Three-Level Shunt Active Filter Compensating Harmonics and Reactive Power

L. Zellouma and S. Saad

Laboratoire des Systèmes Electromécaniques,
University of Badji Mokhtar-Annaba-Algeria
Emails: saadsalah2006@yahoo.fr, zellouma13@yahoo.fr

***Abstract* — In this paper, the three-level inverter is used as a shunt active power filter, making use of the multilevel inverter advantages of better total harmonic distortion, reduced semiconductor switches ratings and reduced switching losses. This inverter is based on typical PWM and is employed as active powers filter (APF) used to compensate reactive power and suppress harmonics drawn from a nonlinear load. Most previously reported three-phase active power filters are based on two-level inverters, which are suitable for low voltage systems.**

In this paper, topologies and control schemes are proposed for three-level three-phase active power filters.

The paper presents the principles of operation and design criteria for both the power and control circuits. Finally, the viability of the proposed scheme is validated with computer simulation using Matlab. The obtained results showed that source current is sinusoidal and in phase with source voltage. The proposed solution has achieved a low total harmonic distortion demonstrating the effectiveness of the presented method.

***Keywords* — Multilevel inverter, Harmonics and reactive power compensation, PWM control, Shunt active power filter.**

1. INTRODUCTION

Active power filter implemented with two levels voltage source inverters have been widely studied and used to eliminate harmonics and compensate reactive power [1-2]. Due to power handling capabilities of power semi-conductors these active power filters are limited in medium power applications. Hybrid topologies shunt passive filter and series active filter were proposed to achieve high power filters [3].

Recently, there has been an increasing interest in using multilevel inverters for high power drives and reactive power and harmonics compensation [4-10]. Multilevel pulse width modulation inverters can be used as active power filter for high power applications solving the problem of power semiconductor limitation.

The use of neutral-point-clamped (NPC) inverters allows equal voltage shearing of the series connected devices in each phase.

This paper presents an active power filter implemented with a three level NPC voltage source inverter. The proposed current control and DC capacitor voltage control schemes are simple to implement.

The PWM technique is employed to generate the inverter switching signals and *p-q* theory [11, 12] for harmonic current identification. MATLAB power system blocks are used to carry out the simulation work.

2. DESCRIPTION OF THE APF TOPOLOGY

Fig.1, describes the structure of the proposed APF based on a three-phase three-level voltage inverter. The diodes are used to make the connection with the point of reference O to obtain Midpoint voltages. In order to produce a voltage of N-Levels, N-1 capacities are required. The voltage across each condenser is equal to E/(N-1), E is the total voltage of the DC source. Each couple of switches (S_1, S_3) form a cell of commutation, the two switches are ordered in a complementary way.

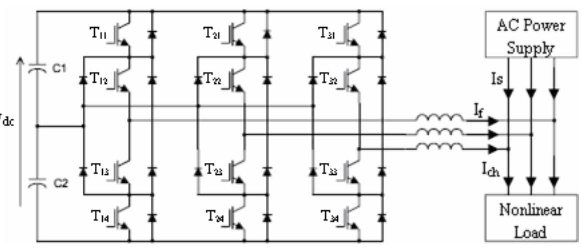

Fig.1. Active power filter operation

The inverter provides three voltage levels according to (1):

$$Vio = Ki \cdot E/2 \qquad (1)$$

Where *Vio* is the phase-to-middle fictive point voltage, *Ki* is the switching state variable (*Ki* = 1, 0, -1), *E* is the DC source voltage, and *i* is the phase index (*i = a, b, c*). The three-level voltages are shown in Table 1 (E/2, 0, -E/2).

TABLE 1: OBTAINING OF THREE-LEVEL INVERTERS

Ki	Ti1	Ti2	Ti3	Ti4	*Vio*
1	1	1	0	0	*E*/2
0	0	1	1	0	0
-1	0	0	1	1	-*E*/2

The phase-to-neutral point voltage V_{in} is linked to *Vio* via:

$$V_{in} = V_{io} - V_{no} \qquad (2)$$

Assuming that the system is balanced, then:

$$V_{an} + V_{bn} + V_{cn} = 0 \quad (3)$$

By substituting (3) in (2), the equation presented below is obtained:

$$V_{no} = \frac{1}{3}\left(V_{ao} + V_{bo} + V_{co}\right) \quad (4)$$

The expressions of instantaneous inverter phase output voltages are obtained by replacing (4) in (2):

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ -1/3 & 2/3 & -1/3 \\ -1/3 & -1/3 & 2/3 \end{bmatrix} \cdot \begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix} \quad (5)$$

The line to line voltages are determined by the following equation:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} V_{ao} \\ V_{bo} \\ V_{co} \end{bmatrix} \quad (6)$$

3. REFERENCE CURRENT CALCULATION

Several methods were proposed for the identification of the harmonic current references. Mainly, the methods based on the FFT (Fast Fourier Transformation) in the frequency domain and the methods based on instantaneous power calculation in the time domain. In this study, the *p-q* theory method is used allowing the compensation of harmonic currents, reactive power and unbalanced currents.

The reference currents (harmonic currents) identification is based on α-β transformation to obtain real and imaginary powers.

The voltages (V_{S1}, V_{S2}, V_{S3}) and currents (I_{S1}, I_{S2}, I_{S3}) are transformed to bi-phase system according to the following equation:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \quad (7)$$

The instantaneous active and reactive powers of the system are calculated as follows:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{pmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{pmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (8)$$

Instantaneous powers are composed from a constant part and a variable part corresponding to fundamental and harmonic currents respectively.

$$\begin{bmatrix} I_{h\alpha} \\ I_{h\beta} \end{bmatrix} = \frac{1}{V_{s\alpha}^2 + V_{s\beta}^2} \begin{bmatrix} V_{s\alpha} & -V_{s\beta} \\ V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (9)$$

4. HARMONIC CURRENTS CONTROL USING PWM

This control implements initially a proportional controller which starts from the difference between the injected current (active filter current) and reference current (identified current) that determines the reference voltage of the inverter (modulating wave). This standard reference voltage is compared with two carrying triangular identical waves shifted one from other by a half period of chopping.

The control of inverter arm constituting the filter is summarized in the two following stages.

- Determination of the intermediate signals V_{i1} and V_{i2}.

If error ≥ carrying 1 => $V_{i1} = 1$
If error < carrying 1 => $V_{i1} = 0$
If error ≥ carrying 2 => $V_{i2} = 0$
If error < carrying 2 => $V_{i2} = -1$

- Determination of control signals of the switches Tij (j = 1, 2, 3, 4).

If $(V_{i1} + V_{i2}) = 1$ => $T_{i1} = 1$, $T_{i2} = 1$, $T_{i3} = 0$, $T_{i4} = 0$
If $(V_{i1} + V_{i2}) = 0$ => $T_{i1} = 0$, $T_{i2} = 1$, $T_{i3} = 1$, $T_{i4} = 0$
If $(V_{i1} + V_{i2}) = -1$ => $T_{i1} = 0$, $T_{i2} = 0$, $T_{i3} = 1$, $T_{i4} = 1$

The general block diagram of control currents is illustrated in Fig.2.

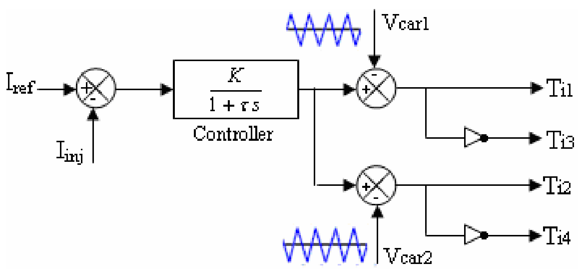

Fig.2. PWM synoptic block diagram of currents control

5. DC CAPACITOR VOLTAGE CONTROL

The capacitors (*C1* and *C2*) average voltage (*Vdc1, Vdc2*) has to be maintained at a fixed value. The main cause of its variation is the active filter switching losses and output filter.

To ensure inverter permanent and continuous voltage supply, a controlled scheme is adopted as illustrated in Fig.3.

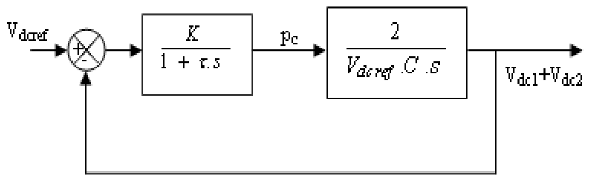

Fig.3. Dc voltage control block.

6. SIMULATION

The simulation is carried out using a program working in MATLAB Simulink environment. The simulation parameters are shown in table.2, presented below.

TABLE 2: SIMULATION PARAMETERS

Supply: V_s, R_s, L_s	220 V, 0.01Ω, 0.1 mH.
DC Load: R_{DC}, L_{DC}	0.5Ω, 0.3 mH.
Active Filter: E, L_f, C_1,C_2	1000 V, 0.2mH,3μF, 3μF
I_{ref} Calculation : f_o	65 HZ
Switching frequency	10 K HZ

The obtained switching signals of the three-phase three-level inverter are shown in the Fig.4.

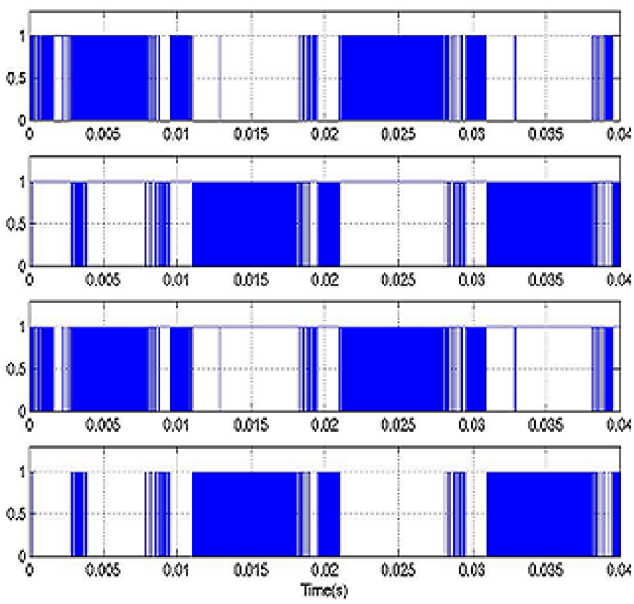

Fig. 4. Switching pulses of APF arm (S11, S12, S13, , S14)

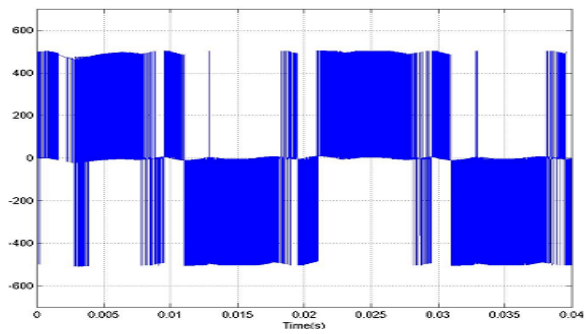

Fig. 5. APF output voltage Vao.

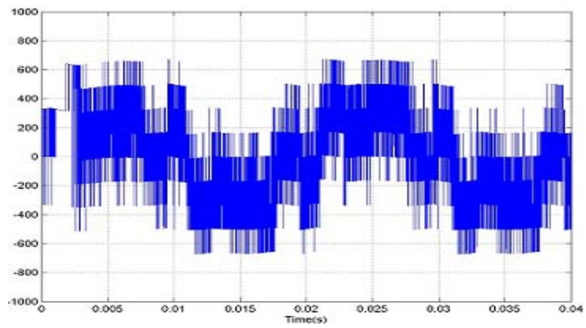

Fig. 6. APF output voltage Van.

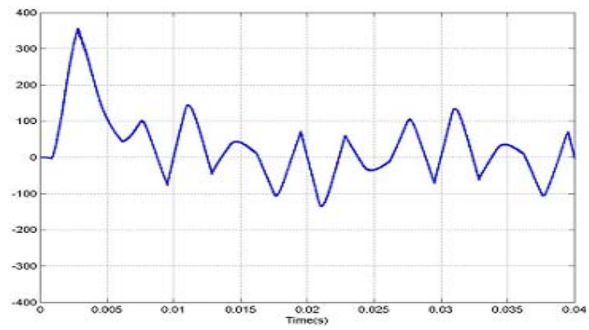

Fig. 7. Active filter current *If*.

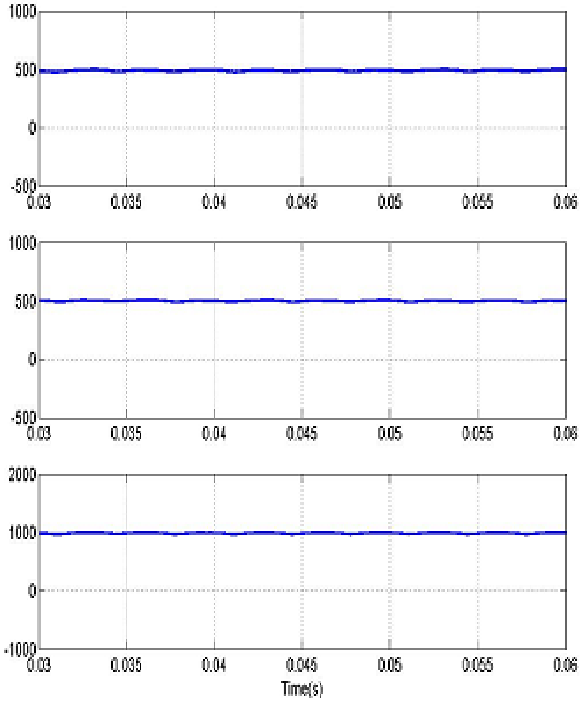

Fig. 8. DC voltage of the condensers
(V_{dc1}, V_{dc2} and Total V_{dc})

The load current obtained by simulation before the use of active filter is illustrated in Fig.9. This current is highly distorted and its THD calculated from the frequency spectrum shown in Fig.10 is equal to 15.66%.

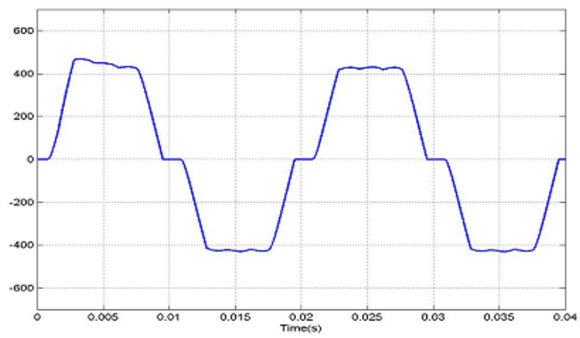

Fig. 9. Supply current *Is* waveform before filtering

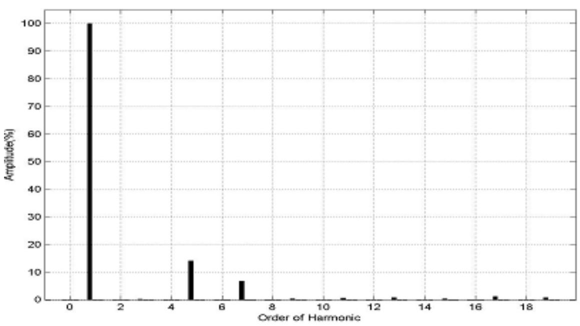

Fig. 10. Source current spectrum without filter

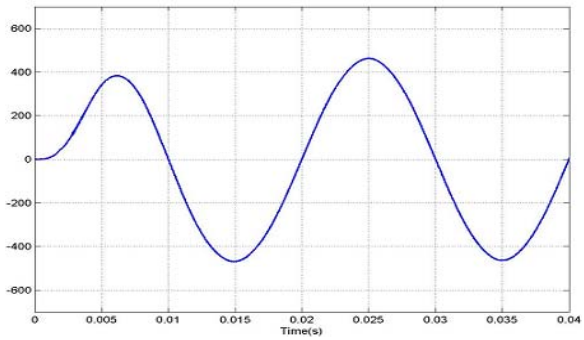

Fig. 11. Supply current *Is* waveform after filtering

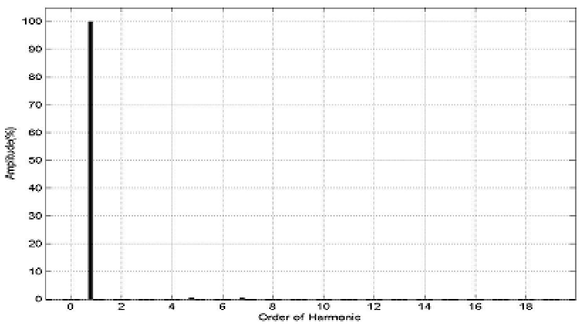

Fig. 12. Source current spectrum with filter

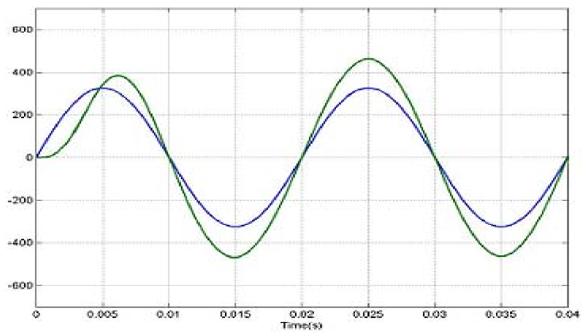

Fig.13. Power factor correction (*Vs, Is)*

7. RESULTS AND DISCUSSIONS

Three-level shunt active power filter performances are related to current references quality, *p-q* theory is used for harmonic currents identification and calculation the obtained current is shown in Fig.7. This method is very important; it allows harmonic currents and reactive power compensation simultaneously, the obtained current and voltage waveforms are in phase as illustrated in Fig.13.

Fig.8 shows the results of the DC voltage V_{dc1} and V_{dc2} across the capacitors C_1 and C_2 controlled by P controller, the obtained total V_{dc} voltage in constant showing the efficiency of the controlled scheme.

Compared with the standard two-level inverter voltage waveform, from Fig.6 it can be concluded that the three-level inverter contains less harmonic contents. The three level voltages are: 333.33 V, 500 V, and 666.66 V, corresponding respectively to $V_{dc}/3$, $V_{dc}/2$, and $2\ V_{dc}/3$, the DC voltage source (V_{dc}) is 1000V.

The three level active filter has imposed a sinusoidal source current waveform instantaneously as illustrated in Fig.11. The current THD is reduced from 15.66% to 1.3% as shown in the frequency current spectrum of Fig.11 and 12, respectively.

CONCLUSION

A theoretical study with simulatin of three-level shunt active power filter controlled with the PWM modulation was presented and analysed in this paper. The three-level APF provides numerous advantages such as improvement of the supply current wave form, less harmonic distortion and its use in high power/medium voltage with a lower maximum device rating. The effectiveness of the proposed scheme is proved by simulation using MATLAB.

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