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Adaptive Notch Filter for Harmonic Current Mitigation

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***Abstract*—**This paper presents an effective technique for harmonic current mitigation using an adaptive notch filter (ANF) to estimate current harmonics. The proposed filter consists of multiple units of ANF connected in parallel structure; each unit is governed by two ordinary differential equations. The frequency estimation is carried out based on the output of these units. The simulation and experimental results show the ability of the proposed tracking scheme to accurately estimate harmonics. The proposed filter was implemented digitally in TMS320F2808 and used in the control of hybrid active power filter (HAPF). The theoretical expectations are verified and demonstrated experimentally.

***Keywords*—**Adaptive notch filter, Active power filter, harmonic filtering, Time varying frequency.

I. INTRODUCTION

RECENTLY power system has experienced high harmonics pollution due to the wide use of power electronic loads. These nonlinear loads generate harmonics which degrade the distribution system and may effect the communication and control system. Therefore compensation of these undesirable effects is extremely important.

Conventionally, passive filters have been used to eliminate harmonics current and improve power factor. However, they suffer from various problems such as large size, tuning problem, parallel resonance and their inability to compensate random harmonics current variation. To solve these problems active power filters (APF) have been proposed and considered as possible solution for harmonics mitigation [1]-[2].

APF basically works by detecting the harmonic components from distorted signal and injecting these components, with the same magnitude but opposite in phase, into the utility AC power system. Thereby, the aim to suppress harmonics and purify network is achieved. APF can be connected either in series or in parallel to power system; therefore it can operate as either voltage source or current source. The shunt active power filter is controlled to inject a compensate current into the utility system so that it cancels the harmonics current produced by nonlinear loads. The series active power filter is controlled to insert a distorted voltage such that the load voltage is sinusoidal and maintained at a rated magnitude. Active power filters, with a more autonomous operation, can proceed directly and dynamically to compensate harmonics or to damp harmonics resonance in power system. Henceforth numerical methods for harmonic detection are needed to control active power filters [3]-[4]-[5].

Harmonic detectors are an important part in active power filtering and significantly affect their filtering characteristics. Indeed, fast and accurate response is essential to evaluate harmonic components in current or voltage waveforms, especially when time is varying. Harmonic components can be extracted or estimated using the Fast Fourier Transform (FFT), the instantaneous p-q theory, the synchronous d-q reference frame theory or by using suitable analog or digital electronic filters separating successive harmonic components [6]-[7]-[8].

In case of harmonics current determination by digital filters, a cascade structure of a notch filter is widely used. However, notch filter gives better performance only when the frequency of the measured signal remains constant. So when the frequency changes the ideal solution is a notch filter capable to change the notch frequency accordingly by tracking the frequency variation [9]-[10]. Based on adaptive filtering, this paper presents a new and simple structure for an ANF which can decompose a measured signal to its fundamental and harmonic components efficiently. The proposed filter, shown in fig. 1, consists of multiple units of ANF linked together in parallel structure; each unit estimates both magnitude and phase angle for a specified harmonic component. The sum of these harmonic components will be the reference signal for the active power filter to generate the appropriate compensation signal.

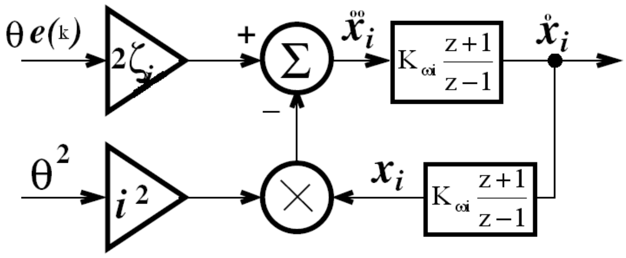

Fig. 1 Adaptive notch filter structure

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II. Harmonic Current Estimation Method

The performance of active power filters depends mainly on current harmonics or voltage extracting method. The proposed detection method is based on the concept of adaptive notch filter. A notch filter is a filter that passes all frequencies except those in stop band centered on a center frequency which is called the notch frequency. This filter can estimate the frequency of a given sinusoidal signal when the frequency remains constant. However, when the frequency change the ideal solution to estimate a sinusoidal signal is a filter capable to change the notch frequency accordingly by tracking the frequency variation. The concept of ANF has already been used for frequency estimation and various architectures have been proposed. The particular ANF structure, which is our concern, is originated from [11]. It is characterized by the dynamic behavior of the following differential equations:

$$\begin{cases} \ddot{x} + \theta^2 x = 2\zeta\theta\left(y(t) - \dot{x}\right) \\ \dot{\theta} = -\gamma x\theta\left(y(t) - \dot{x}\right) \end{cases} \tag{1}$$

where θ represents the estimated frequency and $\dot{x}$ is the estimate signal for the sinusoidal input signal $y(t)$. The coefficients ξ and γ, both real and positive, determine the behavior of the ANF in terms of accuracy and convergence speed. The parameter ξ determines the depth of the notch, hence noise sensitivity of the ANF while the parameter γ determines the adaptation speed, hence capability of the ANF in tracking the frequency variation. The proposed ANF structure is a resonator $\ddot{x}+\theta^2 x=0$ forced with an error $e(t)=y(t)-\dot{x}$. The regressed signal $x(t)$ and the error signal $e(t)$ are incorporated in the second equation of (1) which refers to the θ update law [11]-[12].

So to accurately decompose a measured signal *y(t)* into its constituting components $y_k(t)$ defined as $y_k(t)=A_k\sin(k\omega_0 t+\varphi_k)$, where A_i, φ_i and ω_0 are real unknown time-varying parameters, multiple units of the proposed ANF are linked together in parallel structure; each unit is governed by a set of differential equation mentioned in (1). Therefore, the new structure of the ANF will have the following equations:

$$\begin{cases} \ddot{x}_i + i^2\theta^2 x_i = 2\zeta\,\theta\, e(t) & i=1,2,\ldots,n \\ \dot{\theta} = -\gamma\, x_1\,\theta\, e(t) \\ e(t) = y(t) - \sum_{i=1}^{n}\dot{x}_i(t) \end{cases} \tag{2}$$

where $\dot{x}_i$ is the natural estimation of the component y_i.

By changing (2) from time domain to frequency domain, and by introducing a coefficient K_i to match the transformation at the frequency $H(j\omega)=H_d(e^{j\omega Ts})$, the proposed ANF can be implemented using the following equations:

$$\begin{aligned} \ddot{x}_i &= -i^2\theta^2(k)x_i(k) + 2\xi\theta(k)e(k) \\ \dot{x}_i &= \dot{x}_i(k-1) + K_i\ddot{x}_i(k) + K_i\ddot{x}_i(k-1) \qquad k=1,2,\ldots,n \\ x_i &= x_i(k-1) + K_i\dot{x}_i(k) + K_i\dot{x}_i(k-1) \\ \theta(k) &= \frac{1-\gamma K x_1(k-1)e(k-1)}{1+\gamma K x_1(k)e(k)}\theta(k-1) \\ e(k) &= y(k) - \sum_{i=1}^{n}\dot{x}_i(k) \end{aligned} \tag{3}$$

As we can see the ANF algorithm separates input signal components in a manner that the *i^th^* component is used for the estimation purpose on its own, and in the *i^th^* filter. Moreover the proposed technique does not require a voltage controlled oscillator (VCO). This feature makes it easy to implement and suitable for variety of real time applications

III. Evaluation of the Proposed Tracking Scheme

To test the effectiveness of the estimation technique a waveform of known harmonic contents, *y(t)*, is taken for estimation. *y(t)* represents the current supply of one phase in three phase controlled rectifier. The current supply is defined in (4) and its waveform is shown in fig.2

$$\begin{aligned} y(t) = {} & 100\sin(\omega t-0.3)+20\sin(5\omega t+0.49)+14\sin(7\omega t-0.57) \\ & +8\sin(11\omega t+0.45)+6\sin(13\omega t-0.61) \\ & +3\sin(17\omega t+0.41)+\sin(19\omega t-0.65) \end{aligned} \tag{4}$$

The ANF algorithm is implemented using a sampling time $Ts=0.0001s$, $\xi=0.08$, $\gamma=0.04$ and $f=50Hz$. The input signal *y(t)* passes trough 20 parallel units to estimate both even and odd order harmonic components that exist in *y(t)*. Fig.3 to Fig.11 show respectively the comparison between the real component and the estimated one generated by ANF units.

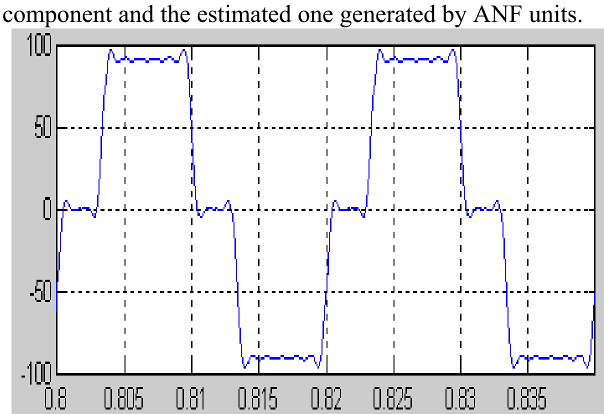

Fig. 2 The input signal *y(t)*

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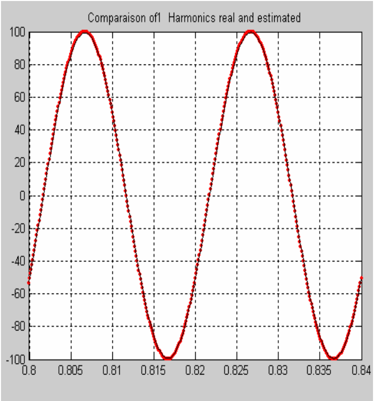

Fig. 3 Fundamental real & estimated

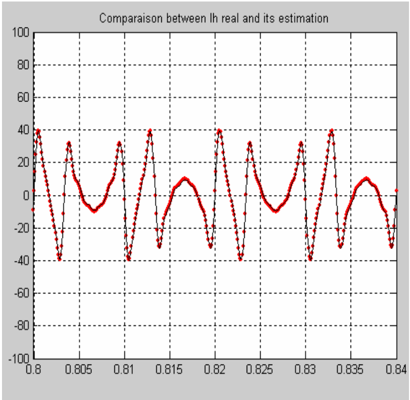

Fig. 4 Total harmonics real & estimated

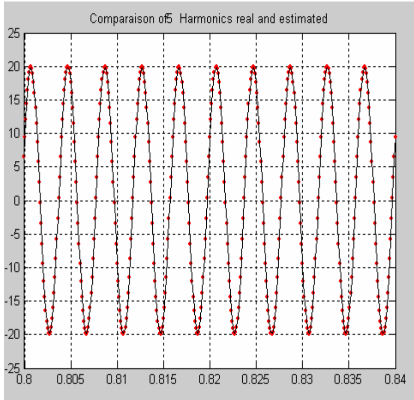

Fig. 5 5th Harmonic real & estimated

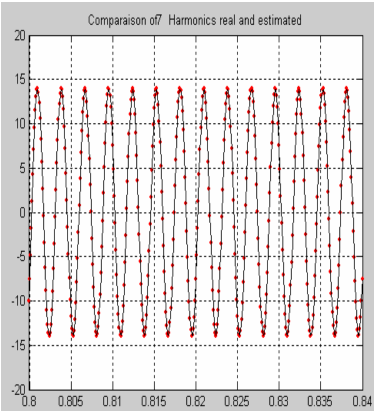

Fig. 6 7th Harmonic real & estimated

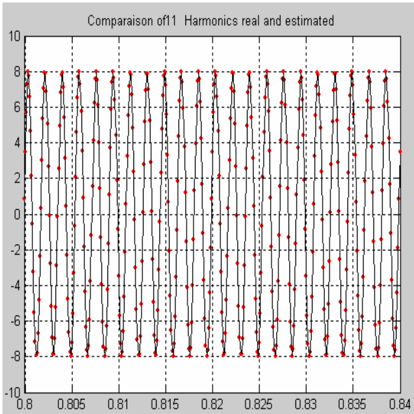

Fig.7 11th Harmonic real & estimated

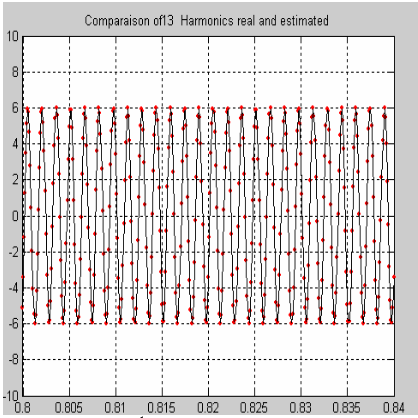

Fig. 8 13th Harmonic real & estimated

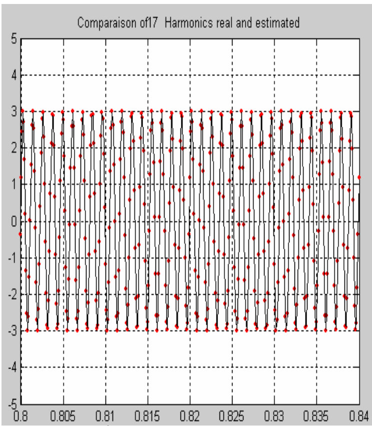

Fig. 9 17th Harmonic real & estimated

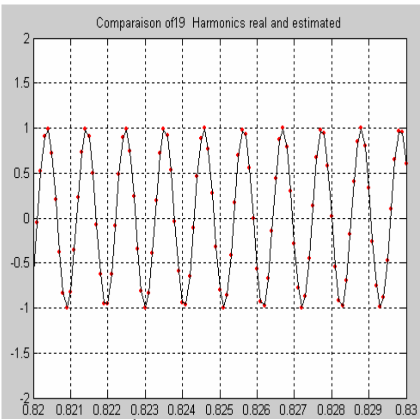

Fig. 10 19th Harmonic real & estimated

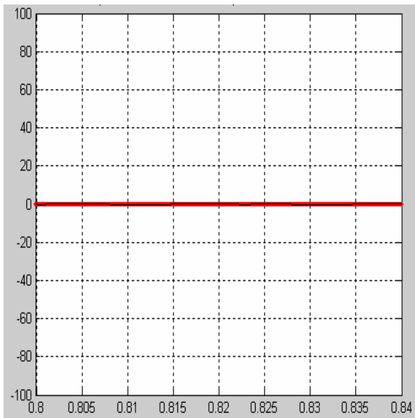

Fig. 11 the even harmonics

When the simulation results are compared with the actual one a good match has been observed. The proposed ANF structure has estimated both magnitude and phase of the fundamental frequency and each odd harmonic component. The results obtained with the even units are zero because the even harmonic components are not included in the input signal. Therefore, the proposed technique is effective to track the frequency variation and decompose the input signal into its constituting components.

Another key feature of this adaptive filter is the adaptation speed defined by the coefficient γ. A simulation results is carried out with different values of γ to show the speed of the filter in estimating the harmonic components.

From Fig.10 to Fig.17, it can be seen that when γ increase the capability of the ANF for tracking frequency increase and the time of converging is fast.

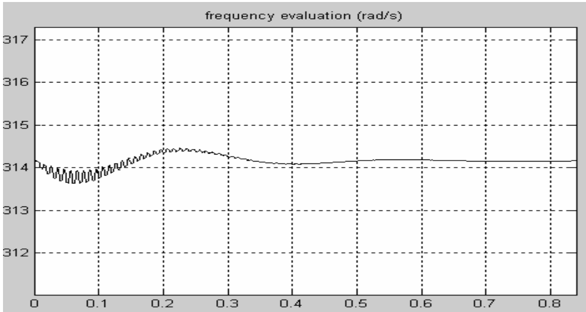

Fig. 12 Frequency evaluation with γ =0.4

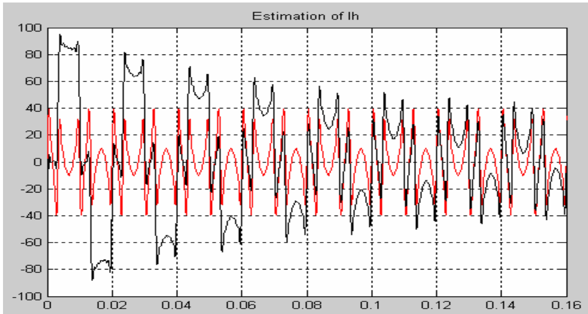

Fig. 13 Comparison between real and estimated total harmonics

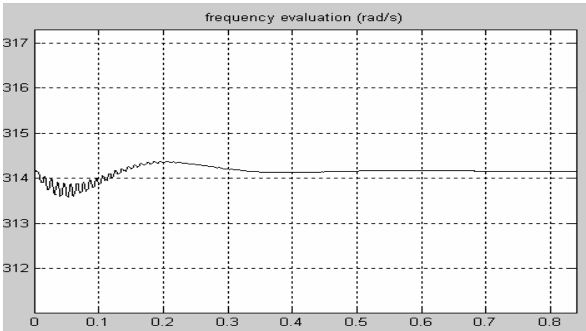

Fig. 14 Frequency evaluation with γ =0.6

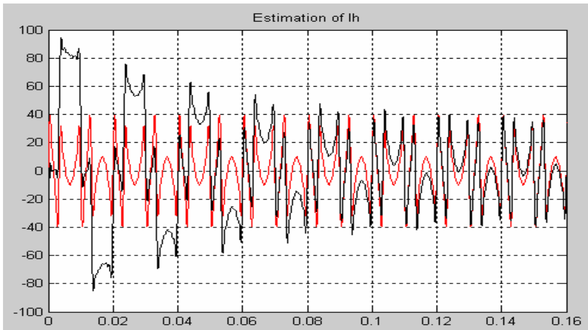

Fig. 15 Comparison between real and estimated total harmonics

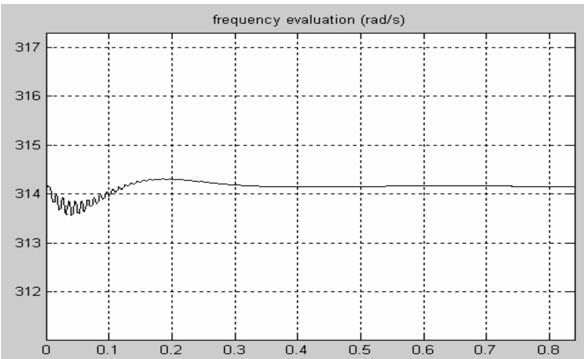

Fig. 16 Frequency evaluation with γ =0.8

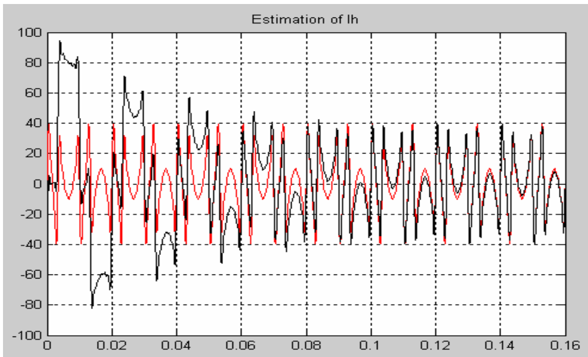

Fig.17 Comparison between real and estimated total harmonics

However, with a very high value of γ the filter will not converge and the estimated signal will have a distorted shape. Thus, it is very important to choose an accurate value of γ. On the other hand, increasing the value of γ can achieve faster estimation but at the same time, ζ should be increased in order to avoid oscillatory behavior.

IV. Active Power Filtering Using ANF

To test the feasibility of the proposed tracking scheme, a hybrid active power filter is built to mitigate harmonics current. The proposed active power filter, shown in Fig.18, consists of a shunt passive filter with a series active power filter. The shunt passive filter is connected in parallel with load and suppresses harmonics current generated by the load, whereas, the active power filter connected in series acts as a harmonics isolator. The output voltage of the series active filter is related to harmonic current and expressed as

$$y(t) = K * Ish(t) \qquad (5)$$

where *Ish* is the main harmonic current and *K* is the equivalent harmonic resistor at the harmonic frequency [13]-[14].

Based on the above fundamental concept, and using the parameters shown in table 1 for both simulation and hardware implementation, the control strategy of the hybrid active power filter consists of sensing the current source *Is,* extracting the harmonics current using the proposed ANF, multiplying the results by a gain *K* and that is the reference signal to the PWM voltage source inverter. Thus the inverter injects harmonics voltage which is proportional to the harmonics current into the line.

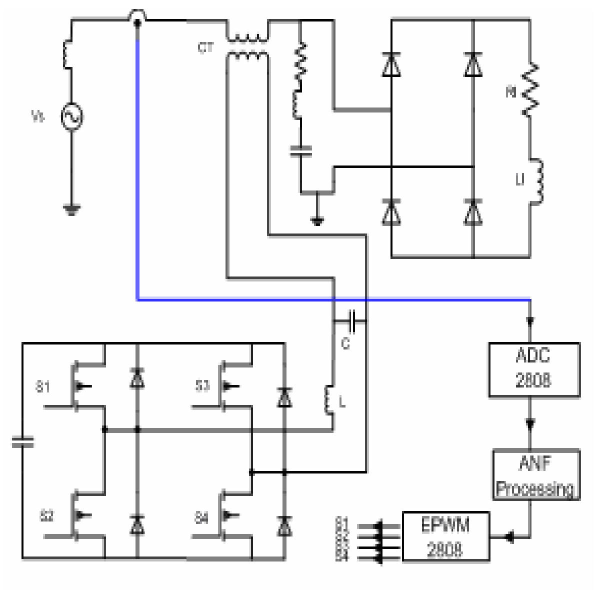

Fig. 18 Hybrid active power filter

TABLE I
HYBRID ACTIVE POWER FILTER PARAMETERS

Components	Values
Source Frequency	50Hz
AC supply voltage	110V
PWM frequency	20kHz
DC bus capacitor	470uF
Load	L=200mH, R=100Ω
Passive filter	L=3mH,C=60uF, R=100Ω

The proposed control strategy of the HAPF is simulated and implemented digitally in DSP TMS320F2808. The current source, *Is*, is sensed and send to the analog digital converter (ADC) of the DSP. The sampling times are governed by the DSP timer called a CpuTimer0, which generates periodic interrupt at each sampling time Ts. At each interrupt service routine (ISR) the following tasks must be executed:

- Read the sampling value of the current source *Is* from the analog digital converter ADC.
- Process the data obtained from the ADC to filter it using the adaptive notch filter equations.
- Multiplying the output from the ANF processing by a gain *K*
- Update the compare value of the pulse width modulation module (ePWM) built in TMS320F2808 DSP

Fig.19 to Fig.22 show respectively the simulation and hardware result for unfiltered current source, filtered current source with only passive filter, total current source harmonic estimated by the adaptive notch filter and the current source filtered with the HAPF. From the result obtained it is clear that the single phase hybrid active power filter proposed for harmonics current mitigation features a great simplicity in the control side with a good performance in harmonics current mitigation showed by keeping the THD of the current source within the acceptable limits. It reduce the supply current THD from 24.33% down to 4.57%. The ability of harmonics current filtering is due to the ability of the proposed ANF to track the frequency variation and extract the harmonic components of the measured signal. The proposed filter has the following advantages:

- The filter is adaptive so it keeps tracking on undesired frequency varying in the power source
- The proposed adaptive notch filter is characterized by two factors that determine the behavior of the ANF in term of accuracy and convergence speed. A good choice of these factors yields a fast and accurate harmonic current estimation.
- The proposed adaptive notch filter can successfully extract the harmonic components in frequency- varying conditions.

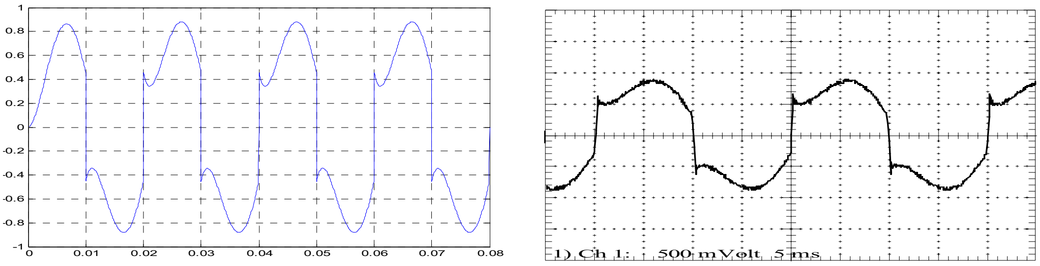

Fig. 19 Simulation and experimental result s of unfiltered current source (0.5 A/div., 5 ms/div.)

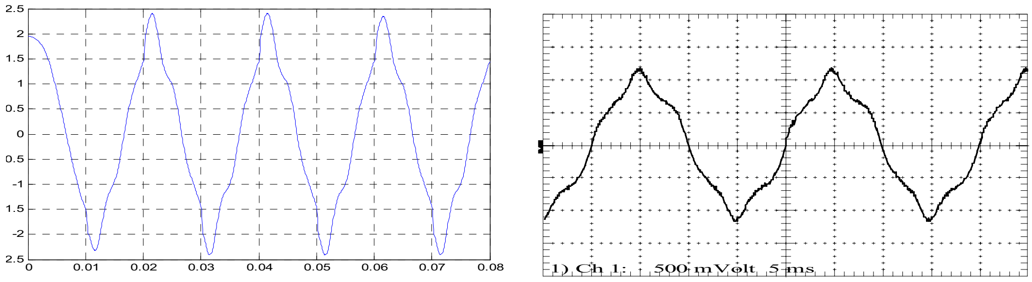

Fig. 20 Simulation and experimental results of current source filtered with passive filter (0.5 A/div., 5 ms/div.)

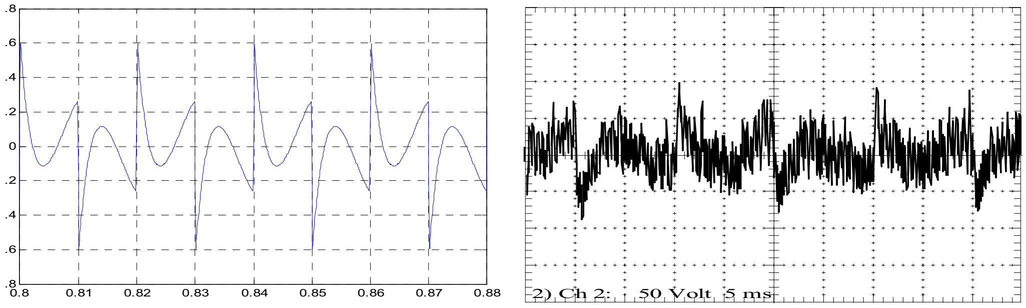

Fig. 21 Simulation and experimental results of harmonics current source (50v/div., 5 ms/div.)

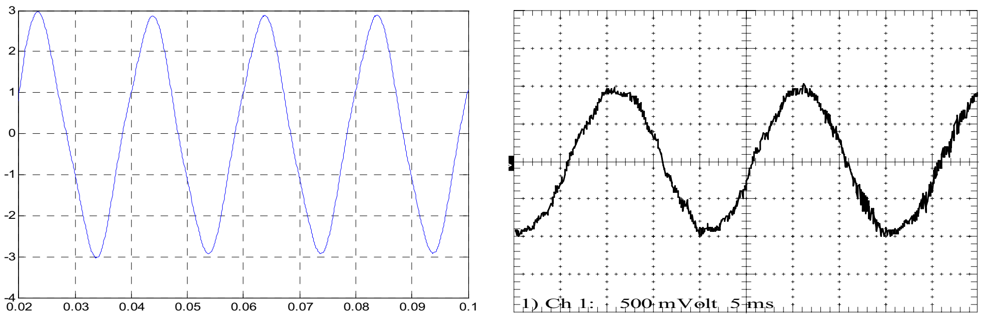

Fig. 22 Simulation and experimental results of current source filtered with HAPF (0.5 A/div., 5 ms/div.)

V. CONCLUSION

In active power filtering, harmonic on line tracking is an essential part for filtering process. The application of an adaptive notch filter to estimate current harmonics is tested experimentally. The results obtained exhibits a good performance in current harmonics estimation. Moreover, the proposed filter ANF is used in the control strategy of the hybrid active power filter. Although the control strategy is simple, the experimental results demonstrate the ability of the HAPF and its control strategy to compensate current harmonics efficiently. The THD is within the limit permitted and equal to 4.57%.

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