Applicability Improvement and Hysteresis Current Control Method Simplification in Shunt Active Filters

H. Heidarzad Moghaddam*(C.A.) and M. Salimi*

Abstract: Hysteresis current control method is widely used in Pulse Width Modulation (PWM) inverters because of simplicity in performance, fast control response and good ability in limiting peak current. However, switching frequency in hysteresis current control method with fixed bandwidth has large variation during a cycle and therefore causes non-optimal current ripple generation in output current. One of basic problems in implementing hysteresis current control is its variable switching frequency that causes sound noise and increase in inverter losses and also high frequency current components injection to the source current. In this paper, a fixed frequency hysteresis current controller is proposed for grid connected inverters. In the proposed approach, the required bandwidth of the controller is calculated according to system parameters. Also, the derivative of the reference current is eliminated to solve the problems associated with practical implementation of the converter. Finally, a shunt active filter has been used for removing the current harmonic components generated by non-linear loads. Proposed method is simple to perform and reliable, and also has been simulated in MATLAB software environment.

Keywords: Harmonic Spectrum, Hysteresis Bandwidth, Optimized Hysteresis Bandwidth, Simplified Hysteresis Bandwidth, Shunt Active Filter.

1 Introduction

Because of power electronics development in recent years, use of nonlinear loads in electric distribution network has increased significantly. Often, these types of loads consist of diode or transistor rectifier and are used vastly in speed controller of DC and AC motors, uninterruptible power supply, battery charger and else. In fact these types of loads use energy but at the price of harmonic current generation (These loads consume energy at expense of harmonic generation) [1, 2]. Current harmonics existence in distribution power network causes voltage waveform distortion at the Point of Common Coupling (PCC). Power quality distortion especially the voltage and current harmonic cause increase in losses of lines, decrease in power factor and resonance creation in power system. Also, instrumentation systems, and communication and control equipments are possibly affected by Electro-Magnetic Interference (EMI) of high frequency harmonics [3]. For this reason, quality has high importance with regard to the energy generation and consumption.

In conventional power systems, LC passive filters, because of their high efficiency and relatively low cost, are used to remove network current harmonics and also power factor correction.

However, network impedance has major effect on operation procedure and also, there is a possibility of series and shunt resonance with load and power supply when using these filters. To overcome these problems using shunt Active Power Filters (APF) has been discussed and in recent years many researchers have investigated aforementioned subject [4-8].

Shunt Active Power Filters (APF) consists of one Voltage Source Inverter (VSI). Although it is common to use the voltage control or current control or both of them to control inverters but, usually, use of current control is preferred to other controlling methods to control shunt Active Power Filters (APF) because this filter is used for load current harmonic correction. There are three common methods to control current of a voltage source inverter in shunt active power filters as follows [9-12]:

1-Linear current control
2-Digital current control
3-Hysteresis current control

Iranian Journal of Electrical & Electronic Engineering, 2015.
Paper first received 08 Mar. 2015 and in revised form 14 Apr. 2015.
* The Authors are with the Department of Electrical Engineering, Ardabil Branch, Islamic Azad University, Ardabil, Iran.
E-mails: Hale_heydarzad@yahoo.com and m.salimi@iauardabil.ac.ir.

Hysteresis current control method is vastly used because of simplicity in implementation. In addition, use of hysteresis current control method has increased because its control loop current response is desirable and also system parameter changing does not affect its response [13].

Unfortunately, nowadays, variable switching frequency and its change in a certain interval have been known as aspects of hysteresis current control method.

Change in inverter switching frequency causes decrease in longevity of semiconductors switches, and noise and low order harmonic generation.

Use of passive heavy filters in inverter output and/or increase in switching frequency can prevent low order harmonic injection to network but it is obvious that these filters are very expensive and also increase in switching frequency can increase inverter switching losses.

To overcome these problems many research papers have been presented [14-17]. Tenti and Malisani proposed hysteresis current control method with schedulable width using Phase Locked Loop (PLL) [14], but use of PLL with passive big filter causes instability problems. In addition to long time transient states, it is possible that PLL becomes instable. Bose calculated hysteresis width to fix switching frequency in induction motors [15]. Although, in this method previous problems were solved, but calculated hysteresis width is not accurate enough and also needs relatively long time for calculation. Therefore, it cannot be used in real time applications.

Bandwidth was calculated in papers [16, 17], exactly. Unfortunately, reference current derivate appears in these equations [18]. Although, these equations have been verified with implementation and also simulation studies, but it is obvious that use of differentiator in electronic circuit causes noise and instability problems. For this reason, use of differentiator in industrial applications is not recommended.

In this paper, a new method for hysteresis width calculation is proposed. In this method, hysteresis width equation is simplified so that use of differentiator is not necessary. In practice, removing differentiator improves application and simplifies hysteresis current control method in shunt active filters.

To prove the accuracy of proposed method, active shunt filter (cascade) - which is discussed in the next section - has been simulated with MATLAB\Simulink toolbox.

2 Shunt Active Filters

Main part of shunt active filters, shown in Fig. 1, is a voltage source inverter that is connected to DC side capacitor. Current harmonic compensation is performed with harmonic component injection by shunt active filter at the Point of Common Coupling (PCC), and therefore, network harmonic component is removed. In this way, power quality in aforementioned system is improved.

In a shunt active filter to achieve harmonic standards, power switches work in range of kHz; for this reason switching losses play vital role in shunt filters. Bounded rating of power semiconductors (100 A< I < 1000 A) and high level of switching losses have led to use of shunt active filter in cascade configuration to increase maximum system output power [19].

Use of two shunt filters improves compensation procedure significantly. In such system, each inverter works in a different switching frequency. In this case, the inverter near to the load works in lower switching frequency and has to compensate reactive power for load.

Several methods have been proposed to detect the current harmonic components which most important ones are categorized as follows:

1-Fast furrier transform.
2-Instantaneous reactive power theory.
3-Synchronous reference axis theory.

In this paper, inverters reference signals of filter are calculated by use of instantaneous reactive power theory [3]. Based on used reference signals, shunt active filter is able to compensate reactive power, remove load current harmonic and balance network. In this method instantaneous components of power $p(t)$ and $q(t)$ are used to calculate reference signal. Instantaneous components of active power $p(t)$ and reactive power $q(t)$ are defined as follows:

$$p(t) = V_\alpha(t).i_\alpha(t) + V_\beta(t).i_\beta(t) \quad (1)$$

$$q(t) = V_\alpha(t).i_\beta(t) - V_\beta(t).i_\alpha(t) \quad (2)$$

which, in above equations p(t) and q(t) include DC and AC components. DC components are related to main components of active and reactive powers and also AC components are related to harmonic components.

With regard to compensating main component of active power by inverter (1) and current harmonic component by inverter (2), inverter side currents can be expressed as:

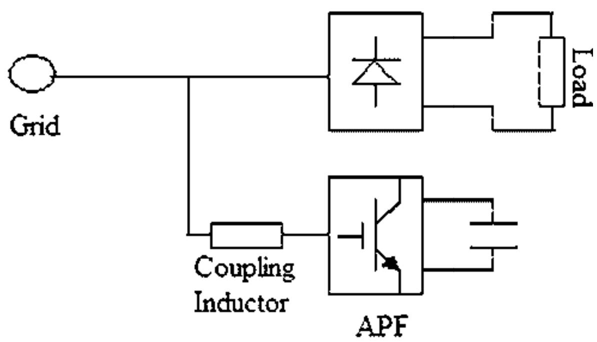

Fig. 1 Shunt Active Power Filters (APF).

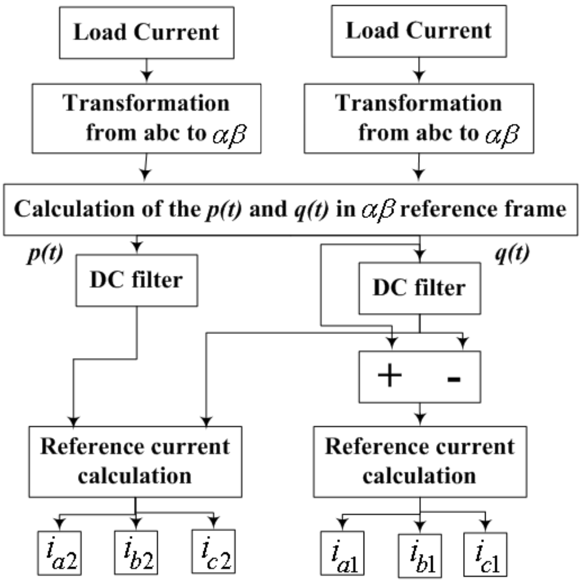

Fig. 2 Source of reference current.

$$\begin{bmatrix} ia_1 \\ ib_1 \\ ic_1 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \cdot \frac{1}{(V_\alpha^2 + V_\beta^2)} \cdot \begin{bmatrix} -V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ \overline{q}(t) \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} ia_2 \\ ib_2 \\ ic_2 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \cdot \frac{1}{(V_\alpha^2 + V_\beta^2)} \cdot \begin{bmatrix} -V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p}(t) \\ \tilde{q}(t) \end{bmatrix} \quad (4)$$

where, in above equations $\overline{q}(t)$ is DC component related to reactive power, $\tilde{p}(t)$ and $\tilde{q}(t)$ are harmonic components of active and reactive powers. In Fig. 2 block diagram of reference signal generator for inverter (1) and (2) are shown.

3 Control of Improved Hysteresis Current

If inverter null point connected, control of hysteresis current uses three similar controllers per phase. One arm of inverter and its related controller are shown in Fig. 3. When line current is greater (lower) than reference current determined with hysteresis width, inverter is switched so that current is decreased and remains in a fixed range continuously [20, 21].

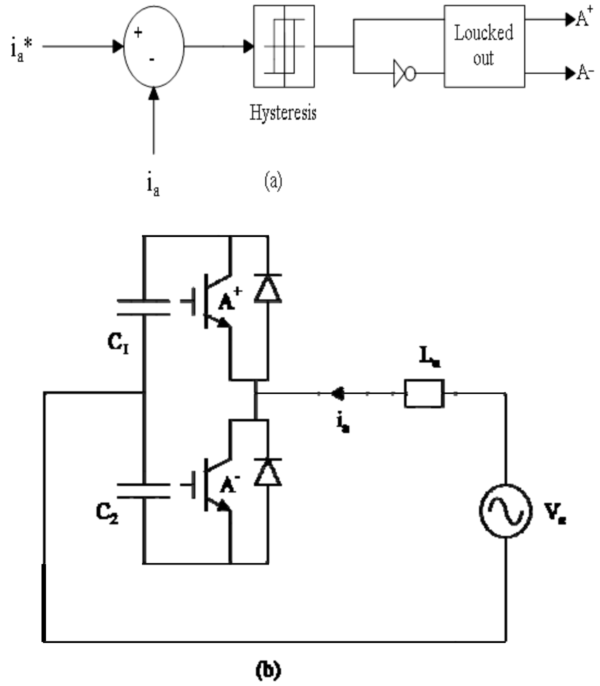

Fig. 3 Current control loop in conventional active power filters (a), Single phase half bridge grid connected inverter (b).

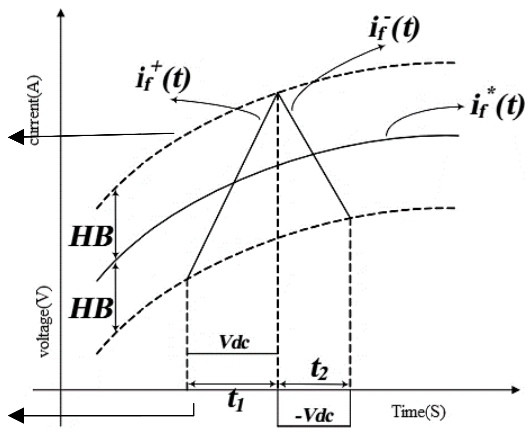

Fig. 4 Voltage and current in hysteresis current control method.

To exactly analyze this, consider inverter A connected to network, which is shown in Fig. 3.

Fig. 4 shows the voltage and current waveforms in hysteresis current control method. When inverter current gets to the lower bound of reference current, switch A is turned on to increase current. Current increment which is shown in the figure as I_a causes the current to get to the upper bound and switch A is turned on at this instant. By ignoring reactor resistance, below equations in time interval between t_1 and t_2 can be written as follows:

It is assumed that, $V_{c1} = V_{c2} = V_{DC}/2$.

$$A^{+}\ is\ on:\ \frac{di_a^{+}}{dt} = \frac{1}{L_a}(V_{c1} - V_a) = \frac{1}{L_a}\left(\frac{V_{DC}}{2} - V_a\right) \tag{5}$$

$$A^{-}\ is\ on:\ \frac{di_a^{-}}{dt} = -\frac{1}{L_a}(V_{c2} + V_a) = -\frac{1}{L_a}\left(\frac{V_{DC}}{2} + V_a\right) \tag{6}$$

From geometric design of Fig. 4 and considering that reference current during switching time intervals is almost linear, below equations can be written:

$$\frac{d}{dt}(i_a^{+} - i_a^{*}).t_1 = 2\delta \tag{7}$$

$$\frac{d}{dt}(i_a^{-} - i_a^{*}).t_2 = -2\delta \tag{8}$$

$$t_1 + t_2 = T_s = \frac{1}{f_s} \tag{9}$$

where, in above equations index δ is hysteresis width and index fs is switching frequency.

By summing Eqs. (7) and (8) and substituting in Eqs. (5), (6) and (9), we have Eq. (10):

$$t_2 - t_1 = \frac{2L_a}{(V_{DC} \cdot f_s)}\left[\frac{1}{L_a}V_a + \frac{di_a^{*}}{dt}\right] \tag{10}$$

By subtracting Eqs. (7) and (8) and substituting in Eqs. (5), (6) and (9), we have Eq. (11):

$$t_2 - t_1 = \frac{4\delta - \dfrac{V_{DC}}{2f_sL_a}}{\left(\dfrac{V_a}{L_a} + \dfrac{di_a^{*}}{dt}\right)} \tag{11}$$

By use of Eqs. (10) and (11), hysteresis width can be written for phase A as below Eq. (12):

$$\delta = \frac{V_{DC}}{8f_sL_a}\left[1 - \frac{4L_a^2}{V_{DC}^2}\left(\frac{V_a}{L_a} + \frac{di_a^{*}}{dt}\right)^2\right] \tag{12}$$

In applications related to shunt active filters, reference current can be considered as sum of reactive current components. So if V_a=$V_m$sin(wt), references currents can be written as below Eqs. (13), (14) and (15).

$$i_a^{*} = i_q^{*} + i_h^{*} \tag{13}$$

$$i_q^{*} = I_q Cos\ wt \tag{14}$$

$$i_h^{*} = I_{hs2}\ Sin(2wt) + I_{hc2}\ Cos(2wt) + I_{hc3}Cos(3wt) + ... \tag{15}$$

To compensate high frequency harmonic components, it is clear that switching frequency of harmonic compensator (APF2) should be greater than switching frequency of reactive compensator (APF1). Considering the fact that increase in switching frequency leads to decrease in maximum output power of inverter, cascade compensation is vastly used in practical applications. In this system which is shown in Fig. 5, the task of filter (1) is reactive current component compensation and its switching frequency is 1 kHz approximately.

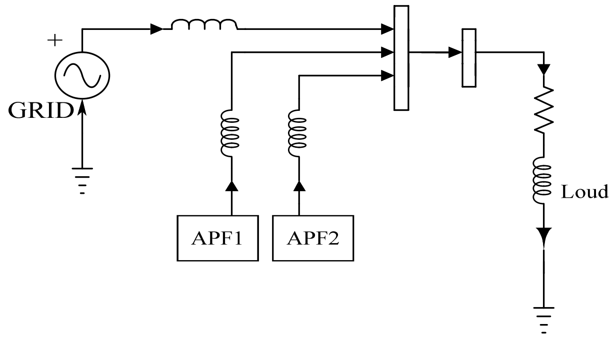

Fig. 5 Shunt filter (cascade).

In practice, low switching frequency in inverter leads to higher output power. The task of filter (2) - which is a high frequency inverter- is harmonic component compensation and it works around 10 kHz. It is obvious that because inverter (2) operates in high frequency, its output power is much less than maximum output power of inverter (1).

Recent equations show that switching frequency of inverter (necessary time for current increase or decrease) is a function of DC capacitor, coupling reactor, network voltage and hysteresis width. Since DC side voltage and coupling reactor are almost constant, it is evident that by changing voltage of network during one cycle, in hysteresis current control with fixed width, switching frequency cannot be constant.

In other words, considering change in network voltage, hysteresis width should be modified so that inverter switching frequency remains constant. This means that in hysteresis current control method with constant frequency, hysteresis width cannot be constant. Reactive and harmonic component separation will improve system's general operation significantly. Equations (3) and (6) show that output current rises and fall times depend on coupling reactor. With regard to relatively fast change of current in filters (1) and (2), to create current controllability in hysteresis method, the inductance value of coupling reactor should be selected relatively small. From Eqs. (5) and (6), it can be concluded that decrease in the value of coupling reactor leads to increase in slop of reactor current changing. Usually, the inductance value of coupling reactor is selected about 100 µH in practical applications.

In cascade compensation, Eq. (12) can be written for inverters (1) and (2) as below Eqs. (16) and (17).

$$\delta_1 = \frac{V_{DC}}{8f_sL_a}\left[1 - \frac{4L_a^2}{V_{DC}^2}\left(\frac{V_a}{L_a} - I_q \sin wt\right)^2\right] \tag{16}$$

$$\delta_2 = \frac{V_{DC}}{8f_sL_a}\left[1 - \frac{4L_a}{V_{DC}^2}\begin{pmatrix}\dfrac{V_a}{L_a} + 2I_{hs2}w\cos(2wt) - \\ 2I_{hc2}w\sin(2wt) + ...\end{pmatrix}^2\right] \tag{17}$$

It is clear that due to different switching in inverter (2):

$$I_{hs2},\ I_{hc2},\ I_{hs3},\ I_{hc3},\ldots << I_q \tag{18}$$

In this system because of very small value of La, both value of di_q^*/dt and di_h^*/dt compared to *va/La* can be ignored (in applications related to shunt active filters and use of cascade configuration). For this reason, hysteresis width in applications related to shunt active filters can be simplified as below Eqs. (19) and (20):

$$\delta = \frac{V_{DC}}{8 f_s L_a}\left[1-\frac{4L_a^2}{V_{DC}^2}\left(\frac{V_a}{L_a}\right)^2\right] \tag{19}$$

$$\delta = \frac{V_{DC}}{8 f_s L_a}\left[1-\frac{4V_a^2}{V_{DC}^2}\right] \tag{20}$$

Equation (20) show that hysteresis width changes according to change in V_a until the frequency is fixed. In new method, calculation of hysteresis width has been expressed based on (20); Hysteresis width is regulated according to V_a changing so that low frequency distortion of V_a is optimized in output current waveform.

4 Simulated System

New proposed method for hysteresis width calculation is simulated in this section. Main part of system is two voltage source inverters with IGBT switches which are directly connected to network by coupling reactors. Neutral point of network is connected to midpoint of inverters' DC link so zero sequence power can be transferred between network and inverter. A Three phase rectifier with one RL load was used to implement a nonlinear load.

Switching frequency of inverter (1) was 1 kHz approximately, and it has the task of compensating the main component of load reactive power. Current harmonic components of load are compensated by inverter (2) and its switching frequency is 10 kHz approximately.

The controller of inverter DC link is shown in Fig. 6. It can be seen that this controller is implemented by a simple PI. In this system, first voltage of DC link is compared to reference value.

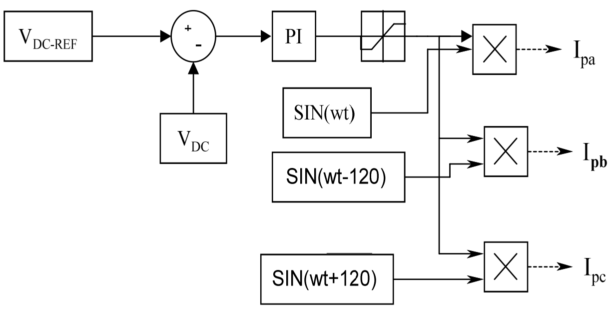

Fig. 6 DC link controller.

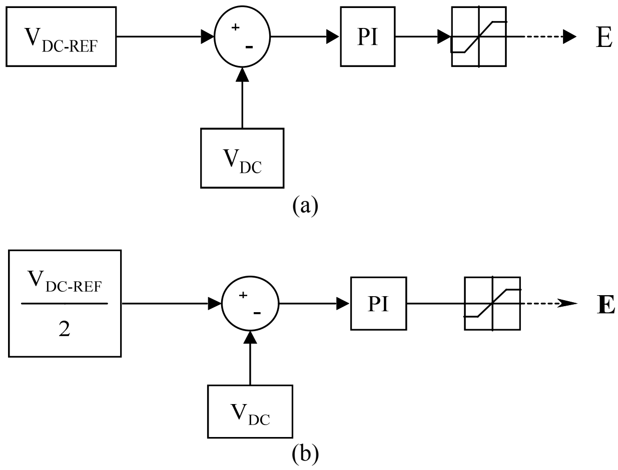

Fig. 7 DC link stabilizer (a), PI controller (b).

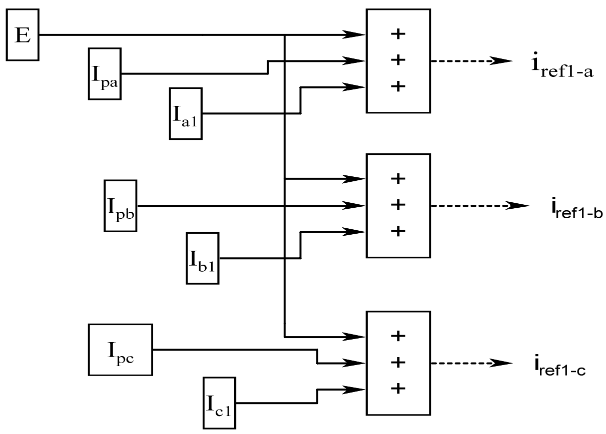

Fig. 8 Final generated reference current in filter (1).

Based on generated error value, PI controller calculates necessary active power so that DC voltage link is bounded in a fixed value under switching losses and steady state losses of circuit switches. To improve optimal operation of system, reference voltage level of DC link capacitors is selected 800 volt.

Although, DC link controller can fix total voltage of DC side, but after a few cycles, the voltages of capacitors C1 and C2 relative to each other are severely unbalanced. To balance the voltage of capacitors C1 and C2, PI controller is used as shown in Fig. 7(b). This controller based on voltage unbalance level of two capacitors, adds security component to three phase reference currents which is shown in Fig. 8. The final generated reference current is applied to hysteresis current controller which its width is calculated by Eq. (20). In this equation, it is assumed that the values of V_{DC}, L and f_s are constant. In this equation because only network voltage is variable, necessary circuit to implement the hysteresis width controller will be very simple. Simulation parameters have been shown in Table 1.

Table 1 The information of simulation parameters.

DC link capacitors (c_1,c_2)	1000 µf
Coupling inductors (L_a, L_b, L_c)	1000 µH
Fundamental frequency	50 Hz
DC link voltage reference	800 V
DC link voltage controller K_P	10
DC link voltage controller K_I	0.5
DC link voltage balancer K_P	0.5
DC link voltage balancer K_P	0.1

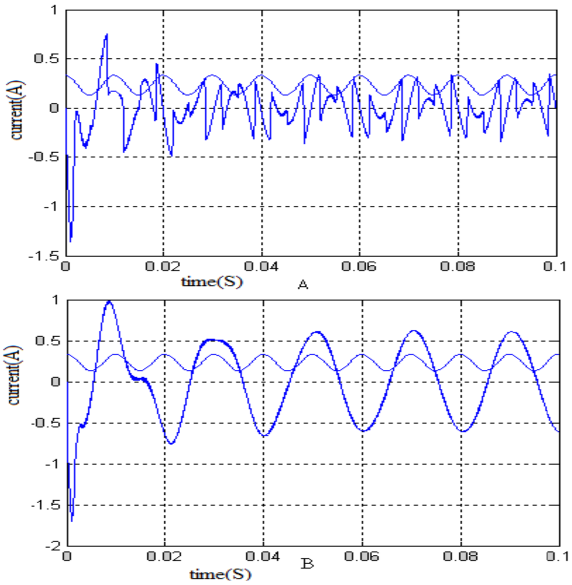

Fig. 9 Hysteresis width change in filters (1) and (2).

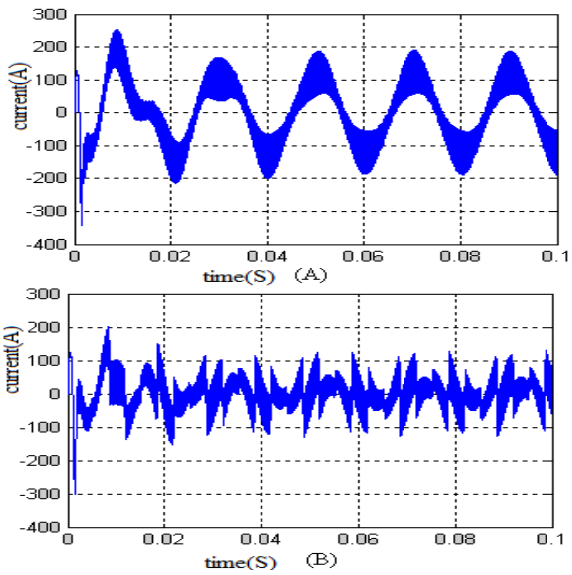

Fig. 10 Output current of filters (1) and (2).

5 Simulation Results

To analyze operation of new proposed method for calculating hysteresis bandwidth, described system in previous section has been simulated with Simulink/ MATLAB. Fig. 9 which shows this controller's outputs, is the changing procedure of hysteresis width of filter (1) and (2) in phase A. output currents of filters (1) and (2) have been shown in Fig. 10. To verify the accuracy of (20), frequency spectrum of filters' output current with two fixed hysteresis width method and method based on (20) have been depicted in Fig. 11. A single phase full bridge rectifier with resistive- inductive load is considered as the nonlinear load. Its resistor is 40 ohm and inductor is 0.01 H.

In hysteresis current control with fixed width, output current includes a large amount of ripple and more important than it, its harmonic components are distributed in a large area which in practice makes filtering difficult. In method based on (20), it is shown that harmonic components often concentrate around the integer products of one frequency.

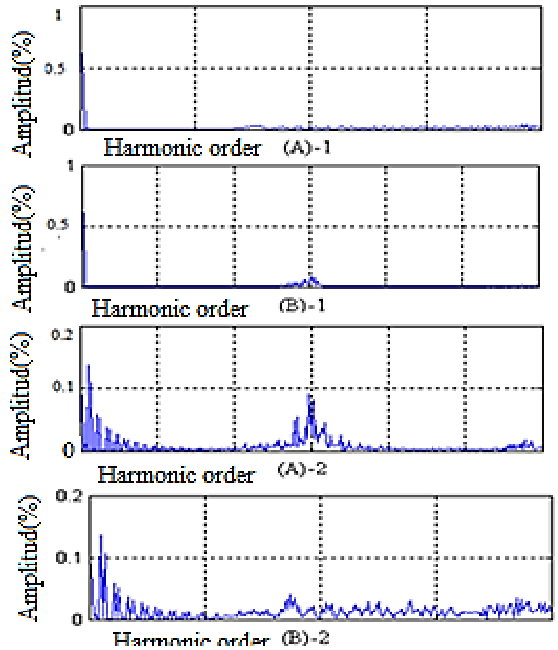

Fig. 11 Output current frequency spectrum of filters (1) and (2). Conventional method with fixed width A-2 and B-2, Proposed new method A-1 and B-1.

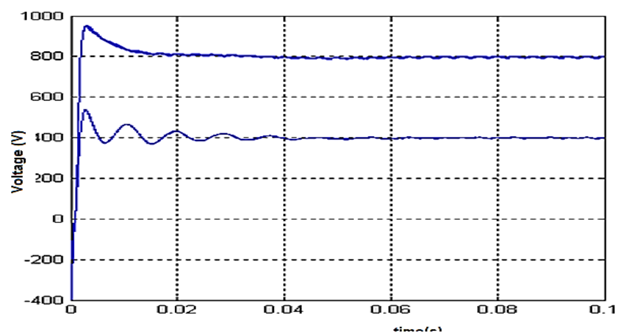

Fig. 12 Controller response and DC side stabilizer.

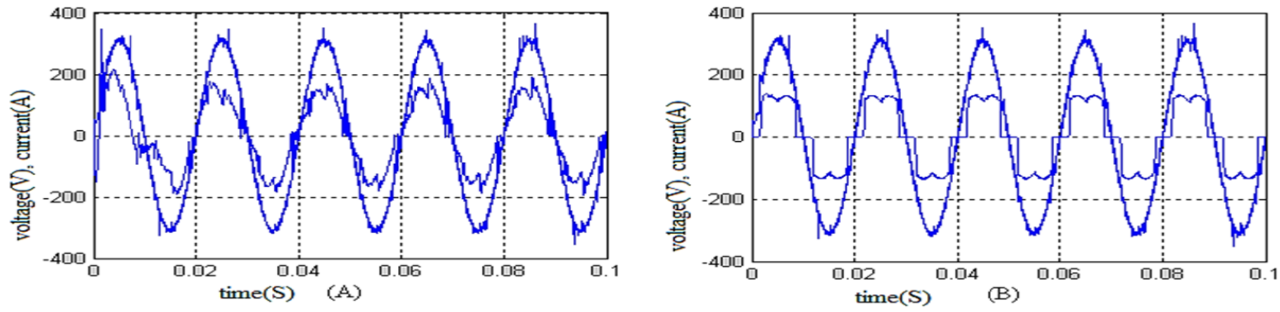

Fig. 13 General performance of shunt active filters.

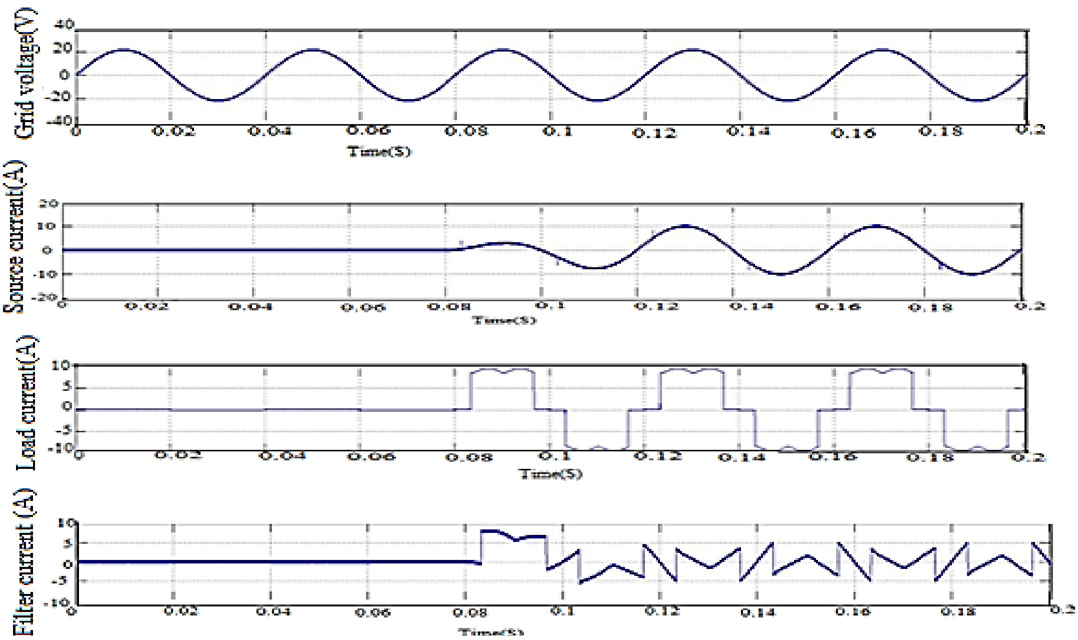

Fig. 14 dynamic response of the proposed control system.

In Fig. 14 the dynamic response of the proposed control system is illustrated. In this figure, initial value of the load current is assumed to be zero. Then, at t = 0.04 s a nonlinear load is connected to the system. It is clear that in spite of step variation of the load current from zero to nominal value, the proposed controller is completely stable with very fast dynamic response.

6 Conclusion

In this paper, hysteresis current control strategy for use in shunt active filters is simplified and optimized. New proposed method is simple and has below advantages in practical applications:

1-There are no noise and instability problems in new proposed method due to removing the derivative components.

2-New proposed method is simple and practical to implement because most parameters in hysteresis width equation can be assumed constant.

As can be seen in new proposed method, switching frequency was fixed and harmonic components of output current are improved as compared to classical method (constant bandwidth).Because of this reason, there is a possibility for use of this method as an approach with high efficiency and also simple to control the current of shunt active filters. Proposed method in this paper can be used for industrial application and also in shunt active filters with cascade connection.

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Haleh Heidarzad Moghaddam was born in Astara, Iran, in 1989. She received the B.Sc. degree in electrical engineering from the Islamic Azad University (IAU) of Lahijan, Lahijan, Iran, in 2012 and, and the M.Sc. degree in power engineering from the Islamic Azad University (IAU) (Science and Research Branch) of Ardabil, Ardabil, Iran, in 2015.

Mahdi Salimi was born in Ardabil, Iran, in 1979. He received the B.Sc. and M.Sc. degrees in electrical engineering from K.N.T University of Technology, Tehran, Iran, in 2000 and 2002, respectively, and the Ph.D. degree in power electronics from the Islamic Azad University (IAU) (Science and Research Branch), Iran, in 2012. Since 2003, he has been with IAU, where he is currently an Assistant Professor with the Department of Electrical Engineering. His research interests include power electronics, control engineering, and renewable energy.