Real Time Individual Harmonic Measuring Method for Active Harmonic Compensation

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ABSTRACT

A basic criterion that determines the behaviour of an active power filter is the method of measuring the reference harmonic current. In this paper, the performance of individual harmonic detection methods is proposed, and evaluated in terms of accuracy and speed of response when signal amplitude and phase angle is varying. The harmonic detection method is based on an efficient least squares algorithm that does not require matrix inversion. The proposed algorithm can provide the specific or all harmonic components to be compensated in an active power filter with a fast response and high accuracy in real time. The identification results are used to generate the reference signal for the active power filter. Results obtained by simulation with MATLAB/SIMULINK are presented to prove the suitability of harmonic detection method for use in an active power filter application.

1. INTRODUCTION

Harmonics in power systems generated by nonlinear loads are causing widespread concern to power system engineers and have attracted considerable interest. These harmonics cause an array of problems such as: radio frequency interference, equipment overheating, machine vibration, motor failures, blown capacitor fuses, excessive neutral current, inaccurate power metering and increased power losses. Therefore, filtering the harmonics in line currents is considered essential, so that voltage harmonics in power systems are kept under control.

Conventionally, passive LC filters have been used to eliminate line current harmonics. However, these passive LC filters based on the resonant principle have many disadvantages, such as their inability to compensate random harmonic current variation, large size, tuning problems and parallel resonance. To solve these problems, active power filters (APF) have been introduced [1] – [5] and considered as an effective solution for reducing current harmonics. The principle of APF is to inject harmonic current with the same amplitude and opposite phase of the load's harmonic current into the line and eliminate harmonics in the source current. The performance of active power filters is based on the methods used to obtain the current reference and the control laws to generate the compensation current. Consequently, accurate and fast response is essential to evaluate harmonic components in the load current waveform, especially when their characteristics are varying with time.

The general current harmonic reference method is based on the rotating axis transform which transforms the signal into a rotating axis and then used a low pass filter to extract the desired harmonic signal [1]. However, as a result of using a low pass filter, it is difficult to achieve both a fast response and accurate detection ability at the same time. A variety of methods are used for current harmonic detection for an active power filter spectrum analysis such as the Discrete Fourier Transform (DFT) and neural network [2]-[3]. These methods are effective in computing the harmonic distortion components of the periodic signals in the steady state. However, it is not very suitable for identifying the harmonic load currents due to the presence of noise in real power systems. Also, it is inefficient in tracking sudden changes in waveforms. In addition to that, harmonic detection using the DFT technique has a significant delay which is more than two cycles of the fundamental waveform. It uses the first cycle for collecting the data and the next one or more cycles for analysing the collected data. Therefore, it can lead to poor harmonic compensation in an active power filter for the random variation of a nonlinear load current.

An advanced APF for the compensation of real time individual harmonic current components is presented. A measurement method based on an efficient least squares algorithm [6] is introduced in this paper. The proposed method can provide the magnitude and phase angle of the fundamental and each of the harmonic components.

The paper is structured as follows. The concept of the individual harmonic component detection technique based on an efficient least squares algorithm is presented and explained in Section 2. The scheme of criteria to derive the required reference signal for achieving the desired level of harmonic elimination is given and discussed in Section 3. In Section 4, the computer simulation results obtained with MATLAB/SIMULINK are provided to verify the validity of the theoretical analysis and demonstrate the effectiveness of the harmonic detection method. The method is applied to control an APF for a single-phase system. The results obtained prove that the method is fast and accurate. Therefore, the proposed method is suitable for real time applications. The summary and conclusion are presented in Section 5.

2. THE PROPOSED INDIVIDUAL HARMONIC DETECTION METHOD

The harmonic current generation is accomplished using a full bridge current controlled voltage source inverter with a hysteresis controller. A single phase diode full bridge-rectifier generates harmonics with the following order:

$$i = 4r \pm 1 \qquad (1)$$

where, *i* is the order of the current harmonic and *r* is an integer 1, 2, 3, …, *r*.

In general, a time varying waveform of distorted nonsinusoidal instantaneous voltages source (v_s) and current load (i_L) in a single-phase system of known fundamental angular frequency, ω, with harmonics of unknown magnitudes and phases can be expressed as:

$$v_s(t) = \sum_{i=1}^{k} V_{si} \sin\left(\omega_i t + \alpha_i\right) + e\left(t\right) \qquad (2)$$

$$i_L(t) = \sum_{i=1,3,5,\ldots}^{k} I_{Li} \sin\left(\omega_i t + \beta_i\right) + e\left(t\right) \qquad (3)$$

where V_{si} and I_{Li} are the unknown magnitude values of the voltage supply and current load, ω_i is the angular frequency and α_i is the unknown phase angles of the i^{th} harmonic (i=1, 3, 5,…,k) and k is the total number of harmonics. The variable *e(t)* represents an additive Gaussian noise with unity variance. This section overviews the efficient least squares method which is used as the building block of the proposed measurement as shown in figure 1.

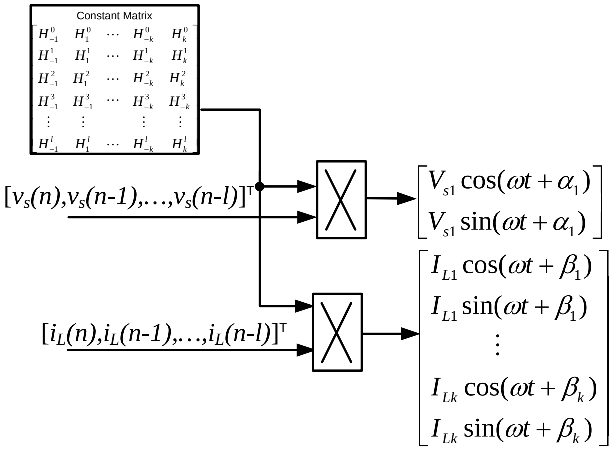


Figure 1: Building block of the proposed method for measuring harmonic components.

The main difference of this structure compared to that of the conventional linear least squares method is to solve the system equations without inverting any matrices with real number elements in rotation matrix. The proposed algorithm multiplies each set of the signals by the same constant matrix. It will be noted that, the elements of a rotation matrix are mostly complex exponentials of the form $e^{j\omega nT}$. However, it can be represented in rotation matrix form with real numbers, by letting the matrix H_i^l be an equivalent representation of $e^{-j(\omega nT)l}$. Mathematical properties of the efficient least squares method are examined in [6]. Consequently, the active and reactive term of each harmonic of voltage source and load current can be obtained using the proposed method as below

$$\begin{bmatrix} H_{-1}^{0} & H_{1}^{0} & \cdots & H_{-k}^{0} & H_{k}^{0} \\ H_{-1}^{1} & H_{1}^{1} & \cdots & H_{-k}^{1} & H_{k}^{1} \\ H_{-1}^{2} & H_{1}^{2} & \cdots & H_{-k}^{2} & H_{k}^{2} \\ \vdots & \vdots & & \vdots & \vdots \\ H_{-1}^{l} & H_{1}^{l} & \cdots & H_{-k}^{l} & H_{k}^{l} \end{bmatrix} \begin{bmatrix} v_s(n) \\ v_s(n-1) \\ \vdots \\ i_L(n) \\ i_L(n-1) \end{bmatrix} = \begin{bmatrix} V_{s1}\cos(\omega t+\alpha)_1 \\ V_{s1}\sin(\omega t+\theta_1) \\ \vdots \\ I_{Lk}\cos(\omega t+\beta_{Lk}) \\ I_{Lk}\sin(\omega t+\beta_{Lk}) \end{bmatrix} \qquad (4)$$

where $H_i^l = \begin{bmatrix} \cos\omega_i nTl & -\sin\omega_i nTl \\ \sin\omega_i nTl & \cos\omega_i nTl \end{bmatrix}$

l is the number of measured sample (ie., l>2k)

k is the total number of harmonics

i is the harmonic order

T is sampling period

The resultant magnitude value of voltage source is V_{sm}. A sinusoidal signal of unit magnitude and synchronized with the utility voltage source for an active power filter control block, sin(ωt) is determined from (5) and (6) respectively.

$$V_{sm} = 2\sqrt{\left(V_{s1}\cos(\omega t+\alpha_1)\right)^2 + \left(V_{s1}\sin(\omega t+\alpha_1)\right)^2} \qquad (5)$$

$$\sin(\omega t) = \left(\frac{V_{s1}\sin(\omega t+\alpha_1)}{V_{sm}}\right) \qquad (6)$$

The proposed method uses sum of selected harmonics to generate the compensation current. It can be expressed as follows:

$$i_h = \sum_{i=3,5,..}^{k} I_{Li}\cos\left(\omega t + \beta_i\right) \qquad (7)$$

where, i_h is the sum of the selected harmonics of the load current.

The current reference for compensation i_c is obtained as follows:

$$i_c = i_h - i_F \qquad (8)$$

where, i_F is current output from an active power filter.

3. THE COMPENSATION CURRENT METHOD

3.1. BASIC PRINCIPLE

The shunt active power filter is a voltage source inverter controlled as a current source. Figure 2 shows an overview of a system with shunt active power filter. As can be seen in figure 2, the shunt active power filter is connected in parallel with the nonlinear load that is to be compensated. The filter generates the harmonic current that is required by the load so that the mains has to supply only the fundamental current and the harmonics are eliminated from the power lines.

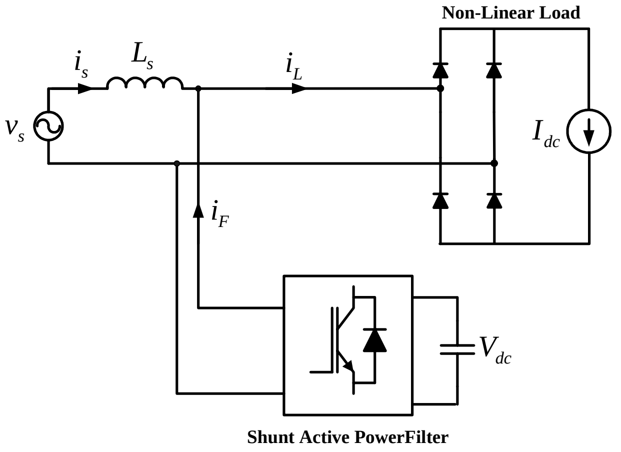


Figure 2: Voltage source inverter as a shunt active filter.

3.2. SYSTEM DESCRIPTION OF PROPOSED ACTIVE POWER FILTER

The complete system is illustrated in figure 3. The active power filter consists of a single-phase voltage source inverter, a dc-side capacitor, and an inductance in series with the ac-side of the inverter. The resistor in series with the inductor represents the line resistance. A full-bridge rectifier with DC current source is used to represent the nonlinear load. The single phase supply is represented as an ideal source and an inductor which characterises the transformer and power cable inductance of the supply. All of these are illustrated in figure 3.

The proposed individual harmonic measurement method is used to obtain the selected harmonic currents. The harmonic current is computed by summation of selected harmonic current components (i_h). The method also extracts the magnitude of fundamental component of voltage source (V_{sm}) and the unit sinusoidal ($\sin(\omega t)$) which rotates at the synchronous speed according to the frequency of the supply voltage.

To generate the compensation current that follows the current reference, usually two types of control method, namely PWM control and hysteresis control are used. The hysteresis control method is adapted for the proposed active power filter. The hysteresis current controller determines the gating signal of the single-phase current controlled voltage source inverter so that it can follow the reference current. The gating signals are applied to the inverter through the gate drive system.

3.2.1. HYSTERESIS CURRENT CONTROLLER

The hysteresis current controller is known for its quick response, easy implementation, maximum current limit and insensitivity to load parameter variations [7]. It is used to control the current in a voltage source inverter so that it can produce an output current which follows a reference current signal. This technique controls the switches in an inverter such that it can force the current to go up and down to track a reference current signal. In this way, the difference current between current i_c and i_c^* is driven to follow a hysteresis controller, as shown in figure 3.

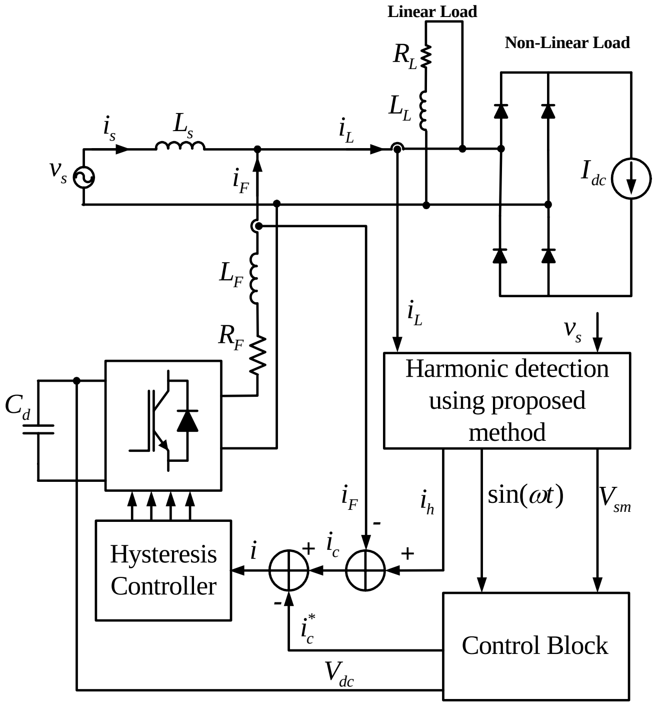


Figure 3: The proposed harmonic compensation method for active power filter.

3.2.2. INVERTER DC SIDE VOLTAGE CONTROL

The DC side voltage of the hysteresis controlled voltage source inverter should be controlled and kept at a constant value to maintain the normal operation of the inverter. Because there is an energy loss due to conduction and switching power losses associated with the diodes and IGBTs of the inverter in the active power filter, which tend to reduce the value of V_{dc} across the capacitor, a feedback voltage control circuit needs to be incorporated into the inverter. The usual methods of obtaining the magnitude and the unit sinusoidal component of the fundamental component of supply voltage are mainly based on a Phase Locked Loop (PLL) technique. Consequently, the low-pass filter in the PLL affects the dynamic behaviour and stability of the control loop significantly. The proposed method provides the fast determination of magnitude and unit sinusoidal of fundamental component of supply voltage and hence results better dynamic performance. Figure 4 shows a detailed diagram of the control block indicated in figure 3. The DC bus voltage of the active power filter is regulated via a PI controller. The output of the PI controller is combined with the magnitude and unit sinusoidal signal to generate the reference signal i_c^* as indicated in figure 4.

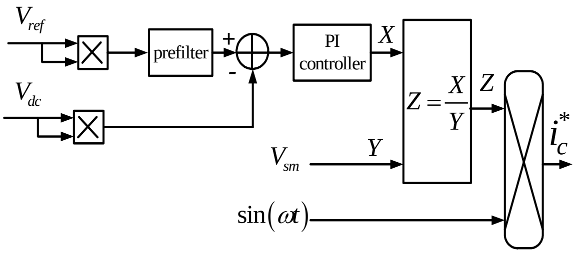


Figure 4: Operation of the control block.

4. SIMULATION RESULTS

4.1. PERFORMANCE OF THE PROPOSED INDIVIDAUL HARMONIC MEASUREMENT

The performance of the proposed individual harmonic measurement method is presented in this section. MATLAB/SIMULINK software tools have been used for modelling and simulations. A distorted 240V, 50Hz test signal has been used to investigate the performance of the proposed method. The harmonic constitution of the postulated signal is shown in table 1.

The postulated signal is also assumed to be corrupted by a white Gaussian noise with signal to noise ratio (SNR) = 26 dB (i.e. zero mean and a standard deviation of σ = 12). The postulated waveform and the white Gaussian noise are shown in figure 5.

Table 1: Harmonic content of the postulated signal waveform

Order of Harmonic	1	3	5	7	9
value	100%	30%	20%	10%	8%

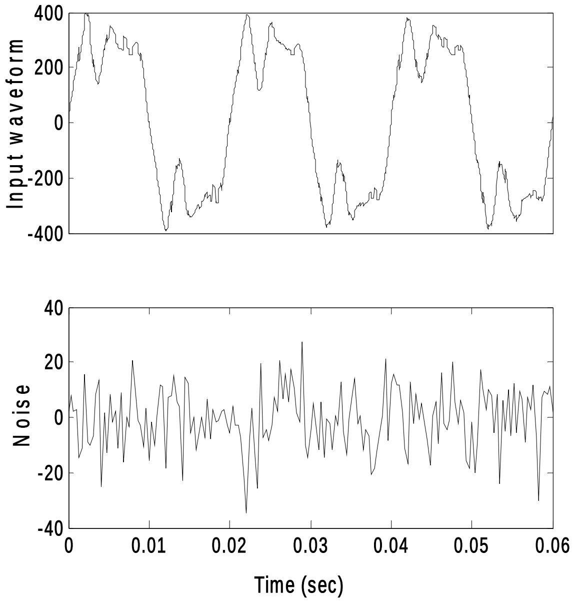


Figure 5: The postulated signal waveform

Figure 6a shows the comparison of actual, and identified fundamental waveform obtained from the proposed method. For this example, a 3 kHz sampling frequency and 30 number of samples (i.e. l=30) are chosen. Figure 6a shows the identified fundamental component together with the actual fundamental component of the postulated signal. The identified phase and sum of the harmonics are shown in figure 6b and 6c respectively.

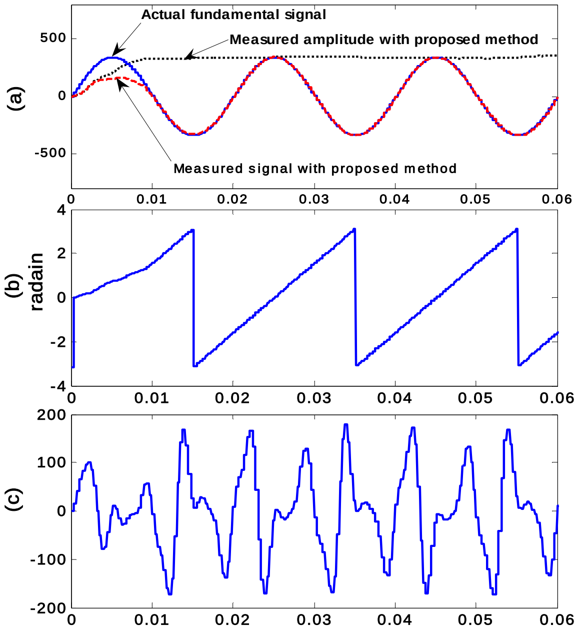


Figure 6: (a) Actual, and identified fundamental component using proposed method (b) identified phase of fundamental component (c) the sum of the harmonics.

As can be observed from figure 6, the proposed method is capable of tracking the actual signal in half of a cycle, and this is far better than the performance of the PLL and DFT algorithms which required transient periods of 2 to 3 cycles [8].

4.2. PERFORMANCE OF THE PROPOSED INDIVIDUAL HARMONIC MEASUREMENT APPLICATION IN AN ACTIVE POWER FILTER

The system with proposed active power filter shown in figure 3 is modeled in MATLAB/SIMULINK. The system parameters for the modeled system are listed in table 2.

Table 2: Design specifications and circuit parameters

Sampling frequency (f_s)	10kHz
Inverter DC side capacitance (C_d)	2000µF
Fundamental frequency (f)	50Hz
AC supply voltage (V_s)	240V
Inverter DC voltage (V_{dc})	500V
Reference voltage (V_{ref})	500V
Linear load inductance (L_L)	20mH
Linear load resistance (R_L)	50kΩ
Inverter side inductance (L_F)	5mH
Inverter side resistance (R_F)	0.25Ω
Proportional gain of PI controller (K_P)	0.178
Integral gain of PI controller (K_I)	7.90
DC-link current of a single-phase full-bridge rectifier (I_{dc})	20A and 50A

The 3rd, 5th, 7th, 9th order harmonics were chosen to be compensated since they are the most significant harmonics present in general power systems. The individual harmonic measurement method extracts the selected harmonics and sums them to obtain the harmonic current i_h for the controller.

In order to compare the performance of the proposed active power filter with the individual harmonic extraction method, active power filter with conventional harmonic compensation method is modelled with the same system parameters. The active power filter with total harmonic compensation based on PLL method is illustrated in figure 7.

In both systems, a single phase uncontrolled rectifier is selected as the nonlinear load to have a high level of harmonics. The load on the DC side of the uncontrolled rectifier is modelled as a current source assuming the load inductance is very large. The systems are simulated for two step increases in DC load current (20A at t = 0.1 sec and 50A at t = 0.2sec) to investigate the dynamic responses of the active power filter systems.

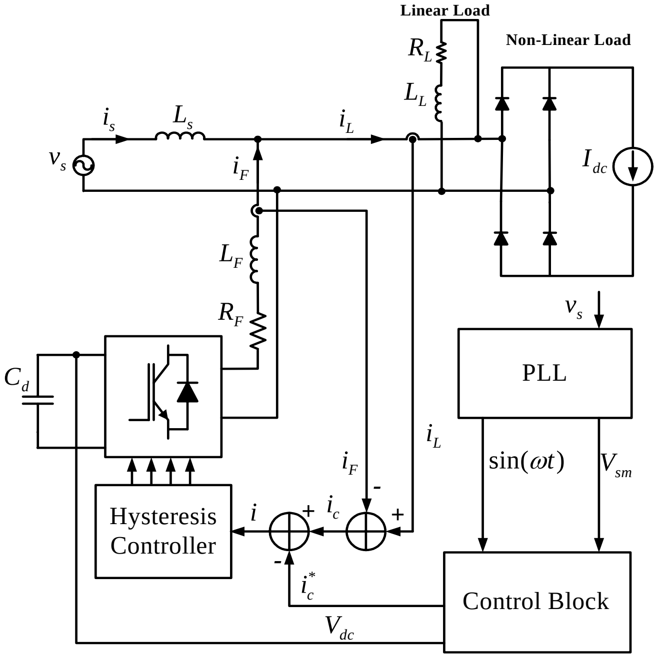
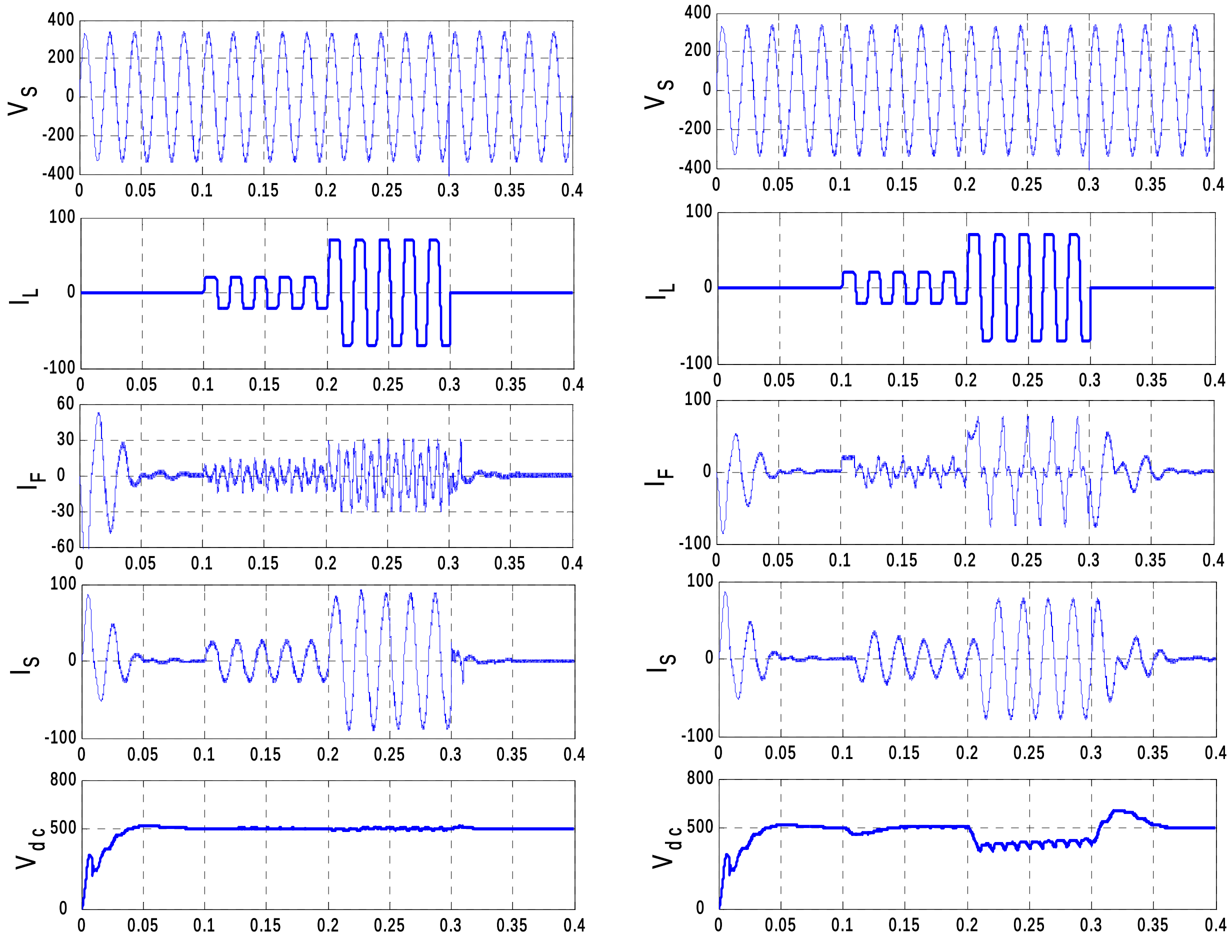


Figure 7: Active power filter with conventional harmonic compensation based on PLL method.



(a)

(b)

Figure 8: Performance of the active power filter: (a) with proposed harmonic compensation method (b) with conventional harmonic compensation method.

Figure 8a and 8b show the performance of the proposed and conventional active power filters that have been described. The nonlinear load current (i_L) is a square wave and shows two magnitudes corresponding to the step increase in DC load current. It can be seen that with a low level of load current (20A), both proposed and conventional methods of harmonic compensation show comparable performance. However, at high load currents (50A), the conventional method shows poor dynamic performance due to slow response of the PLL algorithm. This can be clearly seen from figure 8b, particularly the DC voltage (V_{dc}). The proposed method shows excellent dynamic performance as indicated in figure 8a. This is due to fast identification of fundamental voltage and harmonics currents. The DC bus voltage in the proposed method exhibits excellent regulation for step increase of load current as shown in figure 8a.

5. CONCLUSIONS

An effective single-phase active filter is developed by adopting a measurement method for harmonic current based on a least square method. This technique does not require matrix inversion and is therefore fast. The method allows the extraction of individual harmonics efficiently up to a reasonably higher order. The performance of the method is confirmed through computer simulation which shows excellent agreement between actual and identified signals. The measurement technique is applied into a single phase active power filter based on the selected harmonic compensation technique. The performance of this filter is compared with an active power filter based on the conventional total harmonic compensation scheme. The proposed active power filter shows excellent transient response, particularly at high magnitude nonlinear loads. The slower transient response in conventional scheme results from the delay in the electronic filters used in the algorithms. The transient response is a very important criteria for an active power filter to be used in practical applications where the load current varies randomly.

REFERENCES

[1] J. S. Tepper, J. W. Dixon, G. Venegas and L. Moran, “A simple frequency independent method for calculating the reactive and harmonic current in a nonlinear load,” IEEE Trans. Industrial Electronic, vol.43, pp.647-654, December 1996.

[2] Rukonuzzaman, M. and Nakaoka, M, “An advanced active power filter with adaptive neural net work based harmonic detection scheme,” IEEE Power Electronics Specialist Conference (PESC, pp.1602-1607), 2001.

[3] S. Srianthumrong and S. Sangwongwanich, “An active power filter with harmonic detection method based on recursive DFT,” IEEE 8th international conference on harmonics and quality of power (ICHQP), vol.1, Athens, Greece, pp.127-132, October 1998.

[4] H. P. To, M. F. Rahman and C. Grantham, “An adaptive algorithm for controlling reactive power compensation in active power filters,” IEEE Industry Applications Conference, 39th IAS Annual Meeting (IAS 2004), pp. 102-107, October 2004.

[5] H. P. To, M. F. Rahman and C. Grantham, “A current source active power filter with minimising number of current sensor,” Proceeding of Australasian Uni Power Eng Conf. (AUPEC 2003), Christchurch, New Zealand, September 2003.

[6] T. Manmek, C. Grantham and B. T. Phung, “A novel algorithm for identification and tracking of power system harmonics”, IEEE Proc. International Power Electronics and Motion Control Conference (IPEMC'04), pp.1346-1350, August 2004.

[7] Dahono P. A. and Krisbaiantoro I., “A hysteresis current controller for single-phase full-bridge inverters,” IEEE International Conference on Power Electronics and Drive Systems, 4th PEDS, vol.1, pp.415-419, October 2001.

[8] M. Karimi-Ghartemani, Hossein Mokhtari, M. Reza Iravani and Mohammad Sedighy, “A signal processing system for extraction of harmonic and reactive current of signal-phase systems,” IEEE Trans. on Power Delivery, vol. 19, no.3, pp.979-989, July 2004.