International Journal of Electrical and Power Engineering 2 (2): 127-133, 2008
ISSN: 1990-7958

A Novel Adaptive Hysteresis Current Controller for Three Phase Shunt Active Power Filter with Constant Switching Frequency

Nouri Belhaouchet, Lazhar Rahmani and Souhila Begag
Department of Electrotechnic, Ferhat Abbas University Setif, Algeria

Abstract: In this study, a new substantial improvement of the hysteresis current control technique is proposed for shunt active power filter to eliminate harmonics and to compensate the reactive power of three-phase rectifier. A simple and fast prediction of the hysteresis band is added to a phase-locked-loop control, in order to ensure constant switching frequency and tight control of the position of modulation pulses. This allows high accuracy in tracking highly distorted current waveforms and minimises the ripple in three-phase systems. This technique is very simple and robust, its implementation employs a small number of conventional, inexpensive analog and logic components. The proposed technique determines the switching signals of the three-phase shunt active power filter and an algorithm based on the dc bus capacitors voltage regulation using Proportional-Integral (PI) is proposed to determine the suitable current reference signals. The behavior of the proposed technique has been fully verified by simulation using MATLAB/SIMULINK.

Key words: Three-phase active power filter, dead-beat, switching frequency, phase-locked-loop, interference phenomena

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 (Gouraud, 1997).

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. Since then, the theories and applications of active power filters have become more popular and have attracted great attention (Kale and Ozdenir, 2003).

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 techniques proposed for such active power filter configurations, but in terms of quick current controllability and easy implementation, the hysteresis band current control technique has the highest rate among other current control methods such as sinusoidal PWM (Attia, 2005). 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 (Nicolas, 1996). In principle increasing inverter operation frequency helps to get a better compensating waveform. However, there are device limitations and increasing the switching frequency cause increasing switching losses, audible noise and EMF related problems. In this study, the control of switching frequency is realized by introducing an adaptive hysteresis band current control technique based on law control called first order dead-beat control and then this law is modified by introducing the Phase-Locked-Loop (PLL) in order to ensure the synchronization of modulation pulses. The application of this technique is used for three-phase Active Power Filter (APF). In this case, the neutral of ac supply is isolated to dc supply

Corresponding Author: Nouri Belhaouchet, Department of Electrotechnic, Ferhat Abbas University Setif, Algeria

midpoint of APF. The isolation of this neutral causes the interference phenomena between the phases. To avoid this problem, a decoupling of the current error must be realized (Sonaglioni, 1995; Malesani *et al*., 1996).

The main aim of this study, is to investigate the affects of this novel technique to Total Harmonics Distortion (THD) of supply current and the characteristics of three-phase APF. In this study, an algorithm based on extension of the dc bus capacitors voltage regulation in order to determine the suitable reference currents is developed. Next, the proposed adaptive hysteresis band current control for the three-phase active power filter is described. Then, simulation results are presented followed by the conclusion.

SHUNT ACTIVE POWER FILTER

The shunt Active Power Filter (APF) is a device that is connected in parallel to compensate the reactive power and to eliminate harmonics of 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.

Figure 1 shows the power circuit of the shunt APF connected to a nonlinear load. The APF consists of three principal parts, the three-phase converter, two capacitors Connected in series give an equivalent value C_{dc} and the inductance of smoothing L_f. The converter is used to charge and to discharge the capacitors in order to provide the required compensation current, the capacitors are used to storage of energy and the inductance L_f is used to smooth and decrease the ripple of the harmonic current injected by APF.

The AC supply provides the required active power and the capacitors of APF provide the reactive power in the permanent state. Therefore, there is no active energy provided by capacitors. Ideally, the average dc bus voltage must be constant, but there is a fluctuation voltage due to the flow of reactive energy. Consequently, to maintain this voltage perfectly constant, we have a method to regulate this latter and to generate the purely sinusoidal reference currents.

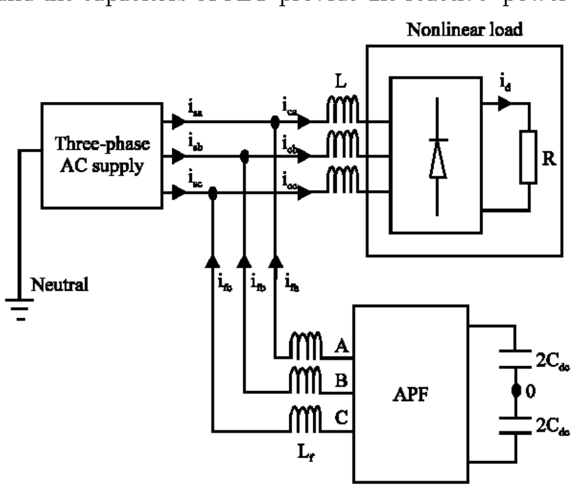

Fig. 1: Shunt APF connected to a nonlinear load with isolated neutral

COMPUTATION OF SUPPLY REFERENCE CURRENTS

The basic operation of this method is shown in Fig. 2. The estimation of the reference currents from the measured dc bus voltage is the basic idea behind the PI controller based an operation of the APF. The capacitors voltage V_{dc} is compared with its reference value V^*_{dc} in order to maintain the stored dcenergy in the capacitors constant. The PI controller is applied to regulate the error between the capacitors voltage and its reference. The output of PI controller gives the magnitude $I^*_{s\,max}$ of the three reference currents and then this value is multiplied by sinusoidal signals of magnitude equal to the unit in order to obtain the instantaneous supply reference currents i^*_{sa} i^*_{sb} i^*_{sc} (Attia, 2005).

The supply reference currents are compared, respectively with the nonlinear load currents i_{sa}, i_{sb}, i_{sc} and the result of comparison of each phase is called the reference compensator current of APF. The result of comparison between this current of APF is sent to hysteresis controller indt order to generate the modulation pulses.

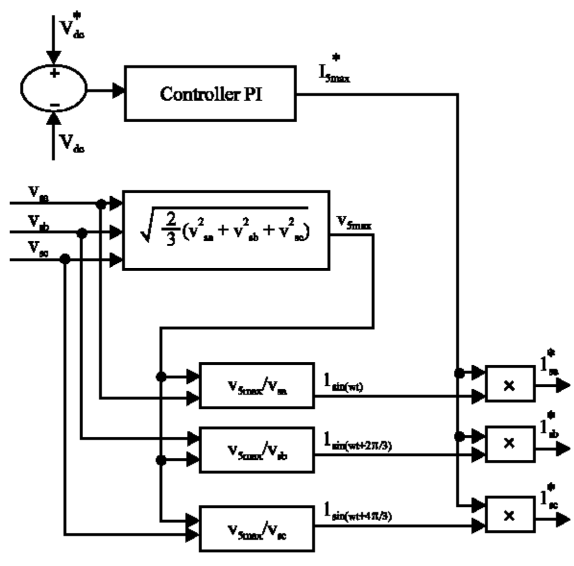

Fig. 2: Reference currents computation

THE NOVEL ADAPTIVE HYSTERESIS CURRENT CONTROLLER

The hysteresis band current control can be implemented to generate the switching pattern in order to get precise and quick response. 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. 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, the modulation pulses are random and interference phenomena between the phases.

The fixed band hysteresis current control called also conventional hysteresis is exploited for the three-phase inverters. Its principle is the same one as in the case of the single-phase inverter. Indeed, it is enough to shift the control signals of 120°. In this technique, the hysteresis band is maintained constant (fix) throughout the period of operation, each leg of inverter (APF) comprises twoswitches must be complementary. The switching times of switches for each leg can be given using hysteresis comparator, when the current error reached one of its limits. As result, the output voltage for each leg passes from $+V_{dc}/2$ to $-V_{dc}/2$, the currents injected by APF are forced to follow its reference currents with desired band hysteresis. For three-phase systems, the neutral of the ac supply can be isolated to the midpoint of the dc supply 0 of the APF as shown in Fig. 1.

Since, the APF and ac supply are symmetrical, one phase only needs to be considered, so that for phase a.

The phase voltage and the current injected by APF relationship is:

$$L_f \frac{di_{fa}}{dt} + v_{sa} = u_a - u_0 \qquad (1)$$

Where, u_0 is the voltage between neutral ac supply and dc supply midpoint. Its expression is given as:

$$u_0 = \frac{(u_a + u_b + u_c)}{3} \qquad (2)$$

In practice, u_a can only take the values $\pm V_{dc}/2$, depending on the state of the phase leg switches. However, if the ideal reference current i^*_{fa} is assumed to flow through phase a of APF, the a fictitious phase voltage u^*_a would exist, given by:

$$L_f \frac{di_{fa}}{dt} + v_{sa} = u^*_a \qquad (3)$$

Now, for hysteresis band current control, the difference between the actual and the reference current can be defined as:

$$\varepsilon_a = i_{fa} - i^*_{fa} \qquad (4)$$

Subtracting (3) from (1) and substituting from (4) gives:

$$L_f \frac{d\varepsilon_a}{dt} = u_a = u^*_a - u_0 \qquad (5)$$

Equation 5 shows that, due to the action of neutral midpoint voltage u_0, each phase current error is affected by the commutations in the other phases. This interference causes severe irregularities in the ordinary hysteresis operation.

From (4), the current responses function (i_{fa}-i^*_{fa}) can be decoupled into two parts as:

$$\varepsilon_a = i_{fa} - i^*_{fa} = \zeta_a + \gamma_a \qquad (6)$$

Where:
ζ_a = The decoupled current error
γ_a = The decoupled term

The equation of decoupled term is:

$$-u_0 = L_f * \frac{d\gamma_a}{dt} \qquad (7)$$

An interference-free modulation can be obtained if the hysteresis control is performed on the decoupled current error as:

$$u_a - u^*_a = L_f * \frac{d\xi_a}{dt} \qquad (8)$$

After the decoupling, the term u u_ can be considered constant during a modulation period, thus the decoupled current error $\xi_a(t)$ has a triangular behavior as shown in Fig. 3.

For three-phase systems with isolated neutral, we must work by the decoupled current error in order to avoid the interference phenomena between the phases (Yao and Holmes, 1993; Belhaouchet *et al*., 2005).

Now, using (8) and with reference to Fig. 3, it can be derived:

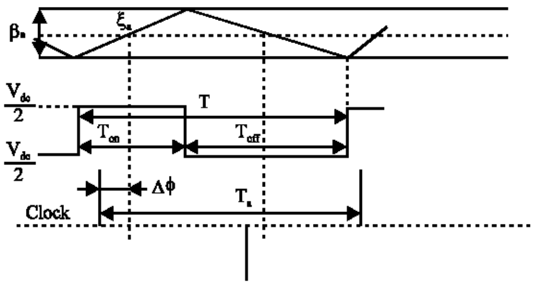

Fig. 3: Upper: Hysteresis-band and decoupled error current, middle: Phase leg voltage of APF, lower: clock of synchronization

$$T = \frac{4.L_f.\beta_a}{V_{dc}(1-u_{na}^2)} \quad (9)$$

Where, u_{na} is the normalized voltage given by:

$$u_{na} = u^*_a/(V_{dc}/2) \quad (10)$$

From (9), we note that if the bandwidth β_a is constant, then the switching period T is variable.

To obtain a constant switching frequency, the hysteresis band β_a has to be dynamically modified, according to this a equation:

$$\beta_a = \frac{V_{dc}(1-u^2_{na})}{4.L_f}T_d \quad (11)$$

Where, T_d is the desired switching period.

The controller maintains its analog structure, but an adaptive bandwidth digital control is added which ensures constant switching frequency. Figure 4 shows the adaptation of the hysteresis band for two successive modulation periods.

From Fig. 4, we deduce the following equations:

$$\forall k: \begin{matrix} S_+.T_{on} = S\_.T_{off} = \beta_a \\ T_{on} + T_{off} = T \end{matrix} \quad (12)$$

$$T(k) = \frac{\beta_a(k)}{S_+(k)} + \frac{\beta_a(k)}{S\_(k)} = \beta_a(k).\frac{S+(k)_+ S\_(k)}{S\_(k).S\_(k)} \quad (13)$$

For a switching period corresponding to k+1, the Eq. 13 is written:

$$T(k+1) = \beta_a(k+1).\frac{S_+(k+1)+S\_(k+1)}{S_+(k+1).S\_(k+1)} \quad (14)$$

For two successive periods, we have the following simplifying assumption:

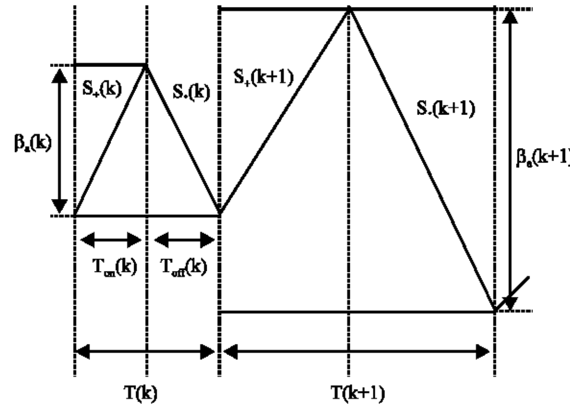

Fig. 4: First order dead-beat control algorithm

$$\begin{matrix} S_+(k) = S_+(k+1) \\ S\_(k) = S\_(k+1) \end{matrix} \quad (15)$$

From (13) and (14), we obtain:

$$T(k+1) = \beta_a(k+1).\frac{T(k)}{\beta_a(k)} \quad (16)$$

From the previous equations, it is possible to derive the control equation:

$$\beta_a(k+1) = \beta_a(k).\frac{T_d}{\beta_a(k)}$$

Where, T_d T (k = + 1) is the desired switching period.

It is worth noting that this reasoning leads to an algorithm which is equivalent to a first order dead-beat control of the switching period. The control algorithm is very simple. Unfortunately, the modulation pulses are not phase-controlled. This means that the allocation inside the modulation period of the switching pulses is random. To avoid this problem, the solution is equivalent to the implementation of a digital Phase Locked Loop (PLL) (Malesani *et al.*, 1997).

When locked to a suitable clock signal, the PLL not only ensures constant modulation frequency, but also minimizes the phase displacement $\Delta\phi$ between the output voltage pulses and the clock itself as shown in Fig. 5. With an accuracy limited only by the control loop gain. This feature is of particular importance for three-phase isolated neutral system. Where the centered pulse condition results in optimal reduction of the current ripple.

In controlling the hysteresis modulation, the ability of the PLL to limit the phase displacement is restricted to slow variations of u_{na}. This because the bandwidth is limited by the wide variations of the loop gain in dependence of u_{na}.

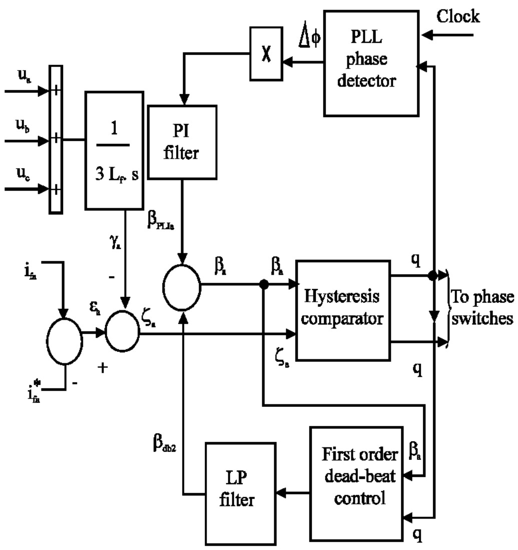

Fig. 5: Block scheme of the digital hysteresis control for phase a

To avoid instability, it is customary to set a lower limit to the band β_a. This corresponds to an upper limit for u_{na}, beyond which the PLL loses the lock.

Finally, with reference to Fig. 5, it can be derived:

$$\beta_a = \beta_{PLLa} + \beta_{dba} \quad (18)$$

$$\beta_{PLLa} = K_p.\frac{1+sT_z}{sT_z}.\Delta\phi \quad (19)$$

$$\beta_{dba} = \frac{f}{f_d}\beta_a$$

Where:

β_{PLLa} = The band given by PLL loop.
β_{dba} = The band given by first order dead beat control.
β_a = The modified total band.

The Eq. 20 shows the first order dead-beat control law with a correction of bandwidth. The role of the low-pass filter used to the output of β_{dba} is to smooth the signal to ensure a proper operation of hysteresis comparator and to ensure the stability.

Similar expressions of hysteresis bands can be written for phases b and c.

RESULTS AND DISCUSSION

In this simulation, we used the parameters which are shown in Table 1.

The harmonic current and reactive power compensation by APF is implemented in a three-phase power system with 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.

Figure 6 shows the waveforms of nonlinear load current, the compensating current and the supply current after harmonic compensation in a-phase, respectively for the conventional fixed band hysteresis control without decoupling error. This conventional technique is able to compensate harmonic of nonlinear load. However, the existence of interference phenomena between the phases affects negatively the regularity of compensation.

Figure 7 shows the harmonic spectrum of the nonlinear load current and of the supply current after harmonic compensation for conventional fixed band hysteresis control with interference phenomena. The Total Harmonic Distortion (THD) is also computed in nonlinear load current as well as in supply current. The THD is 21.95% before harmonic compensation and reduced to 9.88% after harmonic compensation.

Table 1: Design specifications and circuit parameters

Desired Switching Frequency	12KHz
Fundamental Frequency	60Hz
AC supply voltage	127V
APF dc reference voltage	600V
Rectifier load resistance	5 Ω
Rectifier side inductance	1 mH
APF side inductance	1 mH
C_{dc} capacitor dc	1500 µF
PI regulator of PLL	f_z = 500 Hz k_p = 0.5

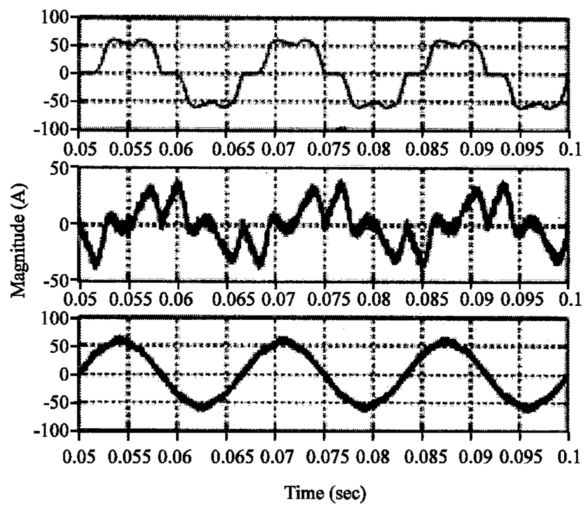

Fig. 6: Simulation results for conventional fixed band hysteresis control with interference phenomena: Upper: nonlinear load current, Middle: compensating current, lower: supply current after harmonic compensation

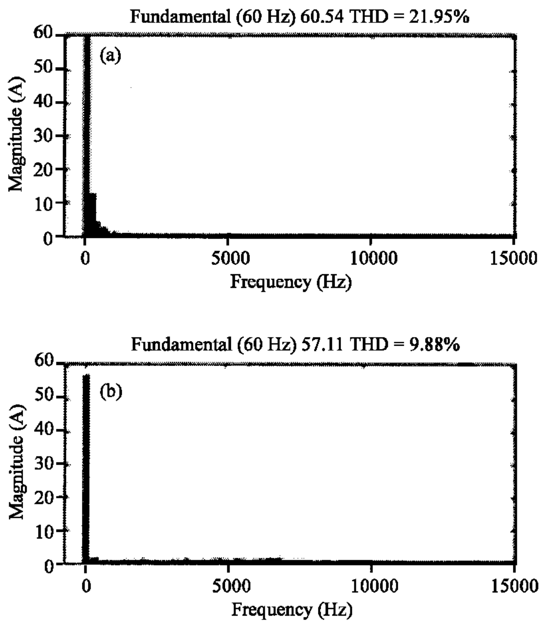

Fig. 7: Harmonic spectrum: (a) nonlinear load current, (b) supply current for conventional fixed band hysteresis control with interference phenomena

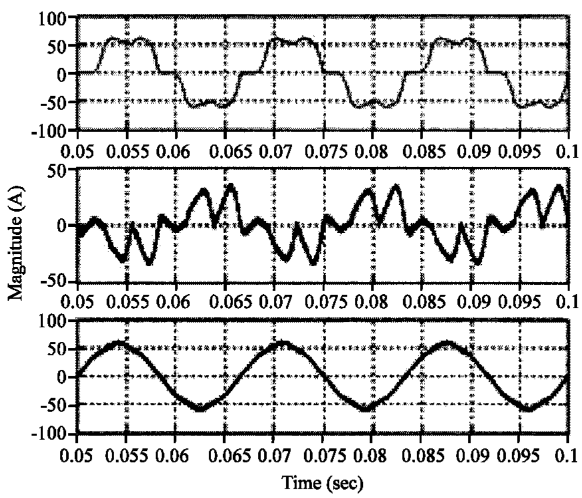

Fig. 8: Simulation results for conventional fixed band hysteresis control without interference phenomena: Upper: nonlinear load current, Middle: compensating current, lower: supply current after harmonic compensation

The waveforms of nonlinear load current, the compensating current and the supply current after harmonic compensation in a-phase, respectively for the conventional fixed band hysteresis control with decoupling error are shown in Fig. 8. The quality of supply current after compensation is improved compared to the conventional fixed band hysteresis control without

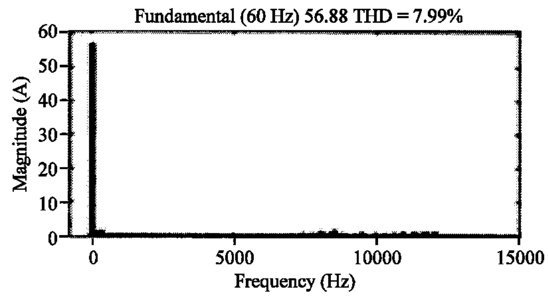

Fig. 9: Harmonic spectrum of supply current for conventional fixed band hysteresis control without interference phenomena

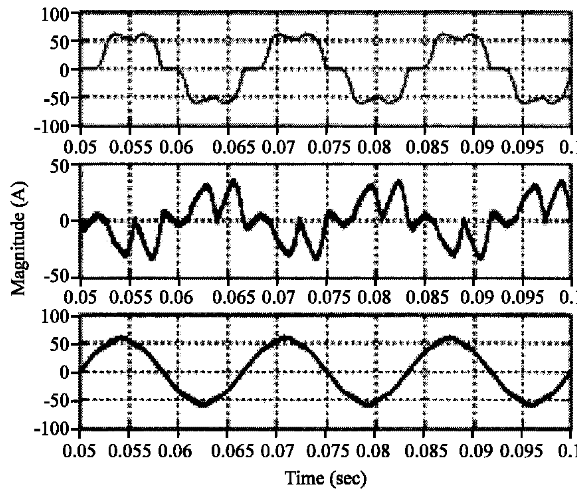

Fig. 10: Simulation results for digital hysteresis control: Upper: nonlinear load current, Middle: compensating current, lower: supply current after harmonic compensation

decoupling error shown in Fig. 6. This improvement is explained by the spectrum harmonic shown in Fig. 9 and thus in this case, the THD is reduced to 7.99%

Figure 10 shows the waveforms of nonlinear load current, the compensating current and the supply current after harmonic compensation in a-phase, respectively for the proposed digital hysteresis control. This digital technique has the ability to compensate harmonics of nonlinear load. The quality of supply current after harmonic compensation is improved compared to the conventional fixed band hysteresis technique. The spectrum harmonic shown in Fig. 11 shows this improvement and thus, in this case, the THD is reduced to 4.12% that is within the limit of the harmonic standard of IEEE 519.

Figure 12 shows the PWM APF switching frequency for conventional fixed band hysteresis control with and without interference phenomena and the proposed

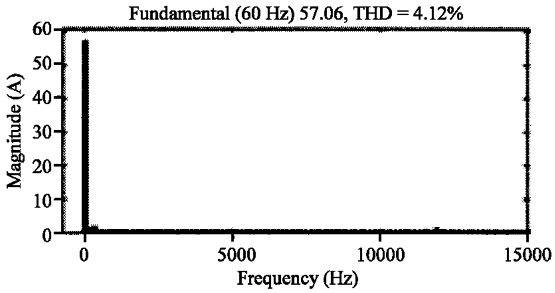

Fig. 11: Harmonic spectrum of supply current for digital hysteresis control

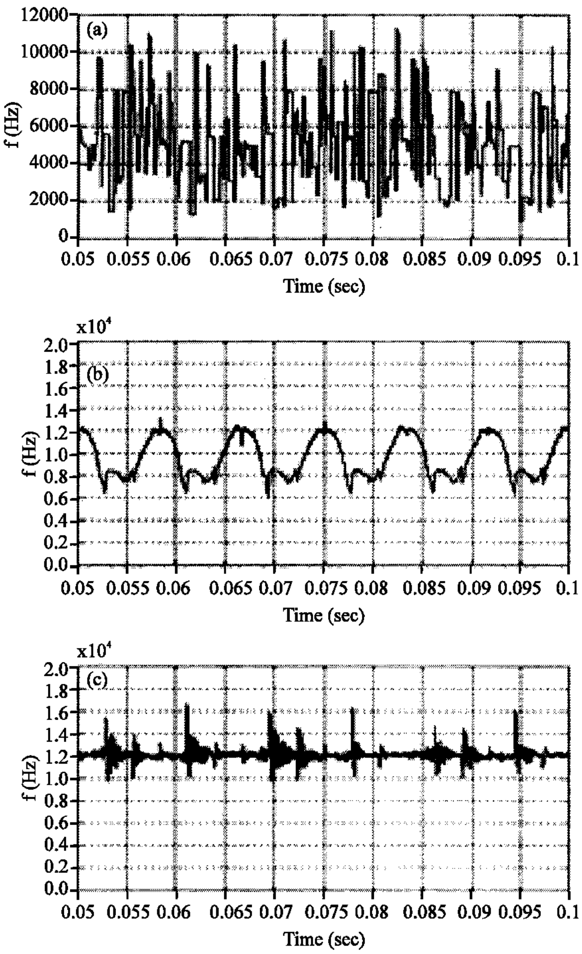

Fig. 12: PWM APF switching frequency: (a) conventional fixed band hysteresis control with interference phenomena, (b) conventional fixed band hysteresis control without interference phenomena, (c) digital hysteresis control

digital hysteresis control, respectively. In the case of conventional fixed band hysteresis control with interference phenomena, the switching frequency varied widely randomly and for conventional fixed band hysteresis control without interference phenomena, the switching frequency varied between a minimum value 7KHz and a maximum value 12KHz. However, for the digital hysteresis control, the switching frequency is more stable around the 12KHz.

CONCLUSION

This study has presented a substantial improvement of hysteresis current control technique for shunt active power filter in order to ensure a constant switching frequency and improved control of the modulation pulses. Thus latter feature is of particular importance in reducing the current ripple in isolated neutral three phase systems. This new technique allowed for the active power filter to make a better compensation in order to have a better power factor of ac supply. The validity of this technique was proved on the basis of simulation results.

REFERENCES

Attia, S., 2005. Commande en Temps réel d'un Filtre Actif de Puissance utilisant la technique par Mode de Glissement: Simulation par MATLAB/Simulink. mémoire de magister, UFAS.

Belhaouchet, N., H. Hamla, F. Krim and L. Rahmani, 2005. Commande par hystérésis à bande adaptative. CISE, Batna, Algérie.

Gouraud, T., 1997. Identification et Rejet de Perturbations Harmoniques dans des Réseaux de Distribution Electrique. Thèse de Doctorat, Ecole doctorale sciences pour l'ingénieur de Nantes.

Kale, M. and E. Ozdenir, 2003. A Novel Adaptive Hysteresis Band Current Controller for Shunt Active Power Filter. IEEE, CCA, Istanbul, Turkey, 2: 23-25 pp: 1118-1123.

Malesani, L. *et al.*, 1996. Digital Adaptive Current Control with Clocked Commutations and Wide Operating Range. IEEE. Trans. Ind. Applicat, 32: 316-324.

Malesani, L., P. Mattavelli and P. Tomasin 1997. Improved Constant Frequency Hysteresis Current Control of VSI Inverters with Simple Feedforward Band with Prediction. IEEE. Trans. Ind. Applicaton, 33: 1194-1202.

Nicolas, B., 1996. Contribution à la commande des convertisseurs statiques. Thèse de doctorat, INP Toulouse.

Sonaglioni, L., 1995. Predictive Digital Hysteresis Current Control. IEEE, IAC, Orlando, FLUSA, pp: 1879-1886.

Yao, Q. and D.G. Holmes, 1993. A Simple, Novel Method for Variable-Hysteresis-Band Current Control of A Three Phase Inverter with Constant Switching Frequency. IEEE. IAS Ann. Meet. Conf. Rec. Toronto, pp: 1122-1129.