Tóm tắt. Mạch lọc tích cực dạng lai ghép (HAPF) có hiệu quả cao trong việc cải thiện chất lượng điện năng trên hệ thống điện. Trong bài báo này, một phân tích ổn định của HAPF có xét đến thời gian trễ đã được thực hiện. Mô hình toán của HAPF với thời gian trễ đã được thành lập. Trên cơ sở đó, miền ổn định của các thông số HAPF đã được xác định dựa vào tiêu chuẩn ổn định Routh. Các kết quả mô phỏng dựa vào phần mềm Matlab đã chứng tỏ được rằng: thời gian trễ có ảnh hưởng rõ nét đến tính năng ổn định của hệ thống HAPF. Nghiên cứu này có ý nghĩa thực tế trong thiết kế và điều khiển của HAPF trong thời gian thực.
Từ khóa: Mạch lọc thụ động, mạch lọc tích cực dạng lai ghép, phân tích ổn định, thời gian trễ.

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