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Research Article

Effects of Time Delay on the Performance of Harmonics Elimination in Active Power Filter

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Abstract: This study begins with a brief overview of the problem of harmonic distortion and its effect on the quality of electric power, how the active power filter mitigate this problems then investigate the effect of control circuit time delay on the performance of Active Power Filter (APF). Active filter is an electronic power system that absorbs harmonic currents in the network, generated by nonlinear loads. The nonlinear load seems the main source of harmonic distortion in the power system. A shunt active power filter with optimized PI discussed in this study. Delay times are inevitable in Digital Signal Processing (DSP) based controllers can significantly degrade the performance of active power filter. Active filter performance can be affected by the delay between the control and measurement of the output current of SAPF and load current harmonics. The proposed filter reduces harmonic distortion is within an acceptable range.

Keywords: Active power filter, current harmonic, current source, time delay, total harmonic distortion

INTRODUCTION

Power electronics equipment connected to the voltage source, causes a lot of problems of power quality. However, it is their load of non-linear nature (Boukadoum *et al*., 2013), which is one of the causes of increased harmonics in grids. The use of Active Power Filter (APF) to reduce harmonics has attracted much attention (Srinivas and Tulasi Ram, 2013). The active power filter produces an output current available more preferred form that when they are injected into the AC line, it overrides the original load generated harmonics (Chaughule *et al*., 2013). The basic block diagram of the principle of compensation includes a nonlinear load shunt active power filter is shown in Fig. 1.

The term active filter is a common one and is used to power a group of power electronic circuits including power switching device and passive components of the energy-storage circuit such as capacitors and inductors.

Functions of these circuits will vary depending on the application. They are usually used to control the harmonic current supply networks in the low level distribution to the medium voltage or reactive power and/or voltage control on a high level current distribution (Arrilaga *et al*., 1985).

Figure 2 shows the classification based on these criteria. Ratings power compensation system and the speed of response plays an important role in determining the control philosophy to implement the necessary filter.

Generally, the cost of any particular system is proportional to the speed of response required (El-Habrouk *et al*., 2000). In recent years, the increasing use of power electronics systems and time-variant nonlinear loads brought a number of power harmonics/interharmonics and the quality of power supply, thus seriously threatened. The presence of interharmonics puts much more difficulty in modeling and measuring the distortion of signals (Lin, 2014). The presence of the power system interharmonics not only brought a lot of problems, such as harmonics, but also produced additional problems (Lin, 2013). The effect of the dead time (delay time) to be considered in all inverters or converters, which is based on PWM. All semiconductor devices used in the inverter have built-in (internal) and a delay when the gate control signal is used, the interval between the on and off switches, called as a dead-time (Selva Kumar *et al*., 2014). Unstable processes are well known to be difficult to control especially when there exists pure time delay. A time delay is introduced into the transfer function description of such system due to the measurement delay or an actuator delay (Yin *et al*., 2014). In practice the dead time varies depending on the device and the output current and temperature, making it less effective compensation, especially at low output current of low frequency and zero current crossings (Chen and Peng, 2007). Actually, it can be shown that the ratio between the steady-state process and load disturbance, proportional to the model gain and delay time. This

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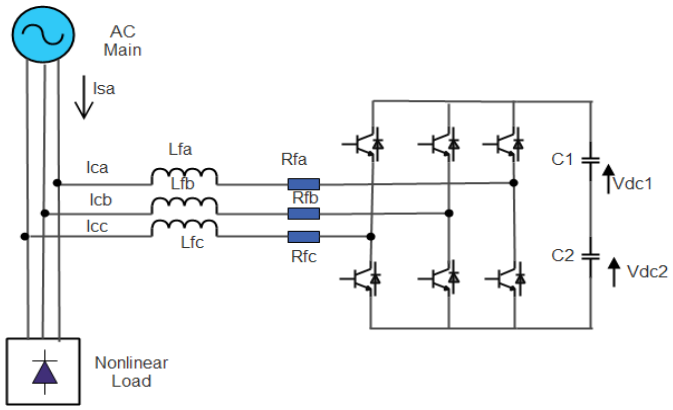


Fig. 1: Three phase Shunt active filter

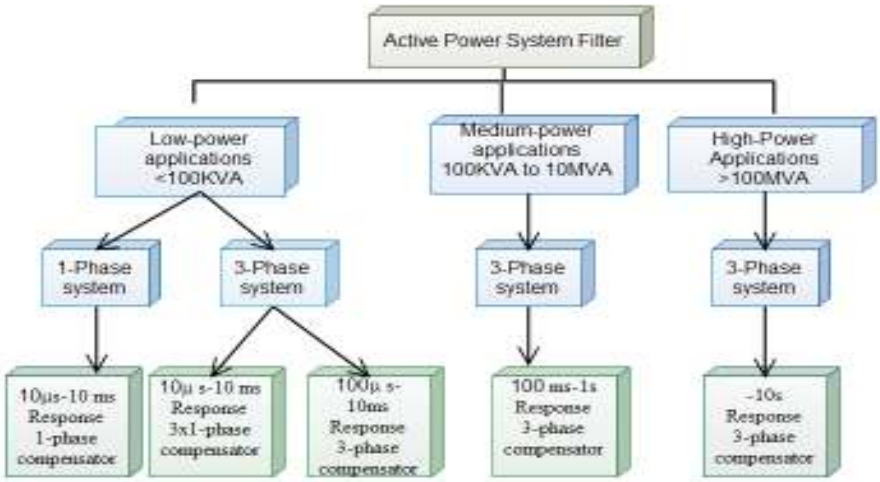


Fig. 2: Subdivision of power system filters according to power rating and speed of response

means that the fundamental disturbance load will not be compensated; or in other words, the controller is not able to reset the steady-state error (Dumitrache *et al*., 2005). Active Power Filter (APF) has a great influence on the existence of time-delay stability and performance. Even if the time delay is very small, less mentioned and sometimes cannot be ignored. Time delay poor performance or even closed-loop system should be careful treatment to prevent possible instability is an important issue (Li and Liu, 2013). The aim of this study is to investigate the impact of time delay on the performance of harmonics elimination in APF.

ACTIVE POWER FILTER

An active filter harmonic currents injected in the system with the same magnitude but of opposite sign as the harmonic currents generated by a nonlinear load. Thus an active filter can be considered as a controlled current source (or voltage). Electronically, this current source may be implemented using Pulse Width Modulation (PWM) technology is generally accomplished using PWM converters (Zhou *et al*., 2004). This is usually non-linear loads absorb non-sinusoidal currents and reactive power consumption. Harmonic currents generated by non-linear loads are injected back power distribution systems via the point of common coupling (Sahu and Asati, 2014). The main circuit of the shunt APF shown in Fig. 3.

To solve this problem, it is necessary to explore the attractive strategy solutions and advanced controls to reduce or even eliminate harmonics, to achieve energy saving and environmental protection (Lenwari and Odavic, 2009). Synchronous Reference Frame (SRF) theory of the effects of time-domain based reference current is developed; SRF reference used to detect harmonic currents. (Vijayasree *et al*., 2012). The SRF algorithm used to generate the compensation reference currents ($i^*c_{a,b,c}$) is shown in Fig. 4.

SRF-based algorithms, mathematical analysis and simulation results are presented to verify the theoretical development and is performed to verify the shunt APFs performance (Da Silva *et al*., 2010). The positive components at the fundamental frequency are converted to dc quantities in the synchronous d-q reference frame rotating at system frequency whereas the negative sequence components and all the harmonics are

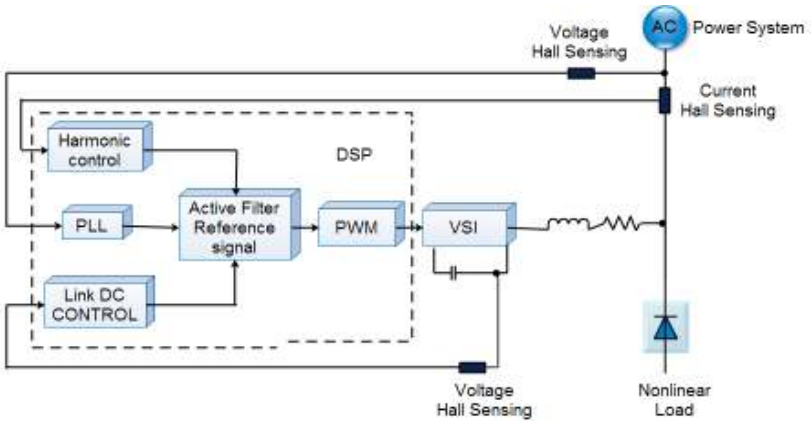


Fig. 3: Shunt APF block diagram

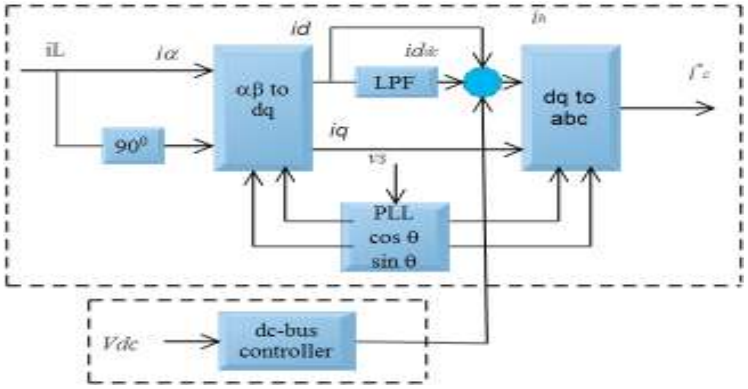


Fig. 4: Block diagram of the current SRF-based algorithm

converted to non-dc quantities and undergo a frequency shift in the spectrum. To extract these dc quantities, the integrators in d-q rotating frame are used (Zhou and Liu, 2012). To regulate and maintain the DC link voltage of the capacitor, the active filter is necessary to control the active power flowing. If the active power flowing into the filter can be controlled equal to the losses in the filter, then can be maintained the DC link voltage at the required value (Arulkumar *et al*., 2014).

Triangular carrier current controller: The controller is the essential part of the functioning of any active power filter and the way has been the subject of numerous researchers in recent years. Among the various modern techniques, triangular carrier current controller the most widely used method. This is easily done with high accuracy and fast response (Chennai and Benchouia, 2014). To determine the switching transition means to an error current [during the required reference current (I^*_{sa}) compared with the actual current source (I_{sa})] multiplied by the proportional gain (K_P). Output signal of the proportional gain compared with the triangular carrier signal. To avoid overlapping with other phases of the converter, the power transistor switching frequency is equal to the frequency of the triangular carrier signal (Arulkumar *et al*., 2014). The difference between the reference current (Chennai and Benchouia, 2014) and the injected current defines the reference signal (e) (Li *et al*., 2011).

Harmonic and interharmonics: The most common harmonics in the power system are those that are integer multiples of the fundamental frequency. Fourier suggested that any function that is constantly repeated in the interval T can be represented as a summation of the DC component, the fundamental sinusoidal component and a number of higher-order sine wave at frequencies that are multiples of the fundamental frequency. An example of a power system signal with harmonic components can be seen in Fig. 5 (Barros *et al*., 2002).

For interharmonics frequency components higher than power frequency, heating effects were observed as those caused by harmonic currents (Gunther, 2001). Frequency components can be defined as follows:

DC	$f = 0$ Hz ($f = h^* f_1$ where $h = 0$)
Harmonic	$f = h * f_1$ where h is an integer > 0
Interharmonic	$f \neq h * f_1$ where h is an integer > 0
Sub-harmonic	$f > 0$ Hz and $f < f_1$

where, f_1 is the fundamental power system frequency (50 Hz) (Drabek and Pittermann, 2011).

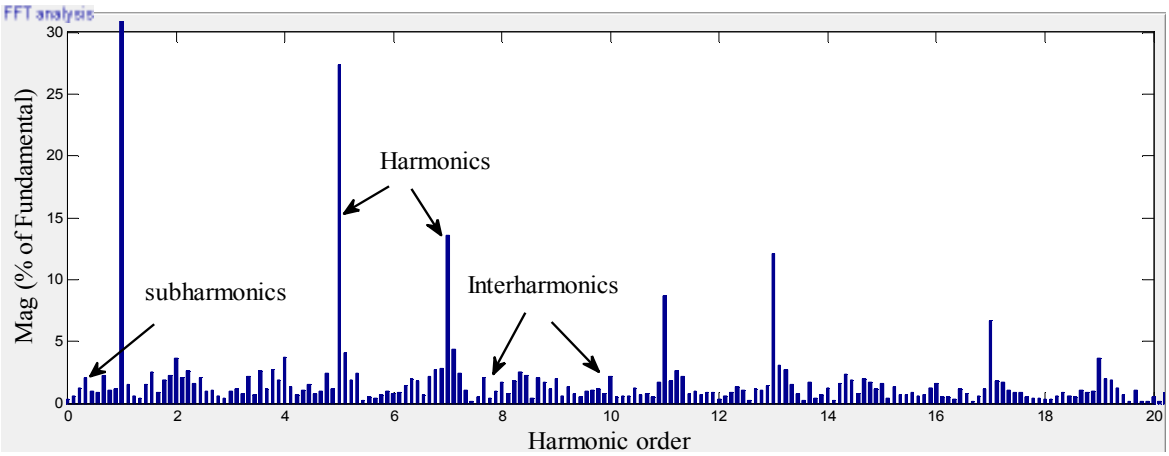


Fig. 5: Power system signal with harmonic components

Essentially, this type of interharmonics can be classified into two categories (Barros *et al*., 2002). The first type is the interharmonics are around sideband frequency and harmonic system caused by changes in the amplitude and/or phase caused by the rapid current changes of facilities. In fact, it is the source of the power supply voltage fluctuations. The second type of semiconductor devices using static converters that asynchronous switching. This is not synchronized with the switching frequency of the power system state. If the system includes DC-link connecting two different AC systems in power electronics plant, this can be a source of inter-harmonics. These systems are, in general, the use of an AC reactor or a capacitor connected between the two sides of DC rectifier and a DC/AC inverter and the DC-link comprises both. Creates ideal characteristic harmonics rectifier with infinite capacitor or reactor as follows:

$$f_h=(p_1 n\pm 1)f \quad (1)$$

where,

p = The pulse number of rectifier

n = Integer

f = The system frequency. i.e., DC-link, depending on the type of substituents, consists of a number of components, so that in practice, a reactor or a capacitor is limited by Current Source Inverter (CSI) and the Voltage Source Inverter (VSI). System voltage may be perturbed as interharmonics voltage is outside the tolerance limits and the effect of the most interharmonics thus may occur flickering light (Lin, 2014). Consider the power supply contains interharmonic components (Karimi-Ghartemani and Iravani, 2005):

$$V(t) = sin(2\pi f_1 t) + asin(2\pi f_i t) \quad (2)$$

where,

f_1 = The power supply frequency

f_i = The interharmonic frequency and a is the amplitude (p.u.) of interharmonic. RMS voltage is defined as:

$$V = \sqrt{\frac{1}{T}\int_0^T v^2\ (t)dt} \quad (3)$$

where, ($T = 1/f_1$) is the period. In accordance with (2) and (3) we can obtain the result shown in Fig. 5. It has been found that the influence by the high frequency interharmonics twice of the fundamental frequency is small. However, the interharmonics cannot be ignored for lower frequency components. It should be noted that the system frequency is 50 Hz (IEEE Interharmonic Task Force, 1997). This figure shows that the most sensitive area is located around the fundamental frequency, particularly at the lower frequency band (Lin, 2014).

THEORETICAL STUDY

To discuss the effectiveness of any given harmonic filter as a function of the control/measurement circuit delay, using simple circuit analysis. Consider, as shown in Fig. 6a the harmonic equivalent circuit for the ac network and active filter. Its associated phasor diagram is as in Fig. 6b. Harmonic current flowing into the side of the system I_{sh} is equal to the total harmonic current I_{ah} and the current generated by the active filter I_f (Zhou *et al*., 2004; Da Silva *et al*., 2008):

$$I_{ah}+I_f = I_{sh} \quad (4)$$

Active filter goal is to generate a current I_f which eliminates harmonic current I_{ah} at the load side, so that the harmonic current I_{sh} becomes zero in the ac system. This means that I_{ah} and I_f should be equal in magnitude and opposite in phase. In the control and measurement system has a time delay, the current I_f and I_{ah} will not be fully valid in a separate phase 180^0 but as shown in

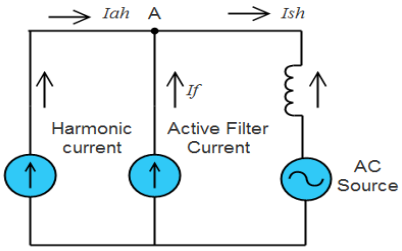


Fig. 6a: Test circuit

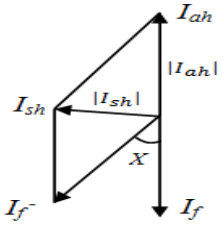


Fig. 6b: Phasor diagram

Fig. 6b, some additional phase shift angle x will experience (b):

$$x = 2.\pi.N.f.\Delta \quad (5)$$

Here N the harmonic order, f is the fundamental frequency and Δ is the time delay in the control systems. For a particular harmonic, filtering error can be characterized by analyzing the relationship between I_{sh} and the phase deviation of I_f from its desired position. y, can be calculated by applying trigonometric relationships to the phasor diagram of Fig. 6b as:

$$y = \frac{|I_{sh}|}{|I_{ah}|} = \sqrt{2 - 2\cos(x)} = 2.\sin(\frac{x}{2}) \quad (6)$$

$|I_{ah}|$ = The magnitude of load harmonic current I_{ah}
x = The phase deviation due to the delay

A value of y = 1 and y = 0 respectively, results in either or none of the load harmonic current entering the ac.

180^0 angle may look great, but it should generally be noted that contains a large number of individual harmonic distorted wave. Reason for the delay is relatively small in terms of sub-harmonics but as in Eq. (5) can be rapidly increases with the harmonic order. This means that good cancellation of harmonics of lower order, compared with the higher order ones. On the other hand, Eq. (6) can be inverted to yield the delay angel x which gives a specified level of harmonic reduction y as in (7):

$$x(y) = cos^{-1}(\frac{2-y^2}{2}) \quad (7)$$

The above analysis leads us to the following conclusion:

If it is desired to put up an active filter to minimize the portion of N^{th} order harmonic entering the ac network to y, the permissible delay in control system T is given by Zhou *et al*. (2004) and Gole and Meisingset (2001):

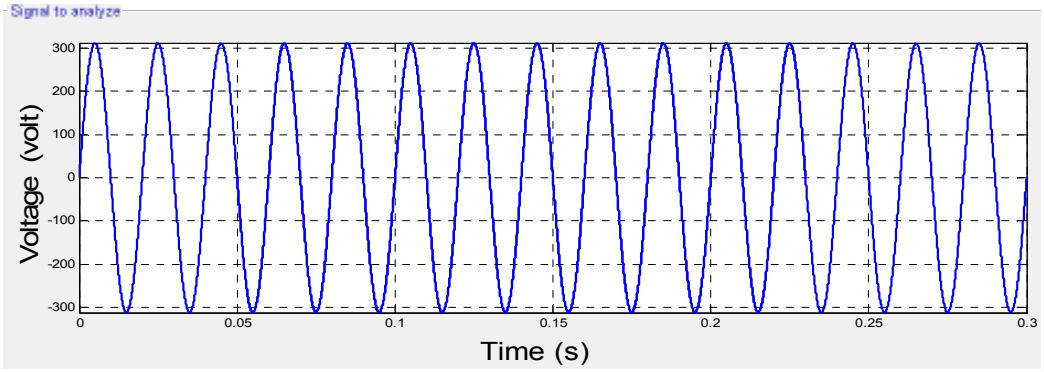
$$T = \frac{1}{2\pi Nf} cos^{-1}(\frac{2-y^2}{2}) \quad (8)$$

SIMULATION RESULTS

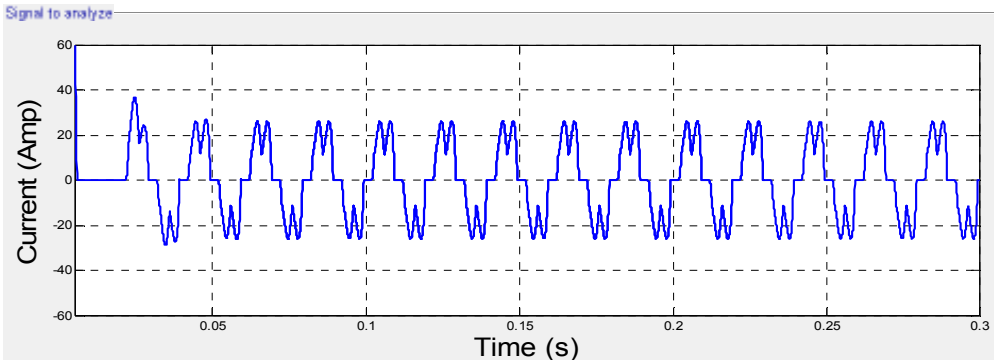
In order to eliminate the harmonic currents, an APF to be used must be able to respond quickly following variable of the harmonic currents. Table 1 shows the parameters of the system. The current source and the THD spectrum waveform in a-phase of the grid with APF control strategy, the Simulation waveforms of APF without delay time are shown in Fig. 7.

Table 1: The parameters of the system

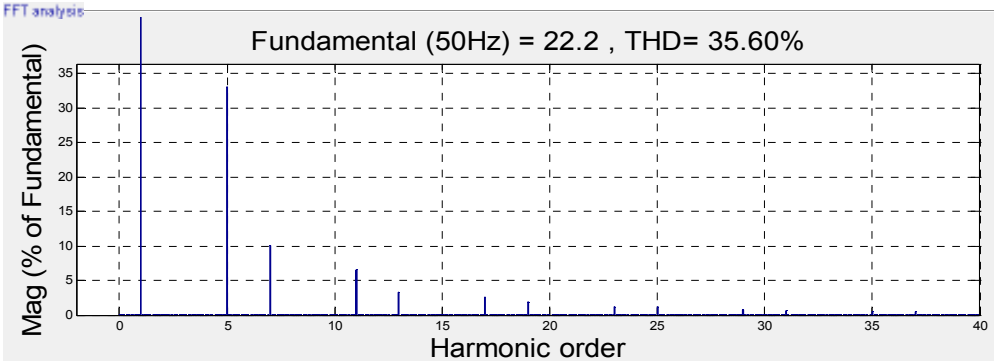
Supply phase voltage (peak)	311 V
Supply frequency fs	50 Hz
Line inductor L_L	2 mH
Filter inductor L_f&resistor R_f	0.9 mH, 0.5 Ω
DC link capacitor C_{dc}	1000 μF
DC link capacitor Voltage	650 V
Sample time T_S	50 μs
Load rectifier bridge	25Ω, 65 mH
Output capacitor $C_{o/p}$	1 mF
PI Parameters: K_P	0.1226
K_I	30.8782



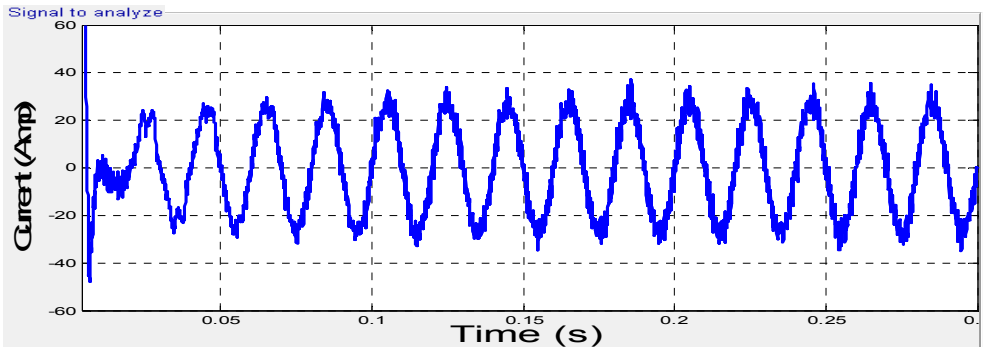
(a)


Signal to analyze
Current (Amp)
Time (s)

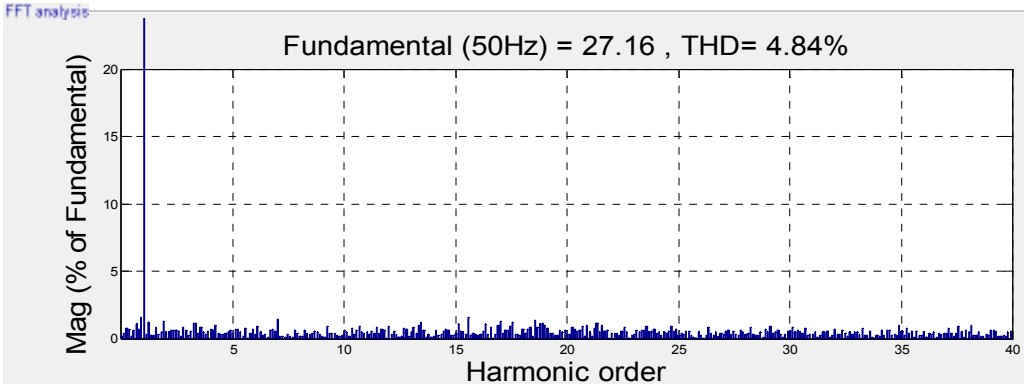
(b)


FFT analysis
Fundamental (50Hz) = 22.2 , THD= 35.60%
Mag (% of Fundamental)
Harmonic order

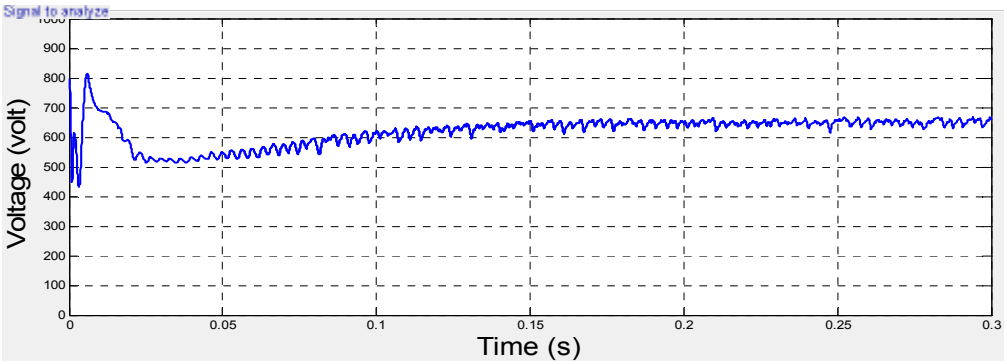
(c)


Signal to analyze
Time (s)

(d)

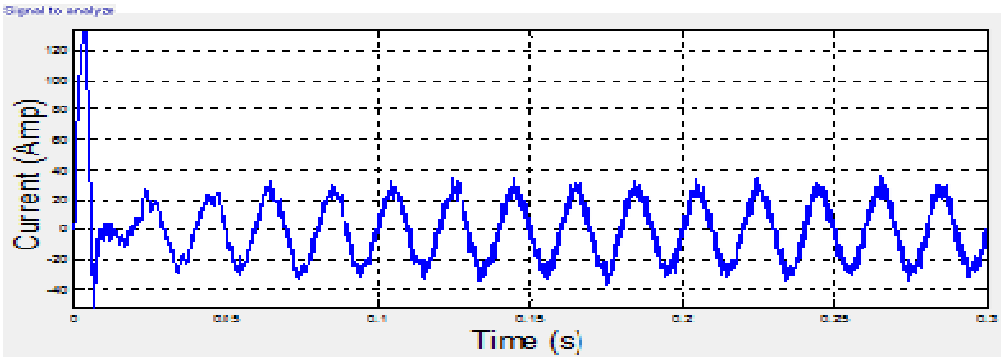

FFT analysis
Fundamental (50Hz) = 27.16 , THD= 4.84%
Mag (% of Fundamental)
Harmonic order

(e)

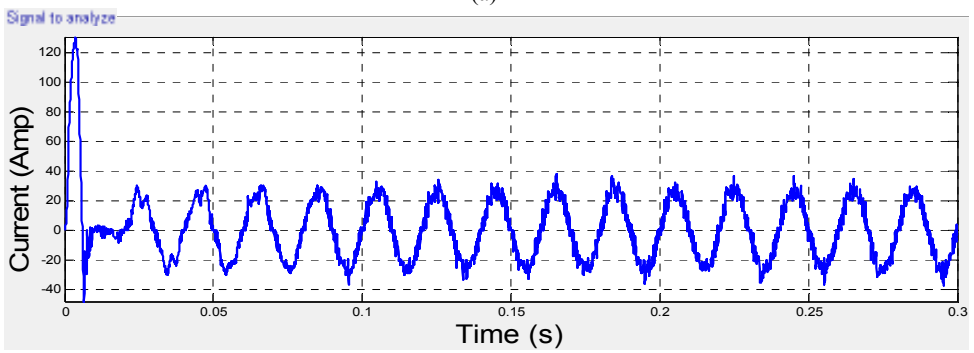


(f)

Fig. 7: Simulation waveforms of SAPF; (a) Voltage source simulation waveform, (b) Current source waveform without APF, (c) THD of the current source waveform without APF, (d) Current source waveform with APF, (e) THD of the current source waveform with APF, (f) Capacitor voltage waveform



(a)



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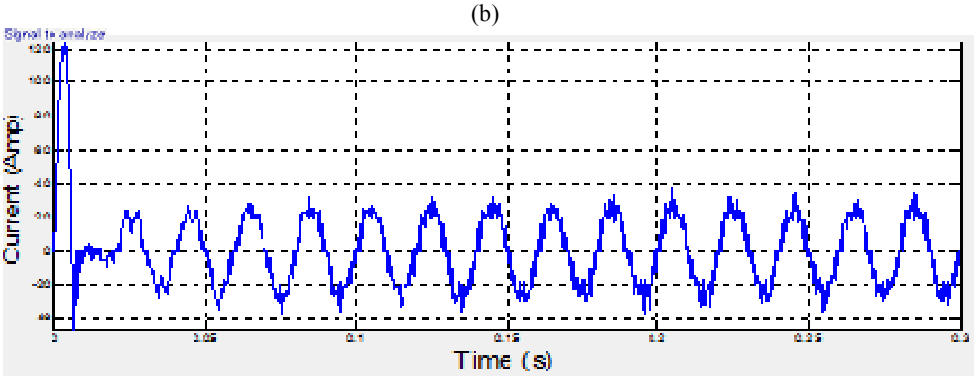
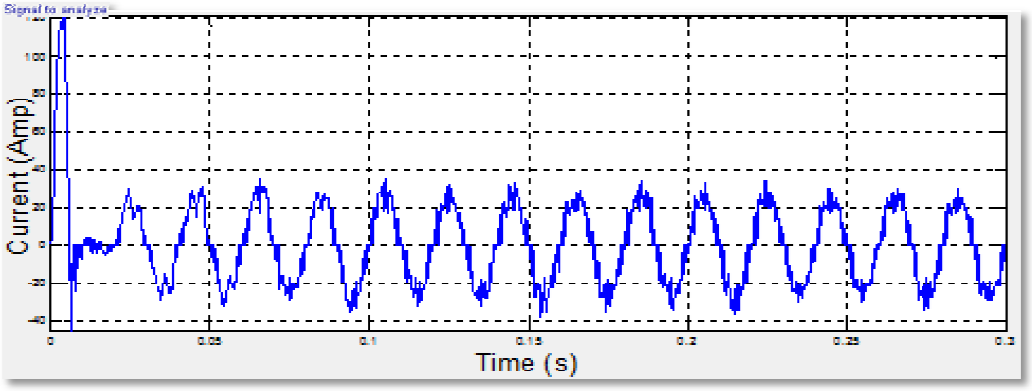


(c)



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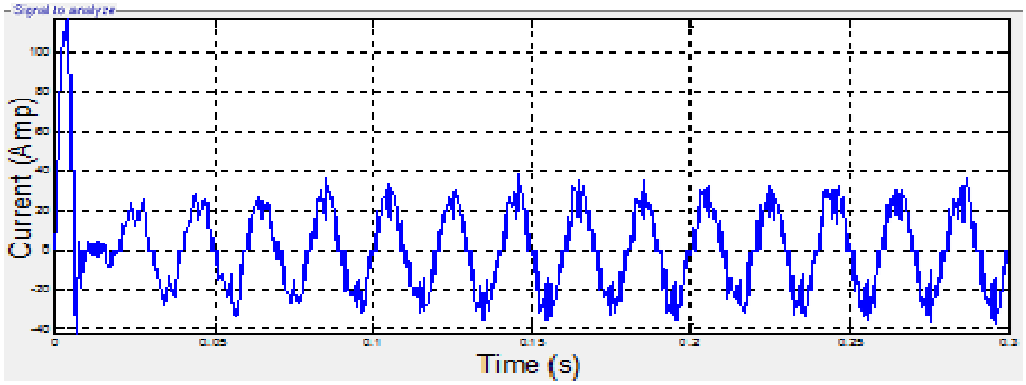
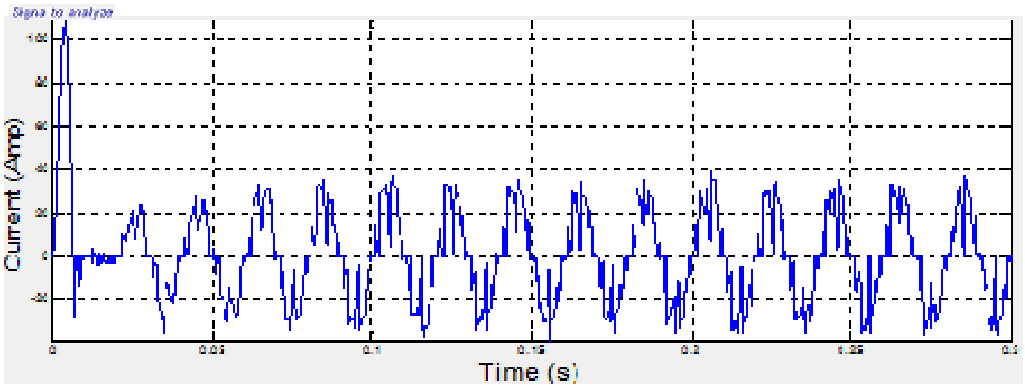


(e)



(f)

Fig. 8: Current source waveforms of APF with different time delay (TD); (a) TD = 1e-6 s, (b) TD = 1e-4s, (c) TD = 2e-4s, (d) TD = 3e-4s, (e) TD = 5e-4s, (f) TD = 9e-4s

Table 2: The response of APF with different cases of time delay

IEEE Harmonics Stand. Limit			THD% With APF and Time Delay (TD) TD (sec)											
Order of harmonics	THD%	THD% Without APF	0	1e-6	1e-4	2e-4	3e-4	4e-4	5e-4	6e-4	7e-4	8e-4	9e-4	1e-2
5	4.0	33.08	0.380	1.45	3.830	5.240	6.73	10.68	13.76	13.93	16.85	21.61	25.56	33.06
7	4.0	10.11	1.420	1.21	1.970	3.150	2.16	3.02	1.61	6.860	4.600	4.200	8.520	10.11
11	2.0	6.620	0.460	0.17	0.390	0.700	1.82	2.49	2.63	6.470	7.210	9.630	10.66	6.620
13	2.0	3.370	0.480	0.83	1.030	2.120	1.98	3.84	3.34	4.710	5.820	6.160	8.510	3.370
17	1.5	2.580	1.280	0.79	0.640	1.160	0.69	2.90	7.05	6.270	7.740	9.360	8.910	2.570
19	1.5	1.980	0.980	0.96	0.450	1.610	2.59	5.79	4.95	6.460	5.580	4.220	2.050	1.960
23	0.6	1.180	0.330	1.07	0.370	1.020	2.23	5.15	5.76	2.540	3.020	3.100	2.090	1.180
25	0.6	1.150	0.280	0.64	0.440	1.850	2.28	4.54	3.87	3.970	1.630	0.450	2.800	1.150
THD%	5.0	35.59	4.840	5.87	8.010	10.08	12.29	17.81	20.09	21.52	23.35	28.12	32.63	35.58
Fund. (R.M.S)		15.70	19.21	19.3	18.98	18.77	18.89	18.97	18.82	17.52	18.57	18.67	18.82	15.71

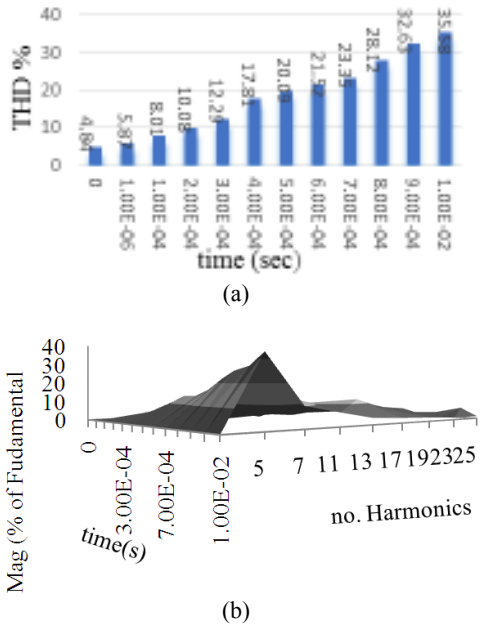


Fig. 9: (a) Relation between THD and delay time, (b) Relation between THD, time delay and the number of harmonics

Simulation results of a system have been shows the dynamic response of SAPF when control methods are adopted without delay time, the THD reduces to 4.84% from 35.59% to show the effect of the time delay on the APF performance simulations are applied on the APF system where the APF control algorithm with- and time delay is implemented as in Fig. 8.

A system was analyzed for its harmonics, sub-harmonics and interharmonics through the use of Fourier analysis to gain insight on the problem areas of the APF. It is because the time delay of the case in Fig. 8, making the APF performance worse. For example, if the time delay becomes 1μs, THD of source current increases to 5.87%. Table 2, describe the response of SAPF with different time delay. Due to this delay time, the short circuit of the power supply in the inverter will happen and it will lead to output distortions. Figure 9a shows how the Total Harmonic Distortion (THD) increases with increasing the delay time. Figure 9b shows the relation between THD and delay time, take into account the number of harmonics.

CONCLUSION

The SRF theory based shunt active power filter has been proposed to improve the power quality by compensating harmonics and reactive power requirement of the nonlinear load. The performance of a shunt active power filter has been studied with an optimized PI Controller. In case of current-source active power filter application, the time delay can cause oscillations and distortion in the source current if it is not compensated properly. Simulation results are presented to show effect of the time delay on the APF response and there is a still a small amount of oscillation in the sub-harmonic and interharmonic frequencies that surround the fundamental frequency but the total harmonic distortion was significantly reduced from the original signal that was being fed back into the original system. From the simulation results it is obvious that the THD of the source current after Compensation is well below 5%, the harmonic limit imposed by the IEEE-519 standard. It can be seen that the source current without time delay is not affected by the oscillations, whilst the source current with delay has more oscillations and distortion. This study is dealing with a summary of delay time effects in APF and various period proposed to demonstrate the performance of the designed active power filter.

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