Hindawi Publishing Corporation
Advances in Power Electronics
Volume 2011, Article ID 397872, 6 pages
doi:10.1155/2011/397872

Review Article

Review and Simulation of Fixed and Adaptive Hysteresis Current Control Considering Switching Losses and High-Frequency Harmonics

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Received 1 February 2011; Accepted 2 May 2011

Academic Editor: Francesco Profumo

Hysteresis Current Control (HCC) is widely used due to its simplicity in implementation, fast and accurate response. However, the main issue is its variable switching frequency which leads to extraswitching losses and injecting high-frequency harmonics into the system current. To solve this problem, adaptive hysteresis current control (AHCC) has been introduced which produces hysteresis bandwidth which instantaneously results in smoother and constant switching frequency. In this paper the instantaneous power theory is used to extract the harmonic components of system current. Then fixed-band hysteresis current control is explained. Because of fixed-band variable frequency disadvantages, the adaptive hysteresis current control is explained that leads to fixing the switching frequency and reducing the high-frequency components in source current waveform. Due to these advantages of AHCC, the switching frequency and switching losses will be diminished appropriately. Some simulations are done in MATLAB/Simulink. The Fourier Transform and THD results of source and load currents and the instantaneous switching frequency diagram are discussed to prove the efficiency of this method. The Fourier Transform and THD results of source and load currents are discussed to prove the validity of this method.

1. Introduction

In recent years, shunt active power filters have being applied by many industries and researchers to remove the current harmonics caused by nonlinear loads [1–3]. An APF as can be seen in Figure 1 is a parallel power inverter with loads that can remove large amounts of current harmonics through the injection of reference current to the power system that contains harmonic components of the source current. Complete compensation occurs when the APF produces the same current as harmonic current with the same amplitude and opposite in sign.

Hysteresis current control is one of the most appropriate PWM switching methods to produce reference current in APFs [4]. Hysteresis current control has desirable characteristics such as high stability, fast and accurate dynamic behavior. On the other hand, conventional hysteresis method includes some undesirable results, such as variable switching frequency that causes audio noises, high switching losses and injection of high-frequency current components to the source current that makes it difficult to design suitable filters to remove these high-frequency harmonics.

Many switching methods are used to produce switching pulse which leads to generate reference current. Hysteresis current control (HCC) has been noticed more than other current control techniques, due to simplicity and quicker dynamic response [5–8].

The main problem of HCC is its variable switching frequency which leads to variable high-frequency components in source current waveform, audio noises and increase switching losses. One of performed methods that can solve this problem is the AHCC method that builds variable band for current tracking, hence the switching speed becomes smooth and the frequency switching will be fixed considerably.

Furthermore, different frequency components in current waveform will appear due to different switching frequencies that make it difficult to design appropriate filters to eliminate these components and make noises affects measuring devices. To overcome this problem, an adaptive hysteresis current control (AHCC) has been introduced. Using this method, variable hysteresis bandwidth is calculated instantaneously, which leads to reducing the switching frequency variation, thus the fixed-band HCC issues will be amended.

In this paper, in Section 2, the instantaneous power theory has been explained to extract the harmonics components of current waveform. Then in Section 3, the fixed-band HCC and AHCC have been clarified. Finally, some simulations have been done with MATLAB/Simulink, and the results consisting of switching frequency diagrams and current THD in high-frequency range have been discussed in Section 4. By comparing the results of simulations, the advantages of AHCC in fixing switching frequency and modifying the above-mentioned problems, especially reducing the high-frequency components in source current waveform and switching losses, have been proved.

2. Instantaneous Power Theory

One of the popular compensation reference current extraction methods is the instantaneous reactive power theory (p-q theory). Although there are some problems with this theory, it is well established and simple in implementation. The p-q theory could be briefly reviewed as follows [8].

Assume a three-phase load with the instantaneous voltages as $\mathbf{v}(t) = [v_a(t)\ \ v_b(t)\ \ v_c(t)]^t$ and the instantaneous currents as $\mathbf{i}_l(t) = [i_{la}(t)\ \ i_{lb}(t)\ \ i_{lc}(t)]^t$ (Figure 1). Using (1), $\mathbf{v}(t)$ and $\mathbf{i}_l(t)$ can be converted to 0-α-β coordination where $\mathbf{C}$ is matrix (2):

$$\left[v_{0\alpha\beta}(t)\right]^t = \mathbf{C}[v_{abc}(t)]^t, \qquad \left[i_{0\alpha\beta}(t)\right]^t = \mathbf{C}[i_{abc}(t)]^t, \quad (1)$$

$$\mathbf{C} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}. \quad (2)$$

Let's assume that the zero sequence current ($i_{l0}(t)$) is null. Thus, the instantaneous active ($p(t)$) and reactive ($q(t)$) powers can be calculated as

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} v_\alpha(t) & v_\beta(t) \\ -v_\beta(t) & v_\alpha(t) \end{bmatrix}\begin{bmatrix} i_{l\alpha}(t) \\ i_{l\beta}(t) \end{bmatrix}; \quad (3)$$

$p(t)$ and $q(t)$ can be decomposed to the average parts ($\overline{p}(t), \overline{q}(t)$) and the oscillating parts ($\tilde{p}(t), \tilde{q}(t)$). It is notable that $\overline{p}(t)$ is produced by the fundamental harmonics of the positive sequence component of the load current. Therefore, in order to compensate the harmonics and the instantaneous reactive power, compensation reference currents can be extracted as follows:

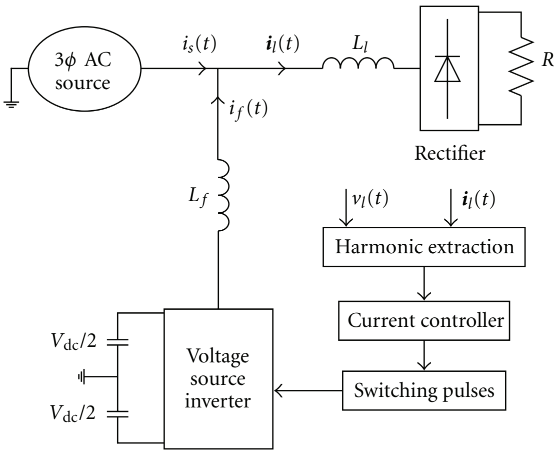


Figure 1: Power System Diagram with APF.

$$\begin{bmatrix} i^*_{f\alpha}(t) \\ i^*_{f\beta}(t) \end{bmatrix} = \begin{bmatrix} v_\alpha(t) & v_\beta(t) \\ -v_\beta(t) & v_\alpha(t) \end{bmatrix}^{-1}\begin{bmatrix} -\tilde{p}(t) \\ -q(t) \end{bmatrix}, \quad (4)$$

$$\left[i^*_{fa}(t)\ \ i^*_{fb}(t)\ \ i^*_{fc}(t)\right]^t = \mathbf{C}^{-1}\left[0\ \ i^*_{f\alpha}(t)\ \ i^*_{f\beta}(t)\right]^t. \quad (5)$$

3. Hysteresis Current Control

Hysteresis current control is used for generating the switching pulses. Among the various current control techniques, HCC is the most extensively used technique because of the noncomplex implementation, outstanding stability, absence of any tracking error, very fast transient response, inherent limited maximum current, and intrinsic robustness to load parameters variations. As indicated in [6, 7] a review of used current control techniques for PWM converters reveals that HCC shows certain superiority for active power filter applications. HCC provides a better low-order harmonic suppression than PWM control, which is the main target of the active power filter. It is easier to realize with high accuracy and fast response. However, as a disadvantage its switching frequency might fluctuate.

In the HCC technique the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteretic controller makes an appropriate switching decision to control the error within the preset band and send these pulses to VSI to produce the reference current as shown in Figure 2.

The outputs of the hysteresis blocks are directly fed as the firing pulse of VSI switches.

3.1. Fixed-Band Hysteresis Current Control.

In fixed-band HCC, the hysteresis bandwidth (HB) has been taken as a small portion related to system current, and in many researches it has been taken as 5% of main current which will be HB = 0.9 A, here.

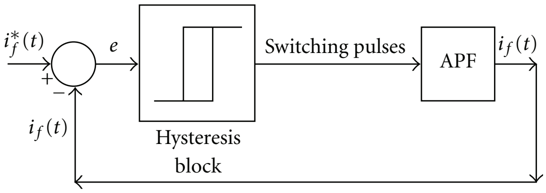


Figure 2: Fixed-band hysteresis current control loop.

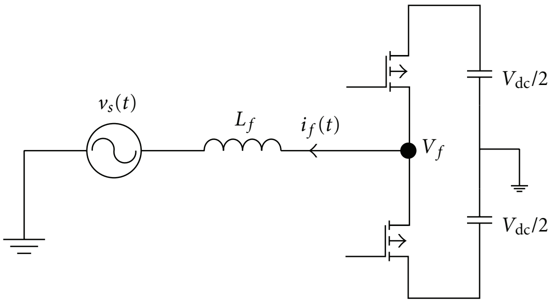


Figure 3: Single-phase diagram of a power system with APF.

3.2. Adaptive Hysteresis Current Control (AHCC). As mentioned above, the crucial concern with the fixed band hysteresis current control is producing a varying modulation frequency of the power converter which, in turn, results in increasing the switching losses. To avoid this situation, adaptive hysteresis current controller methods with the variable hysteresis band have been recommended in the literature [6, 7]. Hence, a variable hysteresis band is defined for each phase so that the switching frequency remains almost constant.

The variable hysteresis band (HB) formula can be calculated based on Figures 1 and 3. The following KVL equation can be easily achieved:

$$\frac{di_f(t)}{dt} = \frac{1}{L_f}\Big(V_f - v_s(t)\Big), \tag{6}$$

where V_f is the inverter-side voltage and can be elaborated as below:

$$V_f = \begin{cases} \dfrac{V_{dc}}{2} & \text{the upper switch is ON,} \\ \dfrac{-V_{dc}}{2} & \text{the lower switch is ON.} \end{cases} \tag{7}$$

Having paid attention to Figure 4, the following relations can be obtained:

$$\frac{di_f^+(t)}{dt} = \frac{1}{L_f}\Big(V_f - v_s(t)\Big), \tag{8}$$

$$\frac{di_f^-(t)}{dt} = \frac{-1}{L_f}\Big(V_f + v_s(t)\Big), \tag{9}$$

Table 1: APF simulation parameters.

Supply phase voltage	155 V
Grid frequency	50 Hz
Load resistance R_l	10 Ω
Inverter side inductance L_f	4 mH
Rectifier side inductance L_l	3 mH
APF dc-link voltage V_{dc}	500 V
Fixed hysteresis bandwidth	0.9 A

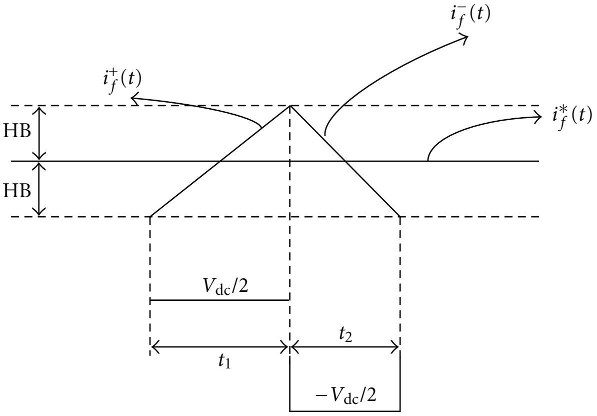


Figure 4: The upper and lower bands of the reference compensation current.

where $i_f^+(t)$ and $i_f^-(t)$ are the rising current and the falling current, respectively. Furthermore, the following relations can be extracted:

$$\begin{aligned} \frac{di_f^+(t)}{dt} \times t_1 - \frac{di_f^*(t)}{dt} \times t_1 &= 2\text{HB}, \\ \frac{di_f^-(t)}{dt} \times t_2 - \frac{di_f^*(t)}{dt} \times t_2 &= -2\text{HB}, \end{aligned} \tag{10}$$

$$f = \frac{1}{t_1 + t_2}, \tag{11}$$

where t_1 and t_2 are switching intervals and f is the switching frequency.

By substituting (8), (9), and (11) in (10), the hysteresis band (HB) can be achieved as follows:

$$\text{HB} = \frac{V_{dc}}{8fL_f} - \frac{L_f}{2fV_{dc}}\left(\frac{v_s(t)}{L_f} + \frac{di_f^*(t)}{dt}\right)^2. \tag{12}$$

The adaptive HB should be derived instantaneously during each sample time to keep the switching frequency constant.

4. Simulation Results

To verify validity of the proposed method some simulations are done using MATLAB/Simulink (Table 1). The nonlinear load consists of a three-phase diode rectifier with a DC-side resistive load. It should be mentioned that the nonlinear

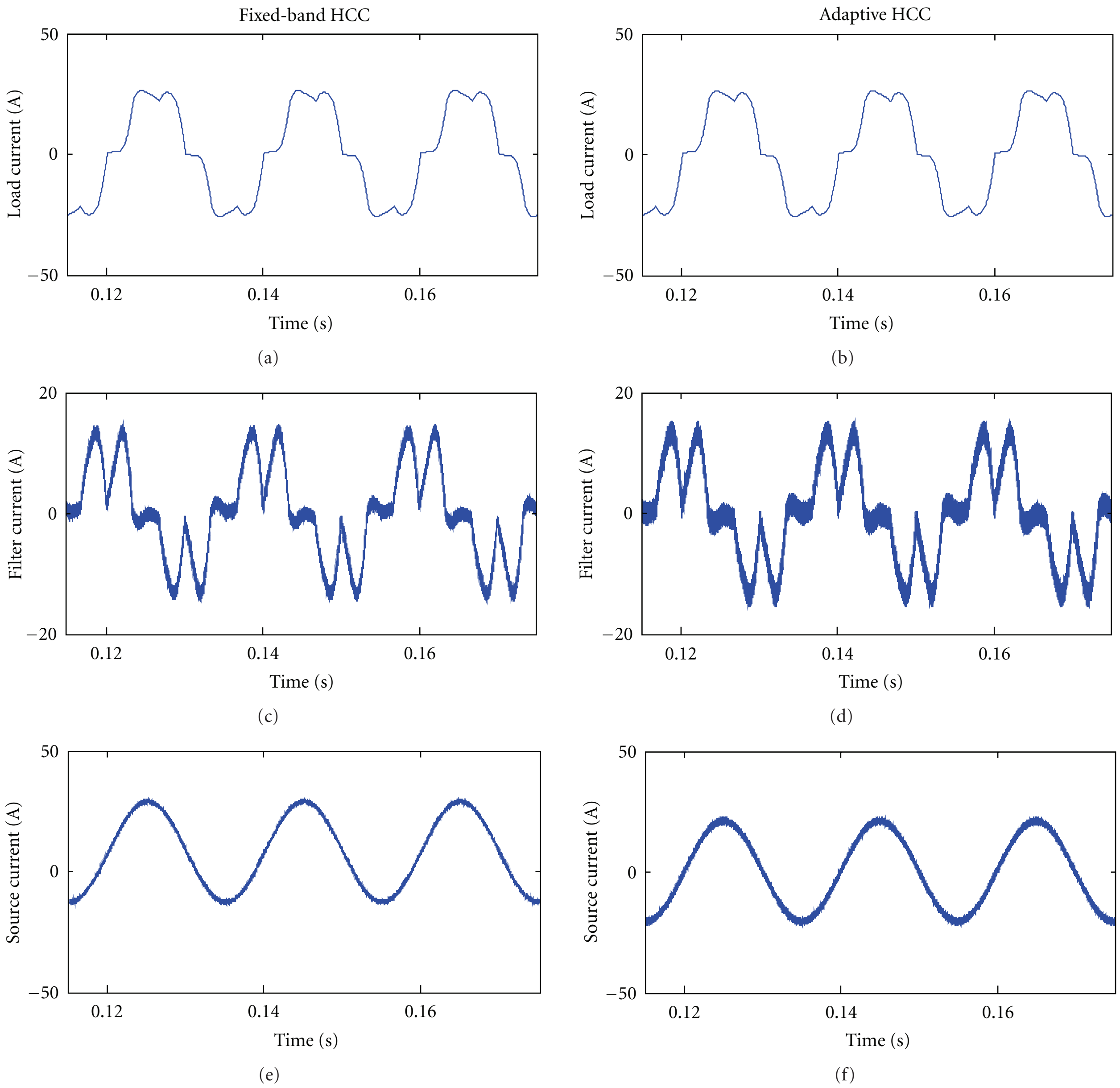


FIGURE 5: The currents for phase (a).

load is connected to the grid via inductances ($L_f = 4\,\text{mH}$). Besides, the load voltages have an rms value of 155 V-50 Hz which leads to a rms value of 18 A for system current.

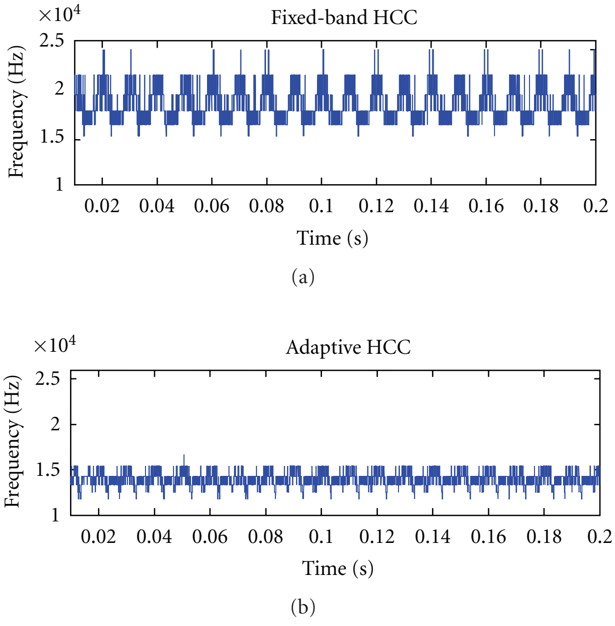
The source voltage has been remained sinusoidal and does not contain any harmonics. Figure 5 shows comparative diagrams of load current, filter current, and source current, respectively, for fixed-band HCC and AHCC methods simulation. These diagrams show a good filtering which leads to eliminate the source current harmonics, so the source current contains just the main component.

The THD results in Table 2 show that AHCC method works properly to track the reference current, and there was a good filtering process. But the following figures show the difference between fixed-band and AHCC. The AHCC distinction will be proved by Figures 5 and 6.

TABLE 2: THD% value of load and source currents.

	Source current THD%			Load current THD%		
	Phase (a)	Phase (b)	Phase (c)	Phase (a)	Phase (b)	Phase (c)
Fixed-band	2.15	2.59	2.83	24.42	24.31	24.55
AHCC	3.73	3.81	3.53	24.42	24.21	24.55

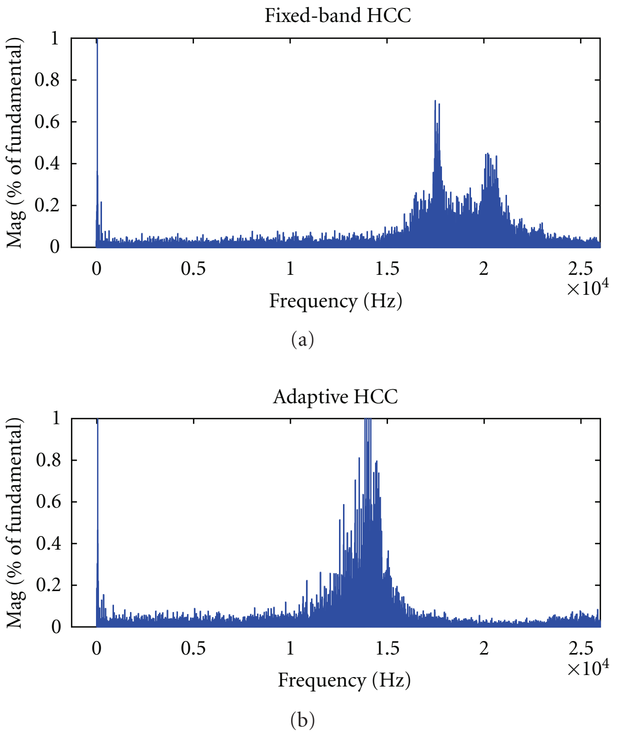
Figure 6 shows the instantaneous switching frequency for the fixed-band HCC and AHCC. It is obvious that the switching frequency in fixed-band HCC varies in vast range (in this case it changed from 15 KHz to 25 KHz) and causes audio noises and injects high-frequency components in source



(a)

(b)

Figure 6: Instantaneous switching frequency.



(a)

(b)

Figure 7: FFT analysis of the source current in high frequency range.

current that makes it difficult to design appropriate filters for eliminating them. In AHCC method, the instantaneous switching frequency remains constant with little deviation contrary to conventional fixed-band hysteretic current control method. In practical application, it is necessary to keep switching frequency to certain limits, in order to determine switching device and decrease its switching losses [9].

Figure 7 proves that many high-frequency components have been injected to the source current due to variable switching frequency, but in Figure 7, the AHCC results prove the fact that this method has worked properly which results in fixing switching frequency (12 KHz to 15 KHz). This result influences the source current THD especially in high-frequency range. Since the variation range of switching frequency has been limited to small domain, the high-frequency components of source current have been reduced to a narrow range which is apparent in Figure 7.

As the variable switching frequency causes audio noises, the AHCC fixes this problem by constant switching frequency, too.

The vast range of high-frequency components of current harmonic is just a source for audio noises as well as producing switching losses due to the switch resistance. Each harmonic order should be multiplied by the square of the switch resistor to obtain the power losses so in fixed-band method this value is higher than AHCC.

Besides, calculating the number of switching on-off pulses proves the fact that fixing switching frequency decreases the switching number and the switching number has a direct relation with the switching losses. In this simulation for 0.2 sec, the switching number has been changed from approximately 11000 to 6000, respectively, from fixed-band to AHCC method. So the switching losses are reduced by about 50%.

5. Conclusion

Shunt active power filters are the most suitable devices in power networks which eliminate the current harmonics and compensate the reactive power. Instantaneous power theory is one of the effective methods which have been explained in this paper. Afterwards, the hysteresis current control has been clarified with two modes: fixed-band and AHCC. The simulation results proved that AHCC technique made the fixed switching frequency that results in reducing the high-frequency components of source current and switching losses.

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