Hysteresis Current Control of the Single - Phase Active Filter

Aurel Botezan, Ioan Vădan and Silviu Ştefănescu
Technical University of Cluj-Napoca, Electric Power Systems and Management Department, Cluj-Napoca, Romania,
aurel.botezan@enm.utcluj.ro

Abstract - **To compensate harmonic current components in case of unbalanced three-phase loads authors will propose a structure composed by three single phase active filters. To begin is implemented the single-phase active filter which will be included in the structure of three-phase active filter for harmonic compensation of unbalanced consumers. Using hysteresis control technique can achieve instant control between two limits, which impose offset signal to follow the estimated reference signal with some deviation estimated by choosing the loop bandwidth. The proposed scheme is implemented with hysteresis current controller with fixed band. To obtain a compensated current with a current ripple as low as possible, the value of hysteresis band should be small. This will lead to high switching frequencies and increasing the switching losses. Advantages of using hysteresis current control are excellent dynamic performance and the ability to control the amount of peak to peak ripple current in specified hysteresis bandwidth. To estimate the reference current the Instantaneous Reactive Power Extension Theorem was used because this theorem is suitable for single - phase active filter control. For testing the command and control strategy was used a single - phase voltage source inverter (full bridge). Using Matlab / Simulink was simulating the active filter model. After connecting of active filter, in point of common coupling, voltage source and current drawn from power supply have sinusoidal variation, are in phase and voltage and current total harmonic distortion is lower than permissible level of disturbances.**

Keywords - *hysteresis current control, active filter, voltage source inverter*

I. INTRODUCTION

Power quality is a responsibility for both the electricity supplier provider and its consumer. In most cases, the consumer of electricity is responsible for altering the power quality in the point of common coupling (PCC). Regarding power quality issues, harmonics has a significant weight, because much of the industrial consumers (over 60% of installed power at industrial consumers) contain non-linear loads, electric motor and static power converter systems [2], [12], [13]. One of the harmonics mitigation methods is to use active filter, which have a static frequency converter component. So, the use of static converters in variable speed drives, on the one hand leads to harmonics, but on the other hand these devices are used to harmonics mitigation.

Power static converters, used to the active systems for harmonics mitigation [14], [16], can be current source inverter or voltage source inverter. The last type of structure is the most commonly used in practical applications.

II. STRATEGIES FOR COMMAND AND CONTROL

The aim of active filters control is to generate signals for switching power devices in accordance with the estimated reference signal. Active filter performances are significantly influenced by the choice of control techniques. For active filter applications can specify a variety of control techniques: linear control [9], the hysteresis control [3], [6], [10], digital deadbeat control [7], [11].

Hysteresis technique assumes instantaneous control between two limits, which require the offset signal, current i_f or voltage u_f, expected to follow the reference signal ($i_{f,\,ref}$ or $u_{f,\,ref}$) with some deviation imposed by the choice of hysteresis band width. Control scheme is illustrated by block diagram in Fig. 1.

This control technique requires a deviation H of a reference signal $i_{f,ref}$ or $u_{f,ref}$, which determine the upper and lower limits of the hysteresis band. Output signals, i_f or u_f, are measured and compared with its reference value $i_{f,ref}$ or $u_{f,ref}$, the resulting error is applied to a controller with a changeover relay. This generates control signals for power switching devices, when the lower (estimated reference - H / 2) or upper (estimated value of reference + H / 2) limit are exceeded. As long as the error is in the hysteresis band, power switching devices will not be switched. Switching occurs when the error is outside the hysteresis band. Active filter is controlled so that the peak to peak value of the compensation signal, current or voltage is limited to specified hysteresis band H.

The proposed scheme is implemented with hysteresis current controller with fixed band H. To obtain a compensated current i_f with a current ripple as low as possible, the value of H should be small. This will lead to high switching frequencies and increasing the switching losses.

Advantages of using the hysteresis current control are excellent dynamic performance and the ability to control the peak to peak value of current ripple in the specified hysteresis band [15]. Implementation of this control technique is simple, which results from the controller structure in Fig. 4. However, the hysteresis control has several unsatisfactory features. The main disadvantage is that results in a variable switching frequency.

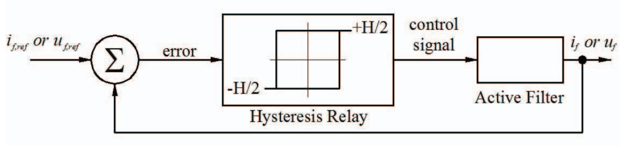

Fig. 1. Block diagram of hysteresis control technique: RBH-changeover hysteresis relay.

On the other hand, irregular switching may affect the efficiency and reliability of active filter.

III. REFERENCE CURRENT ESTIMATION

In case of the active systems for harmonic compensation, the shunt active filter, made with a voltage source inverter, the solution currently meets most of the advantages and has the fewest disadvantages. Considering the block diagram, shown in Fig. 2, we can write the relation between the currents in PCC:

$$i_s = i_L - i_f = i_{L,1} + i_{L,h} - i_{L,h} = i_{L,1} \tag{1}$$

where $i_{L,1}$ is the fundamental current component and harmonic current components $i_{L,h}$ of load current.

Active filter goal is to obtain a sinusoidal current drawn from the source [17] based on (1).

Reference current estimation, can be achieved especially using harmonic analysis in frequency or time domain. If in the first case can using Fourier Transform, for harmonic analysis, in the second case can successfully using Instantaneous Reactive Power Theory, developed by Akagi [1], [4], [5], [8].

For cases, when the active filter is used in single-phase networks, e.g. in the case where energy is used and supplied by a photovoltaic panel, the reference current estimation is accomplished using the extension of instantaneous reactive power theory. Thus, in the case of nonlinear loads supplied from a single-phase grid the load input current can be expressed as:

$$i_L(t) = \sum_{N=1}^{\infty} \sqrt{2} \cdot I_{L,N} \sin(N \cdot \omega \cdot t + \varphi_N) \tag{2}$$

where φ_N is the phase angle of the Nth harmonic load current component

In normal conditions, the supply voltage is sinusoidal,

$$u_{PCC}(t) = \sqrt{2} \cdot U_{PCC} \cdot \sin(\omega t + \varphi_U) \tag{3}$$

where φ_U is the phase angle of supply voltage.

Therefore the instantaneous load active power [9] can be expressed with:

$$p_L(t) = u_{PCC}(t) \cdot i_L(t) = \overline{p}_L + \widetilde{p}_L, \tag{4}$$

and instantaneous load imaginary power has the following expression,

$$q_L(t) = u_{PCC}'(t) \cdot i_L(t) = \overline{q}_L + \widetilde{q}_L. \tag{5}$$

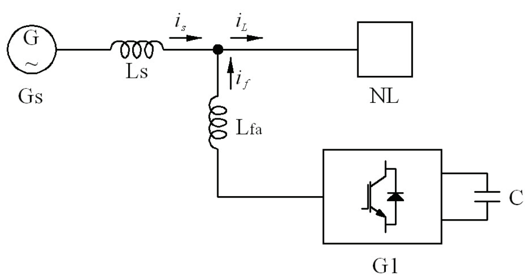

Fig. 2. Block diagram of active filter with voltage source inverter.

$\overline{p}_L$, $\overline{q}_L$ are the DC components, $\widetilde{p}_L$, $\widetilde{q}_L$ are the AC components, and $u'_{PCC}(t)$ is the supply voltage in PCC delayed by 90^0,

$$u'_{PCC}(t) = \sqrt{2} U_{PCC} \sin\left(\omega t + \varphi_U - 90^0\right). \tag{6}$$

Substituting (2) and (3) in (4) can write the AC and DC components of instantaneous active power:

$$\begin{aligned} \overline{p}_L &= U_{PCC} \cdot I_{L,1} \cdot \cos(\varphi_U - \varphi_1) - \\ &- U_{PCC} \cdot I_{L,1} \cdot \cos(2 \cdot \omega \cdot t + \varphi_U + \varphi_1) \end{aligned} \tag{7}$$

$$\widetilde{p}_L = \sum_{N=2}^{\infty} 2 \cdot U_{PCC} \cdot I_{L,N} \cdot \sin(\omega \cdot t + \varphi_U) \cdot \sin(N \cdot \omega \cdot t + \varphi_N) \tag{8}$$

Substituting (2) and (6) in (5) can write expression of DC and AC components of instantaneous load imaginary power,

$$\begin{aligned} \overline{q}_L &= U_{PCC} \cdot I_{L,1} \cdot \sin(\varphi_U - \varphi_1) - \\ &- U_{PCC} \cdot I_{L,1} \cdot \sin(2 \cdot \omega \cdot t + \varphi_U + \varphi_1) \end{aligned} \tag{9}$$

$$\widetilde{q}_L = -\sum_{N=2}^{\infty} 2 \cdot U_{PCC} \cdot I_{L,N} \cdot \sin(\omega \cdot t + \varphi_U) \cdot \sin(N \cdot \omega \cdot t + \varphi_N) \tag{10}$$

Load current components, active $i_{L,p}$, imaginary $i_{L,q}$ and harmonic $i_{L,h}$, are calculated by

$$i_{L,p}(t) = \sqrt{2} \cdot \frac{\overline{p}_L}{U_{PCC}} \cdot \sin(\omega \cdot t) \tag{11}$$

$$i_{L,q}(t) = \sqrt{2} \cdot \frac{\overline{q}_L}{U_{PCC}} \cdot \sin(\omega \cdot t - 90^0) \tag{12}$$

$$i_{L,h}(t) = i_L(t) - i_{L,p}(t) - i_{L,q}(t) \tag{13}$$

Compensation current reference is expressed with following relation:

$$i_{f,ref} = i_{L,q} + i_{L,h} - I_{C2} \cdot \sin(\omega \cdot t) \tag{14}$$

where I_{C2} is the RMS value of the capacitor charging current, from DC bus voltage of the voltage source inverter.

IV. ACTIVE FILTER MODEL AND SIMULATION

The active filter model is implemented using the software Matlab \ Simulink.

Fig. 3 shows the block diagram of model, and consists of: power supply, nonlinear load, active filter command and control, signals acquisition and signals measurements.

A. Block "Active Filter"

"Active filter" block is represented in Fig. 4 and consist in a voltage source inverter, a coupling coil L3 and a capacitor C2, in DC bus circuit.

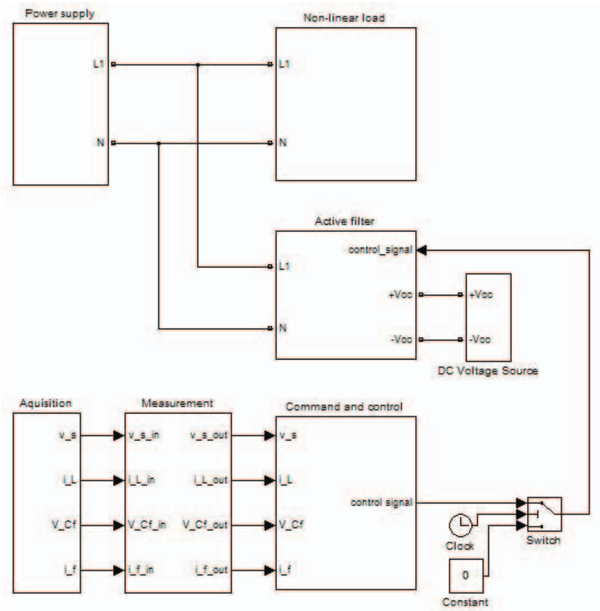

Fig. 3. Block diagram of active filter model.

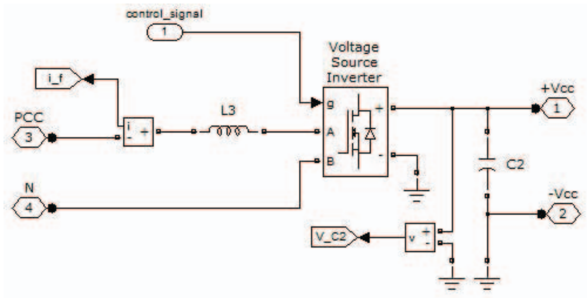

Fig. 4. Voltage source inverter model.

DC bus reference voltage U_{C2} used for simulation is set to the value of 350 V, a value of about 1.5 times higher than the power supply voltage. The maximum values of frequency switching ripple, $f_{sw,max}$, and peak to peak ripple, $\Delta I_{sw,p-p}$, of switching current generated by the inverter are selected to be 10 kHz and 1 A. The minimum value of inductance L3 can be determined as 17 mH and for capacity C2 of 4700 µF.

B. Active Filter Command and Control Block

At the output of control block (Fig. 5) it should generate control signals for power electronic devices. It consists of four blocks as follows: "Reference sine generator", "Reference current estimation", "DC bus voltage regulator" and "Hysteresis current control".

C. Reference Sine Generator Block

On output, the block (Fig. 6) generates two sinusoidal signals with equal amplitude and in phase with the supply voltage at PCC. To remove high frequency noise and zero crossing frequency higher than the fundamental was used a second order discrete low pass filter with cutoff frequency set at 100 Hz.

D. Reference Current Estimation Block

The input signals, power supply voltage in PCC and current drawn by the load is filtered to remove noises with discrete filters (Fig. 7). Their cut-off frequency is set to 2 kHz.

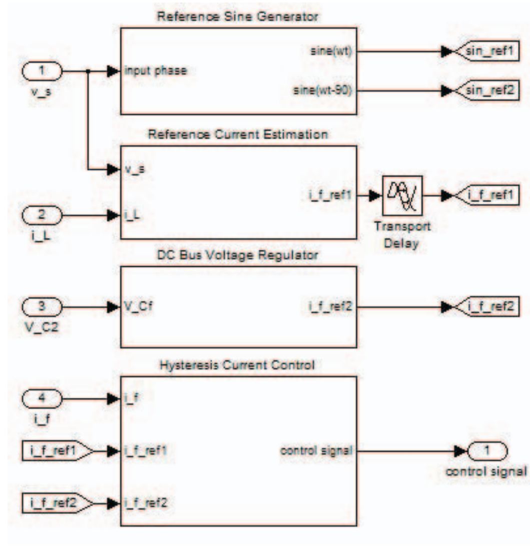

Fig. 5. Active filter command and control block.

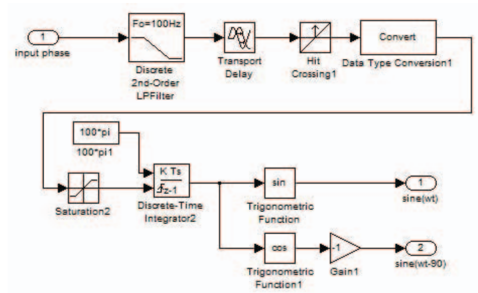

Fig. 6.Reference sine generator block.

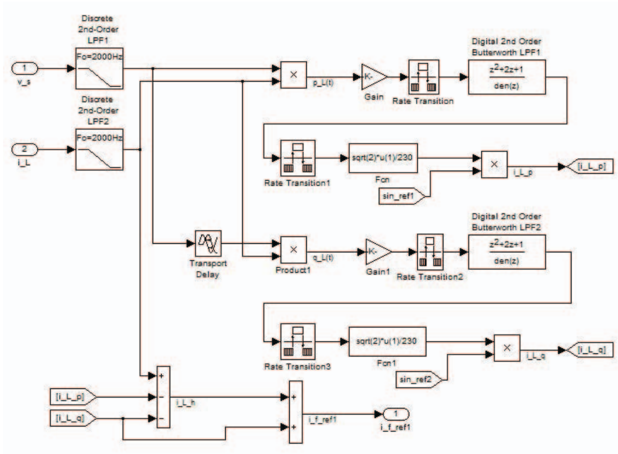

Fig. 7. Reference current estimation block.

E. Hysteresis Current Control Block

Hysteresis control technique requires instant control based on changeover relay (Fig. 8), which forces the estimated compensation reference current to follow the reference current. Resulting error is applied to changeover relay to generate control signals for power switching devices. As long as the error is in the imposed hysteresis bandwidth of the loop the output active filter current may increase or decrease depending on the previous state of power devices, blocked or in conduction. When the difference reaches selected hysteresis thresholds the power devices, which was in conduction, are turned-off, and others two, which was blocked, are in conduction.

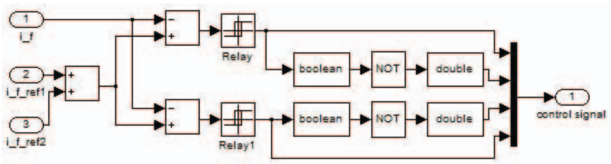

Fig. 8. Hysteresis current control block.

For model simulation the hysteresis bandwidth is set to a value of 1 A.

V. Active Filter Simulation

Waveform of voltage supply in PCC is shown in Fig 9. This have a sine variation with a THD about 0.1 %, and the RMS value of the voltage is 229.9 V.

The waveform of the current drawn by non-linear loads in the absence of active filter is shown in Fig. 10. Harmonic analysis put in evidence distortion of the current waveform, with THD about of 84.87%, and the RMS value of the current is 20.83 A.

At the output of “Reference sine generator” block wave forms obtained are shown in Fig. 11. It is noted that the reference sine waveforms have amplitude equal to unity and *sin*(ω*t*) is in phase with the source voltage, and *sin*(ω*t*-90^0) lags with 90^0.

“Reference current estimation” block generate the estimated reference current used for harmonic compensation (Fig. 12). Fig. 13 presents the waveforms of active and reactive current components. These have sine variations and phase shifted with 90^0.

Hysteresis current control of the active filter means to generate appropriate control signals for the power devices so that the current output from the active filter to follow the estimated current reference (Fig. 14).

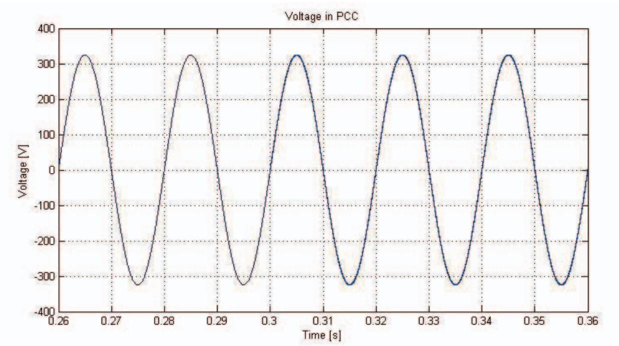

Fig. 9. Waveform of voltage in PCC.

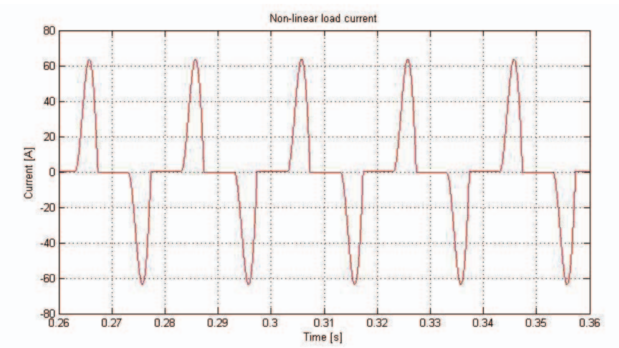

Fig. 10. Non-linear load current.

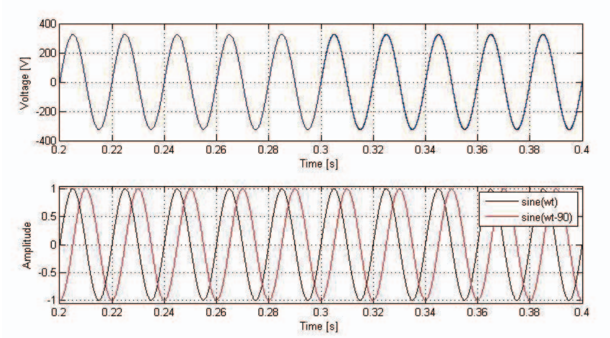

Fig. 11. Reference sine waveforms.

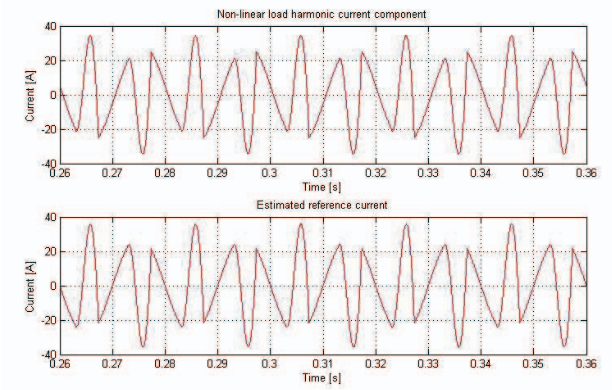

Fig. 12. Harmonic component of the non-linear load and estimated reference current.

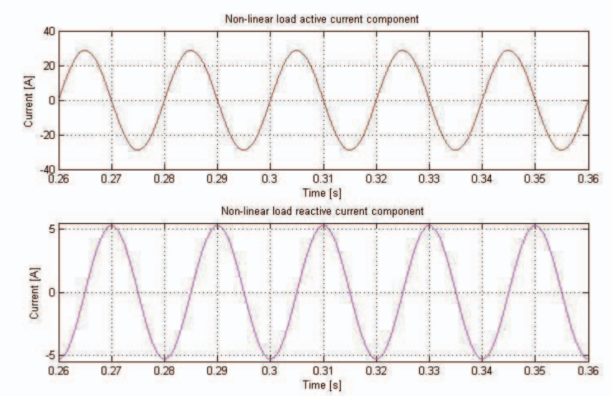

Fig. 13. Active and reactive load current components.

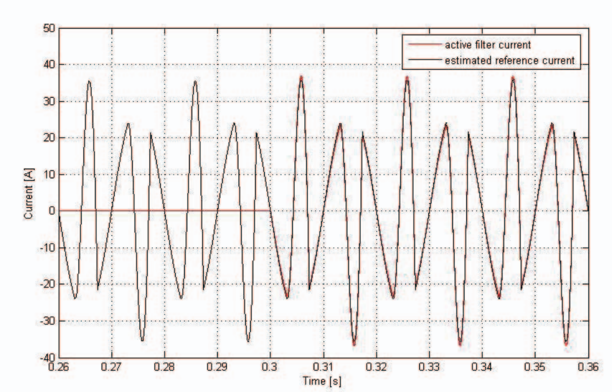

Fig. 14. Estimated reference current and current generated by active filter.

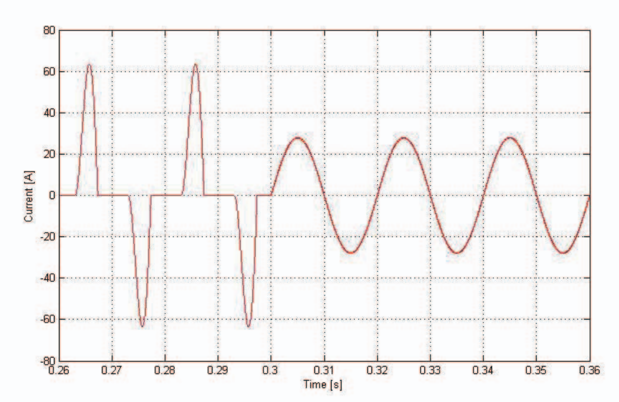

Fig. 15. Waveform of current drawn by the load after active filter operation.

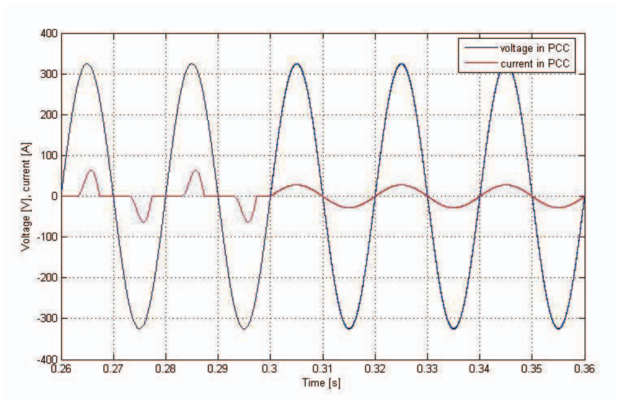

Fig. 16. Waveforms of voltage and current in PCC before and after active filter operation.

Active filter is in operation at time t = 0.3 s.

The waveform of voltage at the PCC and current drawn from the power supply after active filter operation is shown in Figs. 15 and 16.

It is noted that the voltage in PCC is sinusoidal, bold line appears due to the presence of switching ripple and total harmonic distortion factor of voltage increases to 0.3%, which is lower than the permissible values. From the harmonic analysis of current waveform drawn from the source is observed that the total current distortion factor is lower and the value is 0.45%.

VI. CONCLUSION

Using the hysteresis command technique can realize instant control between two limits, which impose the generated current to follow the estimated reference current with some deviation estimated by choosing the loop bandwidth. Advantages of using hysteresis current control are excellent dynamic performance and the ability to control the value of peak to peak current ripple in specified hysteresis band and the implementation of this control scheme is simple.

After connecting the active filter in the PCC, voltage source and the current drawn from the power supply have a sinusoidal variation and are in phase. Harmonic analysis highlights the voltage THD of 0.3 % and current THD of 0.45%, lower than permissible level value of disturbances.

REFERENCES

[1] H. Akagi, E.H. Watanabe, M. Aredes, *Instantaneous Power Theory and Applications to Power Conditioning*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.

[2] A. Baggini, et. all, *Handbook of Power Quality*, John Wiley & Sons, Ltd, 2008.

[3] T. Benslimane, K. Aliouane, and B. Chetate, “Implementation of a New Hysteresis Control Strategy for Autonomous Parallel Active Filter”, *International Journal of Emerging Electric Power Systems*, vol. 4, 2005.

[4] L. S. Czarnecki, “Instantaneous Reactive Power p-q Theory and Power Properties of Three-phase Systems”, *IEEE Trans. on Power Delivery*, vol. 21, no 1, pp. 362-367, Jan. 2006;

[5] M. Depenbrock, V. Staudt, and H. Wrede, “Concerning Instantaneous Power Compensation in Three-phase Systems by using p-q-r Theory”, *IEEE Trans. on Power Electronics*, vol. 19, no. 4, pp. 1151-1152, 2004.

[6] B. Dobrucky, H. Kim, V. Racek, M. Roch, and M. Pokorny, “Single-Phase Power Active Filter and Compensator using Instantaneous Reactive Power Method”, in *Proc. of the Power Conversion Conference* (*PCC*), IEEE 2002, pp. 167-171, April 2002.

[7] S.I. Hamasaki, A. Kawamura, “A Novel Method for Active Filter Current Regulation using Deadbeat Control”*, Electrical Engineering in Japan*, vol. 145, Issue 2, pp. 67-77, 2003.

[8] R.S. Herrera, P. Salmeron, and H. Kim, “Instantaneous Reactive Power Theory Applied to Active Power Filter Compensation: Different Approaches, Assessment, and Experimental Results,” *IEEE Trans. on Industrial Electronics*, vol. 55, no. 1, pp. 184-196, Jan. 2008.

[9] Y. Komatsu, “Application of the Extension p-q Theory to a Mains-Coupled Photovoltaic System”, in *Proc. of the Power Conversion Conference* (*PCC*), IEEE 2002, pp. 816-821, April 2002;

[10] P. L. Leow and A.A. Naziha, “SVM Based Hysteresis Current Controller for a Three Phase Active Power Filter”, in *Proc. of the IEEE International Conference on Power and Energy Conference* (*PECon*), IEEE 2004, pp. 132-136, Nov. 2004.

[11] K. Nishida, M. Rukonuzzman and M. Nakaoka, “Advanced Current Control Implementation with Robust Deadbeat Algorithm for Shunt Single-Phase Voltage-Source Type Active Power Filter”, in *Proc. IEE Electric Power Applications*, vol. 151, no. 3, pp. 283-288, 2004.

[12] D. D. Micu, L. Czumbil, G. Christoforidis, A. Ceclan and Olivia Miron, “User friendly EMI software for induced A.C. potential evaluation”, *The 8th International Conference on Computation in Electromagnetics*, CEM 2011, 11-14 April 2011, Wroclaw, Poland, pp. 34-38.

[13] D. D. Micu, L. Czumbil, and G. Christoforidis, “Layer Recurrent Neural Network Solution for an Electromagnetic Interference Problem”, in *IEEE Transaction on Magnetics*, volume: 47, Issue: 5, May 2011, pp. 1410-1414, ISI Journal Digital Object Identifier 10.1109/TMAG.2010.2091494.

[14] Anca Miron, M. Chindriş and A. Cziker, “Impact of Unbalance in Harmonic Polluted Power Networks”, Session TB1, paper EPQ0035, in *Proceedings of 21st International Symposium on Power Electronics, Electrical Drivers, Automation and Motion, SPEEDAM* 2012, June 20 – 22 2012, Sorrento, Italia, IEEE Catalog Number: CFP1248A – CDR, ISBN: 978 – 1 – 4673 – 1300 – 1.

[15] M. A. M. Radzi and N. A. Rahim, “Neural Network and Bandless Hysteresis Approach to Control Switched Capacitor Active Power Filter for Reduction of Harmonics,” *IEEE Trans. on Industrial Electronics*, vol. 56, no. 5, pp. 1477-1484, May 2009.

[16] M.H. Rashid, *Power Electronics Handbook*, Academic Press, 2001.

[17] P.C. Tan, A. Jusoh and Z. Salam, “A Single-Phase Hybrid Active Power Filter Connected to a Photovoltaic Array, in *Proc. of the International Conference on Power Electronics, Machines and Drives* (*PEMD*), IEE 2006, pp. 85-89, April 2006.