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An adaptive hysteresis band current controller for shunt active power filter

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Abstract

In this paper, an adaptive hysteresis band current controller is proposed for active power filter to eliminate harmonics and to compensate the reactive power of three-phase rectifier. The adaptive hysteresis band current controller, proposed by Bose [An adaptive hysteresis band current control technique of a voltage feed PWM inverter for machine drive system, IEEE Trans. Ind. Electron. 37 (5) (1990) 402–406] for electrical machine drives, is adapted to active power filter (APF). The adaptive hysteresis band current controller changes the hysteresis bandwidth according to modulation frequency, supply voltage, dc capacitor voltage and slope of the i_c^* reference compensator current wave. The hysteresis band current controller determines the switching signals of the APF, and the algorithm based on an extension of synchronous reference frame theory (d-q-0) is used to determine the suitable current reference signals. The results of simulation study of new APF control technique presented in this paper is found quite satisfactory to eliminate harmonics and reactive power components from utility current. All of the studies have been carried out through detail digital dynamic simulation using the MATLAB Simulink Power System Toolbox. The APF is found effective to meet IEEE 519 standard recommendations on harmonics levels.

Keywords: Hysteresis band current controller; Shunt active power filter; Harmonic current compensation

1. Introduction

Recent wide spread of power electronic equipment has caused an increase of the harmonic disturbances in the power systems. The nonlinear loads draw harmonic and reactive power components of current from ac mains. Current harmonics generated by nonlinear loads such as adjustable speed drives, static power supplies and UPS. The harmonics causes problems in power systems and in consumer products such as equipment overheating, capacitor blowing, motor vibration, excessive neutral currents and low power factor. Conventionally, passive LC filters and capacitors have been used to eliminate line current harmonics and to compensate reactive power by increasing the power factor. But these filters have the disadvantages of large size, resonance and fixed compensation behavior so this conventional solution becomes ineffective.

The concept of using active power filters to mitigate harmonic problems and to compensate reactive power was proposed more than two decades ago [1,2]. Since then, the theories and applications of active power filters have become more popular and have attracted great attention [6–8]. Without the drawbacks of passive harmonic filters, such as component aging and resonant problems, the active power filter appears to be a viable solution for reactive power compensation as well as for eliminating harmonic currents.

There are various current control methods proposed for such active power filter configurations, but in terms of quick current controllability and easy implementation hysteresis band current control method has the highest rate among other current control methods such as sinusoidal PWM. As in most PWM applications the interval between two consecutive switching actions varies constantly within a power frequency cycle. It means that the switching frequency is not constant but varies in time with operation point and conditions. In principle increasing inverter operation frequency helps to get a better compensating waveform. However there

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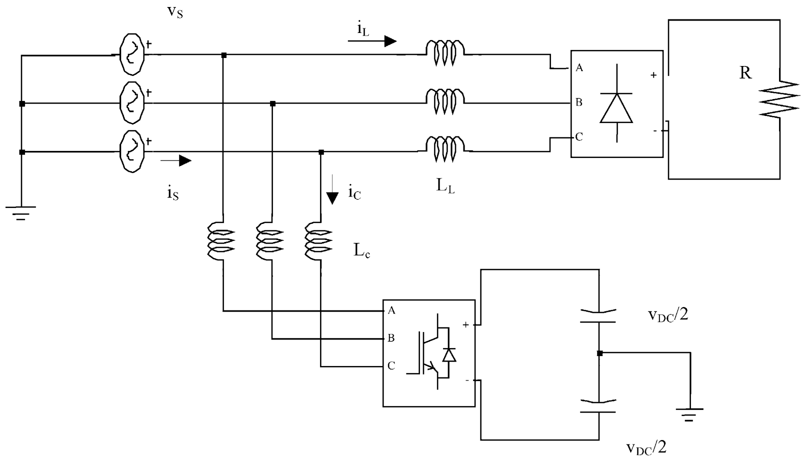

Fig. 1. Basic principle block diagram of a three-phase shunt active power filter.

are device limitations and increasing the switching frequency cause increasing switching losses, audible noise and EMF related problems. The range of frequencies used is based on a compromise between these two different factors. In this paper, the control of switching frequency is realized by introducing an adaptive hysteresis band current control algorithm.

The main aim of this study is to investigate the effects of hysteresis bandwidth to THD of supply current and switching frequency of APF. Adaptive hysteresis band current controller changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and THD of supply current. In this paper, the synchronous d-q-0 reference frame theory is first briefly reviewed. Next, the proposed adaptive hysteresis band current control based compensation strategy for the three-phase active power filter is described. Then, simulation results are presented followed by the conclusion.

2. Shunt active power filter

The shunt active power filter (APF) is a device that is connected in parallel to and cancels the reactive and harmonic currents from a nonlinear load. The resulting total current drawn from the ac main is sinusoidal. Ideally, the APF needs to generate just enough reactive and harmonic current to compensate the nonlinear loads in the line.

In an APF depicted in Fig. 1, a current controlled voltage source inverter is used to generate the compensating current (i_c) and is injected into the utility power source grid. This cancels the harmonic components drawn by the nonlinear load and keeps the utility line current (i_s) sinusoidal. A variety of methods are used for instantaneous current harmonics detection in active power filter such as FFT (fast Fourier technique) technique, instantaneous p-q theory, synchronous d-q reference frame theory or by using suitable analog or digital electronic filters separating successive harmonic components. In this paper, the synchronous d-q-0 reference frame theory based algorithm is proposed.

3. Synchronous d-q-0 reference frame based compensation

The three phase load currents shown in Fig. 2, have already been transformed to the synchronous reference frame (a-b-c to d-q-0 transformation). A high pass filter is used to extract the dc component representing the fundamental frequency of the currents. The coordinate transformation from three-phase load currents (i_{La}, i_{Lb}, i_{Lc}) to the synchronous reference frame based load currents (i_{Ld}, i_{Lq}, i_{L0}) is obtained as follows:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t-(2\pi/3)) & \cos(\omega t+(2\pi/3)) \\ -\sin(\omega t) & -\sin(\omega t-(2\pi/3)) & -\sin(\omega t+(2\pi/3)) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot\times \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{1}$$

The high pass filter to remove the dc component of load current should only be applied to the i_{Ld} current. Q axis current (i_{Lq}) is applied to inverse transformation to compensate reactive power. Zero axis current (i_{L0}) must be used when the voltages are distorted or unbalanced and sinusoidal current are desired. In this study, it is not investigated. The dc side voltage of APF should be controlled and kept at a constant value to maintain the normal operation of the inverter. Because there is energy loss due to conduction and switching power losses associated with the diodes and IGBTs of the inverter in APF, which tend to reduce the value of V_{dc} across capacitor C_{dc}. A feedback voltage control circuit needs to be incorporated into the inverter for this reason. The difference between the reference value, V_{ref} and the feedback value (V_{dc}), an error function first passes a PI regulator and the output of the PI regulator is subtracted from the d axis value of

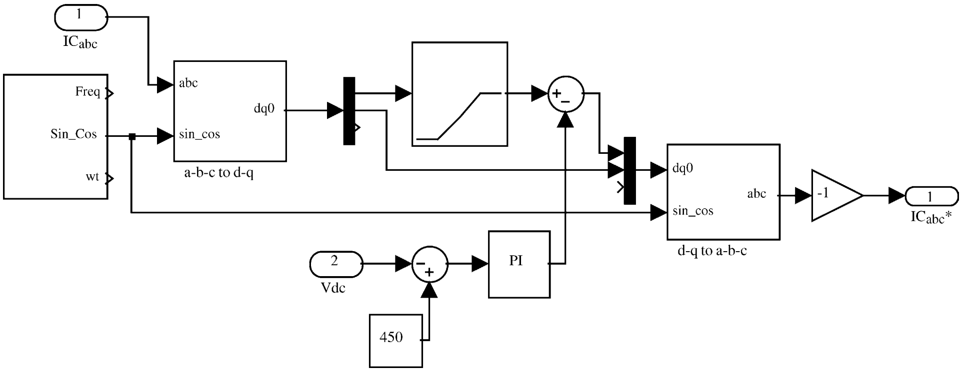

Fig. 2. Synchronous d-q-0 reference frame based compensation algorithm.

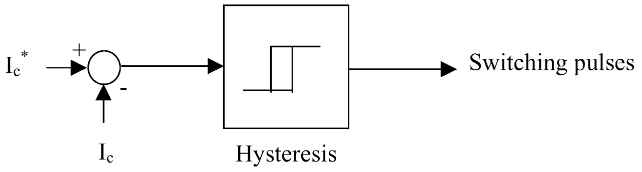

Fig. 3. Conventional hysteresis band current controller.

the harmonic current components. Synchronous d-q-0 reference frame based compensation algorithm, described above, is depicted in Fig. 2. Reference filter currents (i^*_{abc}) are determined negatives of the outputs of the inverse transformation matrix (d-q-0 to a-b-c).

4. The adaptive hysteresis band current controller

The hysteresis band current control technique has proven to be most suitable for all the applications of current controlled voltage source inverters in active power filters. The hysteresis band current control is characterized by unconditioned stability, very fast response, and good accuracy [4,5]. On the other hand, the basic hysteresis technique exhibits also several undesirable features; such as uneven switching frequency that causes acoustic noise and difficulty in designing input filters [10].

The conventional hysteresis band current control scheme used for the control of active power filter line current is shown in Fig. 3, composed of a hysteresis around the reference line current. The reference line current of the active power filter is referred to as I^*_{c} and actual line current of the active power filter is referred to as I_{c}.

The hysteresis band current controller decides the switching pattern of active power filter [11]. The switching logic is formulated as follows:

If $i_{\mathrm{ca}} < (i^*_{\mathrm{ca}} - \mathrm{HB})$ upper switch is OFF and lower switch is ON for leg “a” (SA=1).
If $i_{\mathrm{ca}} > (i^*_{\mathrm{ca}} + \mathrm{HB})$ upper switch is ON and lower switch is OFF for leg “a” (SA = 0).

The switching functions SB and SC for phases B and C are determined similarly, using corresponding reference and measured currents and hysteresis bandwidth (HB).

The switching frequency of the hysteresis band current control method described above depends on how fast the current changes from the upper limit of the hysteresis band to the lower limit of the hysteresis band, or vice versa. The rate of change of the actual active power filter line currents vary the switching frequency, therefore the switching frequency does not remain constant throughout the switching operation, but varies along with the current waveform. Furthermore, the line inductance value of the active power filter and the dc link capacitor voltage are the main parameters determining the rate of change of active power filter line currents. The switching frequency of the active power filter system also depends on the capacitor voltage and the line inductances of the active power filter configuration.

The bandwidth of the hysteresis current controller determines the allowable current shaping error. By changing the bandwidth the user can control the average switching frequency of the active power filter and evaluate the performance for different values of hysteresis bandwidth. In principle, increasing the inverter operating frequency helps to get a better compensating current waveform. However, there are device limitations and increasing the switching frequency causes

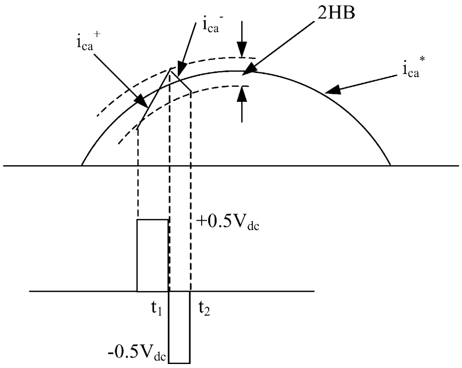

Fig. 4. Current and voltage waves with hysteresis band current control (for APF).

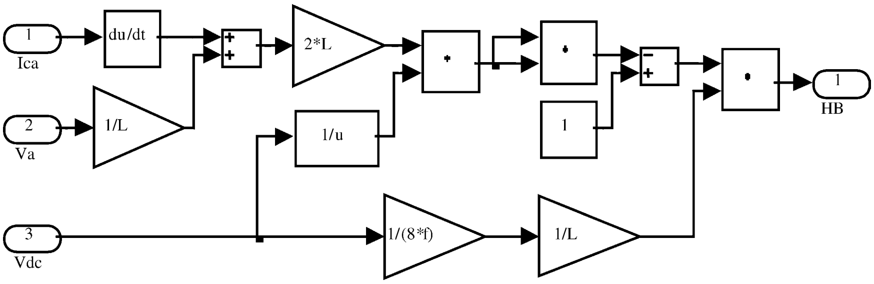

Fig. 5. The adaptive hysteresis bandwidth calculation block diagram.

increased switching losses, and EMI related problems. The range of switching frequencies used is based on a compromise between these factors.

The hysteresis-band current control method is popularly used because of its simplicity of implementation, among the various PWM techniques. Besides fast-response current loop and inherent-peak current limiting capability, the technique does not need any information about system parameters. However, the current control with a fixed hysteresis band has the disadvantage that the switching frequency varies within a band because peak-to-peak current ripple is required to be controlled at all points of the fundamental frequency wave [3]. But interesting improved versions of this technique are presented in literature [9,10].

Fig. 4 shows the PWM current and voltage waves for phase a. The currents i_a tends to cross the lower hysteresis band at point 1, where upper side IGBT of leg "*a*" is switched on. The linearly rising current (i_{ca}^{+}) then touches the upper band at point 2, where the lower side IGBT of leg "*a*" is switched on. The following equations can be written in the respective switching intervals t_1 and t_2 from Fig. 4.

$$\frac{di_{ca}^{+}}{dt} = \frac{1}{L}(0.5V_{dc} - V_s) \tag{2}$$

$$\frac{di_{ca}^{-}}{dt} = -\frac{1}{L}(0.5V_{dc} + V_s) \tag{3}$$

From the geometry of Fig. 4 can be written,

$$\frac{di_{ca}^{+}}{dt}t_1 - \frac{di_{ca}^{*}}{dt}t_1 = 2\mathrm{HB} \tag{4}$$

$$\frac{di_{ca}^{-}}{dt}t_2 - \frac{di_{ca}^{*}}{dt}t_2 = -2\mathrm{HB} \tag{5}$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \tag{6}$$

where t_1 and t_2 are the respective switching intervals, and f_c is the switching frequency.

Adding (4) and (5) and substituting (6), it can be written

$$t_1\frac{di_a{}^{+}}{dt} + t_2\frac{di_a{}^{-}}{dt} - \frac{1}{f_c}\frac{di_{ca}^{*}}{dt} = 0 \tag{7}$$

Subtracting (5) from (4), we get

$$4\mathrm{HB} = t_1\frac{di_{ca}^{+}}{dt} - t_2\frac{di_{ca}^{-}}{dt} - (t_1 - t_2)\frac{di_{ca}^{*}}{dt} \tag{8}$$

Substituting (3) in (8), gives

$$4\mathrm{HB} = (t_1 + t_2)\frac{di_{ca}^{+}}{dt} - (t_1 - t_2)\frac{di_{ca}^{*}}{dt} \tag{9}$$

Substituting (3) in (7), simplifying

$$t_1 - t_2 = \frac{di_{ca}^{*}/dt}{f_c(di_{ca}^{+}/dt)} \tag{10}$$

Substituting (10) in (9), gives

$$\mathrm{HB} = \left\{\frac{0.125V_{dc}}{f_c L}\left[1 - \frac{4L^2}{V_{dc}^2}\left(\frac{v_s}{L} + m\right)^2\right]\right\} \tag{11}$$

where f_c is modulation frequency, $m = di_{ca}^{*}/dt$ is the slope of command current wave. Hysteresis band (HB) can be modulated at different points of fundamental frequency cycle to control the switching pattern of the inverter. For symmetrical operation of all three phases, it is expected that the hysteresis bandwidth (HB) profiles HB_a, HB_b and HB_c will be same, but have phase difference.

The adaptive hysteresis band current controller changes the hysteresis bandwidth according to instantaneous compensation current variation (di_c/dt) and V_{dc} voltage to minimize the influence of current distortion on modulated waveform. In this paper, the adaptive hysteresis band current controller, proposed by Bose [3] for electrical machine drives given by Eq. (11), is adapted to APF.

Eq. (11) shows the hysteresis bandwidth (HB) as a function of modulation frequency, supply voltage, dc capacitor

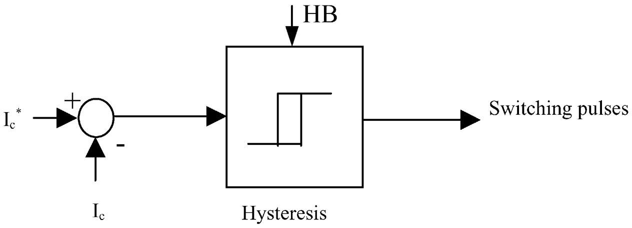

Fig. 6. Variable hysteresis band current controller.

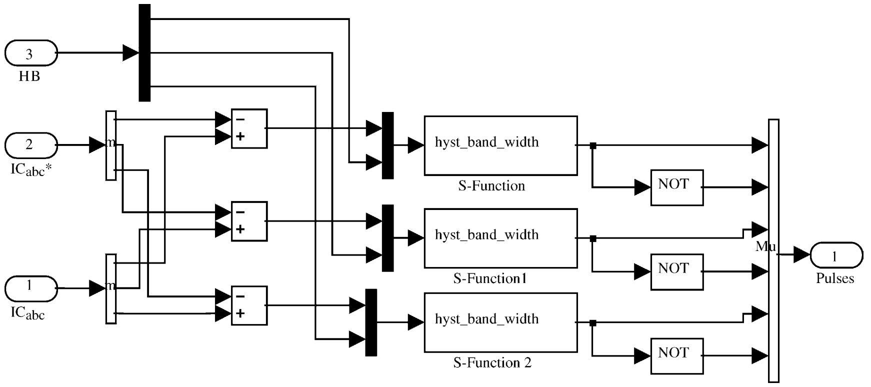

Fig. 7. The block diagram of the variable hysteresis band current controller.

voltage and slope of the i_c^* reference compensator current wave. Hysteresis band can be modulated as a function of V_{dc} and m so that the modulation frequency f_c remains nearly constant. This will improve the PWM performances and APF substantially. The adaptive hysteresis bandwidth calculation block diagram is shown in Fig. 5. The calculated hysteresis bandwidth (HB) is applied to the variable hysteresis band current controller shown in Fig. 6. Block diagram of variable hysteresis band current controller created by s-functions in Matlab is shown in Fig. 7. The produced pulses are sent to IGBT inverter.

5. Simulation results and discussions

In conventional fix band hysteresis current control and adaptive hysteresis band current control method, instantaneous switching frequencies are shown in Fig. 8, respectively. In adaptive hysteresis band current control method, the instantaneous switching frequency remains constant with little deviation contrary to conventional fix band hysteresis current control method. In practical application, it is necessary to kept switching frequency to a certain limits, in order to determine switching device and its switching losses. In

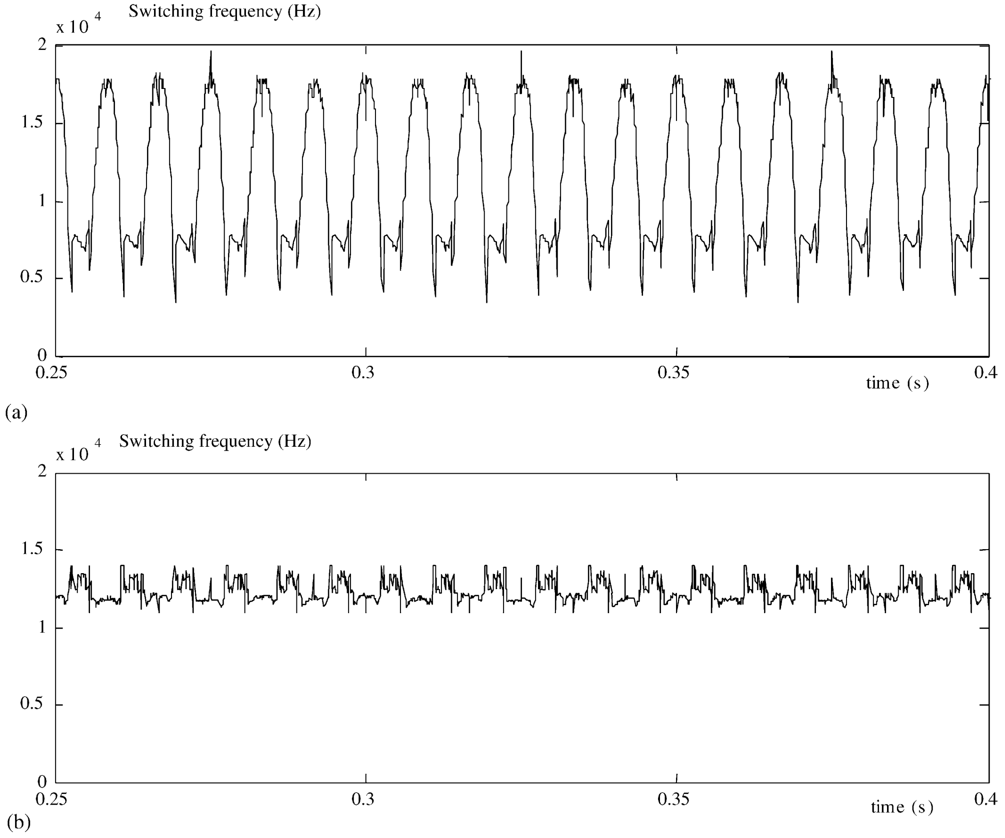

Fig. 8. Instantaneous frequency: (a) conventional fix band hysteresis current controller, (b) adaptive hysteresis band current controller.

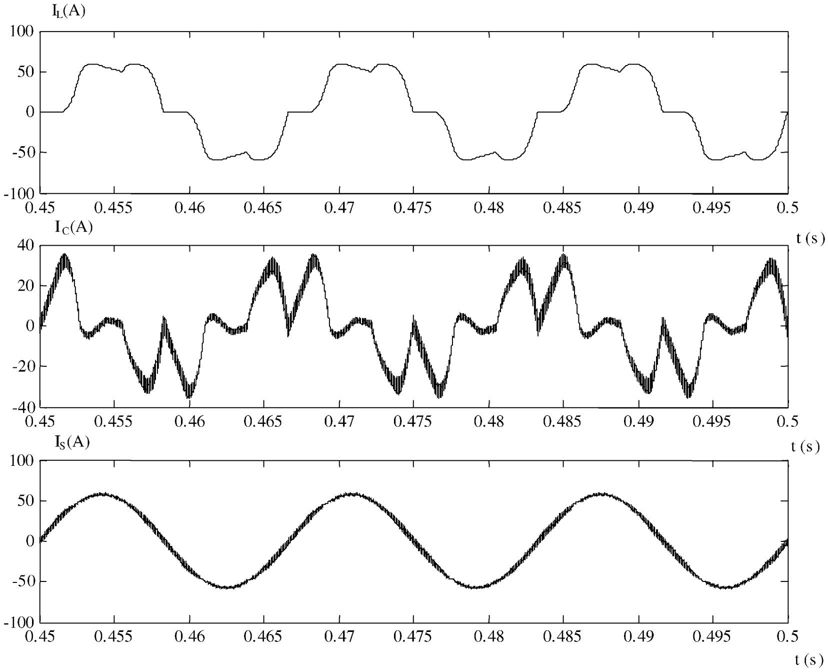

Fig. 9. (a) Load current; (b) compensating current; (c) supply current waveforms after harmonic compensation.

Table 1
Design specifications and circuit parameters

Switching frequency	12 kHz
Fundamental frequency	60 Hz
ac supply voltage	127 V
Inverter dc voltage (V_{dc})	450 V
Rectifier load resistance	5 Ω
Rectifier side inductance	1 Mh
Inverter side inductance	1 mH
C_{dc} capacitor	1500 μF

conventional hysteresis band current controller, it is not possible to determine not only hysteresis bandwidth but also switching frequency according to system parameters (L, V_{dc},). In adaptive hysteresis band current controller, switching frequency remains constant respecting the system parameters and defined frequency.

The harmonic current and reactive power compensation by APF is implemented in a three-phase power system which the utility power supply voltage of 127 V and current source three-phase diode-bridge rectifier with resistive load as the harmonic current compensation object. The design specifications and the circuit parameters used in the simulation are indicated in Table 1. The load current waveform in a-phase is shown in Fig. 9(a). The compensating current waveform in a-phase is illustrated in Fig. 9(b) and demonstrates that controller can exactly keep track the harmonic current components. The utility power source current after the harmonic

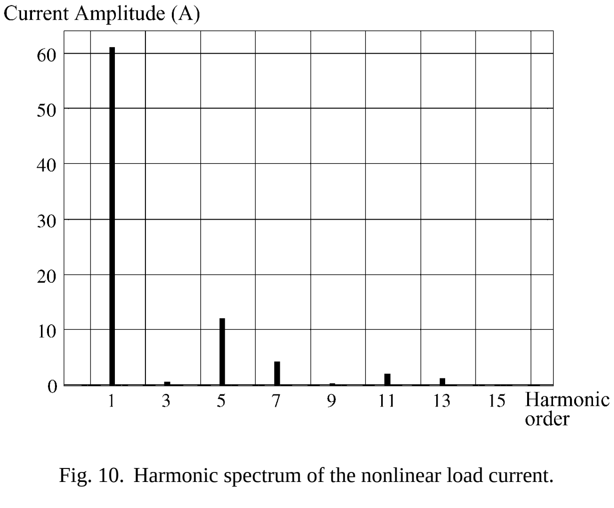

Fig. 10. Harmonic spectrum of the nonlinear load current.

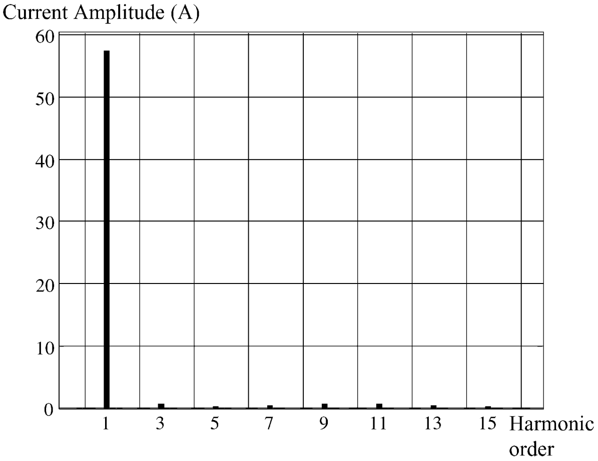

Fig. 11. Harmonic spectrum of the source current with the proposed adaptive hysteresis band current controller.

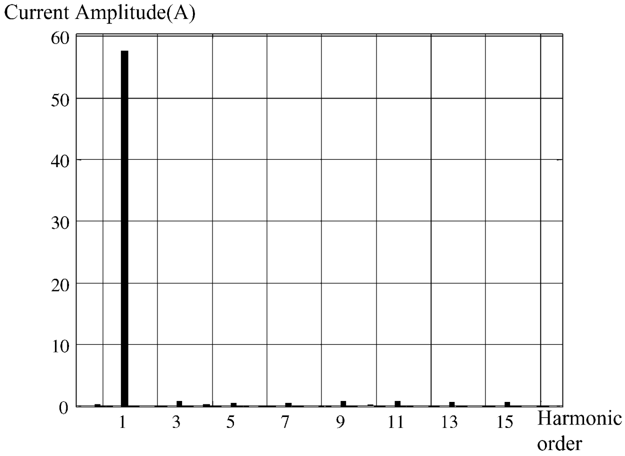

Fig. 12. Harmonic spectrum of the source current with fixed band hysteresis band current controller.

compensation is illustrated in Fig. 9(c). The THD (total harmonic distortion) is also computed in load current as well as in supply current. The THD is 21.88% before harmonic compensation in load current and 4.48% in supply current after harmonic current compensation that is within the limit of the harmonic standard of IEEE 519. The performance of the proposed adaptive hysteresis band current controller regarding harmonics cancellation is compared with a fixed band current controller. Harmonic spectrum of the nonlinear load current is shown in Fig. 10. Harmonic spectrum of the source current with the proposed and fixed band hysteresis current controllers are shown in Figs. 11 and 12, respectively. There is no difference between adaptive hysteresis band current controller and fixed band controller for distortion spectrum.

6. Conclusion

This paper demonstrates the validity of the proposed adaptive hysteresis band current controller for active power filters. Experimental verification of the control system is being performed and test results will be reported in the future papers. The results of simulation study of new APF control technique presented in this paper is found quite satisfactory to eliminate harmonics and reactive power components from utility current. The shunt active power filter (APF) presented in this paper for the compensation of harmonic current components in nonlinear load was effective for harmonic isolation and keeping the utility supply line current sinusoidal. The validity of this technique in order to compensate current harmonics was proved on the basis of simulation results. The APF is found effective to meet IEEE 519 standard recommendation on harmonics levels.

The simulation results show that the fix band hysteresis current control and the adaptive hysteresis band current control are equally good in filtering the harmonics generated by the load. The main difference between the two control methods should be in the high frequency harmonics generated by switching of the IGBTs. The instantaneous switching frequency remains constant in the proposed method contrary to conventional fix band hysteresis current control method. In application stage, the switching frequency must be kept in a certain limit determined by switching devices.

The paper describes an adaptive hysteresis-band current control PWM technique where the bandwidth can be programmed as a function of system parameters to optimize the PWM performance. It is proposed an adaptive hysteresis-band algorithm for the implementation of the fixed-frequency adaptive hysteresis current control for voltage source inverters in active power filters. Although various criteria of optimization are possible, the paper illustrates a case where the modulation frequency is held nearly constant.

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