Power quality improvement using Hardware Implementation of PI Controlled Three-Phase Shunt Active Power Filter

ISMAIL Ghadbane , MOHAMED TOUFIK Benchouia

***Abstract*— The** simulation and experimental study of Proportional Integrator controlled DC bus voltage of three phase shunt active power filter (APF), to improve power quality by compensating harmonics and reactive power required by nonlinear load is proposed. The algorithm used to identify the reference currents is based on the Self Tuning Filter (STF). PWM signal generation is based on hysteresis control comparators to obtain the switching signals. Various simulation and experimental results show the feasibility and the effectiveness of the designed active filter

***Keywords*—**Harmonics, shunt active filter, Proportional Integrator, total harmonic distortion

I. Introduction

The standard norms imposed by utilities force the users to comply with the harmonics injected into the network. Also, an adequate reactive power support is important to improve the electrical grid stability. As it has been observed for recent decades, an increasing part of the generated electric energy is converted through rectifiers, before it is used at the final load. In power electronic systems, especially, diode and thyristor rectifiers are commonly applied in the front end of DC-link power converters as an interface with the AC line power (grid)

Some of the power quality problems can be solved by utilizing shunt active power filters [1]-[11]. However, the cost of shunt active filters is relatively high and they are not preferable for a large-scale system since the power rating of the shunt active filter is directly proportional to the load current to be compensated [12]-[21]. In addition, their compensation performance is better only under current harmonics type of loads than the voltage harmonics type. To reduce the system cost, a shunt hybrid power filter has been proposed and used [22]-[25]. Power electronics devices have been widely used in recent years; while they are convenient in use they cause several power pollutions just like electrical harmonics and low power factor. In high power systems, most electrical devices use three-phase symmetrical power system. But in medium and small power system, single-phase electronic equipments are widely used in domestic, educational and commercial appliances, such as computers, communication equipments and electronic lighting ballasts, etc.

This work was supported in part by the Electrical Engineering laboratory, Research center, university of Biskra, 7000 Algeria.

I Ghadbane is with the Electrical Engineering laboratory, Research center, university of Biskra, 7000 Algeria.
(ghadbanetech@gmail.com).
B. M.Toufik is with the Electrical Engineering laboratory, Research center, university of Biskra, 7000 Algeria.
(benchouiat@yahoo.fr).

These equipments normally have a diode rectifier to convert ac electricity to dc and filter by a huge capacitor.. These equipments behave like nonlinear loads, generating harmonics and cause electromagnetic compatibility problems. For the devices with an alternative input such as: rectifiers, Ac voltage controllers, indirect frequency converters..., the wave shape of the absorptive current of the network is non-sinusoidal. In addition to the fundamental component, this waveform presents harmonic contents which are, in certain cases, very important. These harmonics are propagated from the load towards the network and generate harmonic voltage drops which are added to the fundamental component of the voltage delivered by the network. The result is a form of affected wave, which contains also of harmonic contents; this affected wave can, as mentioned before, cause serious problems of electromagnetic compatibility. Many solutions have been studied in the literature to mitigate the harmonic problems, such as filtering (passive, active, and hybrid) with various topologies (shunt, series or both) [6] Industrial and domestic equipments actually use a large variety of power electronic circuits such as switch mode power converters, adjustable speed drives, rectifiers and dimmers. These ones lead to significant energy savings and productivity benefits. But unfortunately, they also present non-linear impedance to the supply network and destroying equipments and disturbances of communication equipments and precision instruments [1]. So, it is necessary to develop techniques to reduce all the harmonics as it is recommended in the IEEE 519-1992. The first approach consists in the design of LC filters. But, passive filters are not well adapted as they do not take into account the time variation of the loads and the network [1], [2]. They can also lead to resonance phenomena. The active power filter (APF) can solve the problems of harmonic and reactive power simultaneously. The theories and applications of active power filters have become more popular and have attracted great attention since two decades ago. Since its introduction some twenty years ago, the Active Power Filter APF presents a good solution for disturbance treatment, particularly for harmonic currents and/or voltages. APF is an up-to-date solution to power quality problems. The shunt APF allows the compensation of current harmonics and unbalance, together with the power factor correction, and can be a much better solution than the conventional approach (capacitors and passive filters)

The performance of the APF is determined by the kind of control used. It is more emphasized when the voltages of electrical network contain harmonics and/or are unbalanced. Moreover, the Self Tuning Filter STF is proposed for extracting harmonic currents instead of classical harmonics extraction based on High Pass or Low Pass Filters [4], [5]. The three phase currents/voltages are detected using current/voltage sensors. The inverter currents are controlled by using hysteresis comparators,. The hysteresis control is characterized by its simplicity and its intrinsic speed.. [1][3][7]

II. SYSTEM CONFIGURATION

fig.1 presents the shunt active filter topology based on a three-phase voltage source inverter, using IGBT switches, connected in parallel with the ac three-phase three-wire system through three inductors L_f. the capacitor c is used in the Dc side to smooth the Dc terminal voltage. the nonlinear load is a three-phase diode rectifier supplying a RL load. this load generates harmonic currents in the supply system. the proposed control strategy can be divided in two parts. the first part is the harmonic isolator (reference current generation). it consists in generating the harmonic current references and uses STF instead of HPF or LPF usually used in the classical instantaneous real and imaginary power theory, first proposed by H. akagi [5]. this harmonic isolator will be implemented into a DSPACE system (ds1104 prototyping card) in the experimental study.

the second part is the current control of the power converter. this controller generates the suited switching pattern to drive the igbts of the inverter by using a modulated hysteresis current controller. in the experimental study, this controller is implemented into an analogue card.

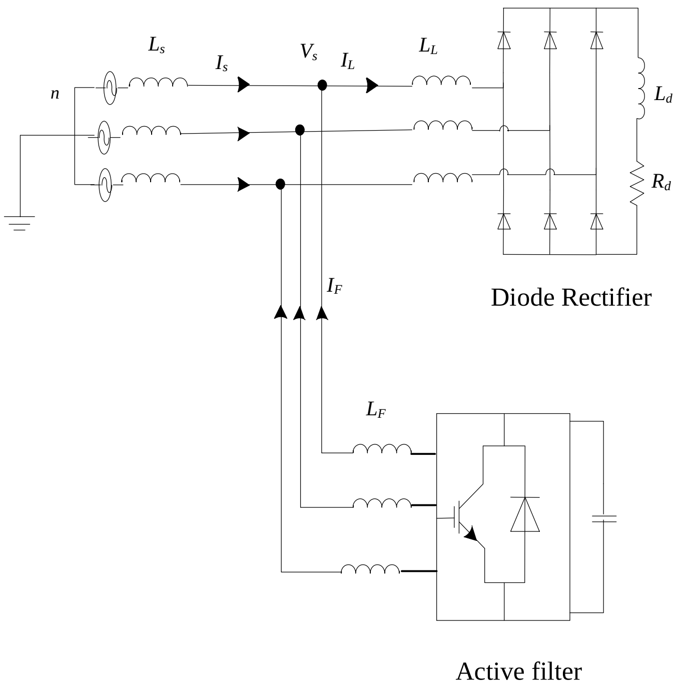


Fig 1. Power system configuration.

The proposed system configuration of a shunt active power filter is shows in Fig.2. Three-phase voltage source inverter using IGBT switches, connected in parallel with the AC three-phase three-wire system through three inductors Lf. The capacitor C is used as energy source. The capacitor is initially charged through the diodes of the inverter. The nonlinear load consists of a three-phase diode bridge rectifier feeding an R-L load. This load generates harmonic currents in the supply system. The proposed control strategy can be divided in three parts. The first part is the harmonic isolator (reference current generation). It consists in generating the harmonic current references using the STF. The identification method of harmonics used is the method of instantaneous power . This harmonic isolator will be implemented into a dSPACE system (dSPACE-1104 prototyping card) in the experimental. The second part is the current control of the power converter. The control generates the suited switching pattern to drive the IGBTs of the inverter using a hysteresis current controller. In the experimental study, the hysteresis controller is implemented on an analogue card developed in our laboratory. Finally The DC capacitor voltage is regulated using the SMC. The sliding surface is designed by imposing a desired dynamic behavior, which allows us to determine the parameters in designing the SMC.

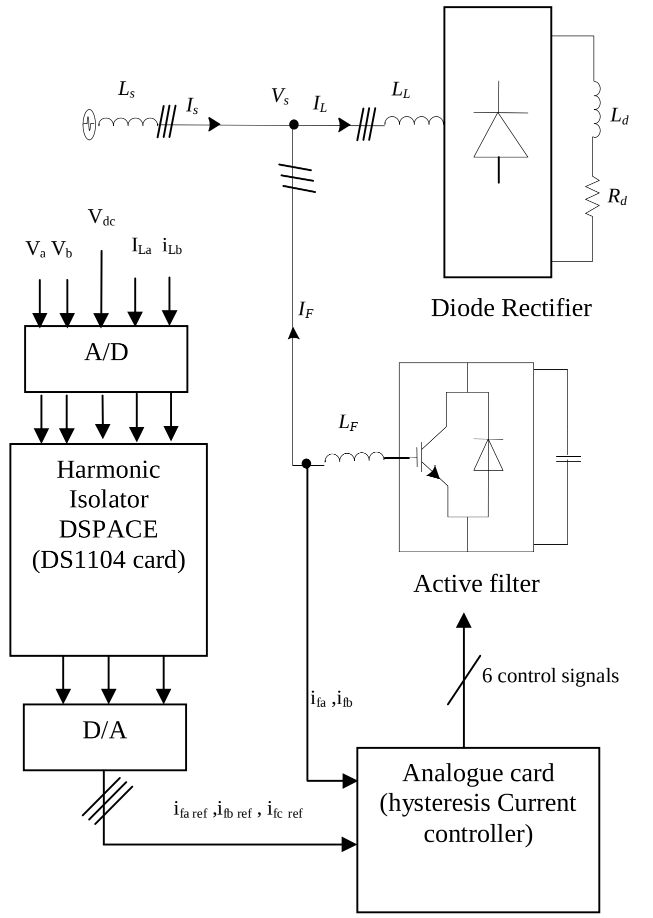


Fig 2. Experimental system

III-HARMONIC ISOLATION

Akagi [1] proposed a theory based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms called as Instantaneous Power Theory or Active- Reactive (p-q) theory which consists of an algebraic transformation (Clarke transformation) of the three-phase voltages in the a-b-c coordinates to the α-β coordinates, followed by the calculation of the p-q theory instantaneous power components by eliminating the DC component of the instantaneous active power (corresponding to the fundamental component of load current) using a selective Filter STF, so the harmonic components can be identified. Figure 3 shows the modified scheme for the identification of reference currents during simultaneous compensation of harmonic currents and reactive power using the method of instantaneous power by using STF

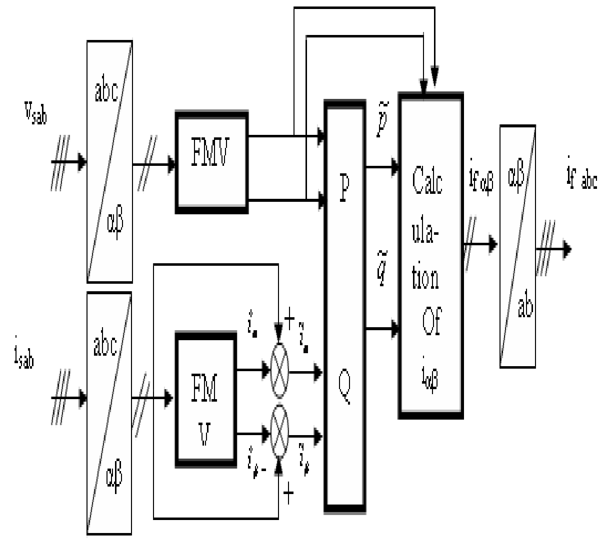


Fig. 3: The method of instantaneous active and reactive power

This method is based on measuring the instantaneous three-phase variables present on the grid with or without zero-sequence components. This method is valid both in steady-state phase. In this control algorithm (Figure 2), measurements of voltages and currents expressed as a three phase (abc) are converted to two-phase system (α-β) is equivalent to using the transform from Concordia leaving the power invariant:

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{LC} \end{bmatrix} \quad (2)$$

In the presence of harmonics, the power is composed of three parts: active (P), reactive (Q) and deformed (D) as shown by the following equation:

$$S = \sqrt{P^2 + Q^2 + D^2} \quad (3)$$

The instantaneous active power, denoted P (t) is defined by the following equation:

$$P(t) = v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} \quad (4)$$

Can be written in the stationary reference:

$$P(t) = v_{sa} i_{sa} + v_{sb} i_{sb} \quad (5)$$

Similarly the instantaneous imaginary power can be written as follows:

$$q(t) = -\frac{1}{\sqrt{3}} [(v_{sa} - v_{sb}) i_{lc} + (v_{sb} - v_{sc}) i_{la} + (v_{sc} - v_{sa}) i_{lb} = v_{sa} i_{lb} - v_{sb} i_{la} \quad (6)$$

Q power a broader meaning than the usual reactive power. In fact, Unlike the reactive power, which considers only the fundamental frequency, the imaginary power takes into account all the harmonic components of current and voltage is why it is given a different name (imaginary power) as a unit with the volt-ampere imaginary (VAI).

The part of the relations (5) and (6), we can establish the following matrix:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_{Sa} & v_{sb} \\ -v_{sb} & v_{Sa} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \quad (7)$$

n the general case, each of the powers p and q has a continuous part and part alternative, which allows us to write the following expression

$$\begin{cases} P = \overline{P} + \tilde{P} \\ q = \overline{q} + \tilde{q} \end{cases} \quad (8)$$

with: $\overline{P}$ Continuous power related to the fundamental component of active power and voltage, $\overline{q}$ Continuous power related to the fundamental component of reactive current and tension, $\tilde{p}$ *and* $\tilde{q}$ Powers of alternatives related to the sum of the components of disruptive current and voltage.
By inverting the relation (7), we can recalculate the currents in the coordinate α β as shown in Equation

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \frac{1}{v_{sa}^2 + v_{sb}^2} \begin{bmatrix} v_{sa} & -v_{sb} \\ v_{sb} & v_{sa} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (9)$$

Considering equations (8) and (9), we can separate the current benchmark in the three components, active and reactive at the fundamental frequency and harmonics.

Finally, it is easy to obtain the reference currents along the axes *abc* by the inverse transformation of Concordia

$$\begin{bmatrix} i^*{}_a \\ i^*{}_b \end{bmatrix} = \frac{1}{v_a^2 + v_b^2} \begin{bmatrix} v_a & -v_b \\ v_b & v_a \end{bmatrix} \begin{bmatrix} \tilde{P} \\ \tilde{q} \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} i^*{}_a \\ i^*{}_b \\ i^*{}_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*{}_a \\ i^*{}_b \end{bmatrix} \quad (11)$$

The self tuning filter is the most important part of this control which allows to make insensible the PLL to the disturbances and filtering correctly the currents in α-β axis.Hong-scok Song [6] had presented in his PhD work how recovered the equivalent transfer function of the integration expressed by The block diagram of the STF tuned at the pulsation ωc is shown in the figure 5. The transfer function of this filter is:

$$H(s) = \frac{\hat{i}_{ab}(s)}{i_{ab}(s)} = K \frac{(s+K) + jw_c}{(s+K)^2 + w_c^2} \quad (12)$$

According to the α-β axes, the expressions linking the components FMV output to input xαβ components are:

$$\hat{x}_a = \left(\frac{K}{s}[x_a(s) - \hat{x}_a(s)] - \frac{w_c}{s}\hat{x}_b(s)\right)$$
$$\hat{x}_b = \left(\frac{K}{s}[x_b(s) - \hat{x}_b(s)] - \frac{w_c}{s}\hat{x}_a(s)\right) \quad (13)$$

We obtain the following block diagram for STF

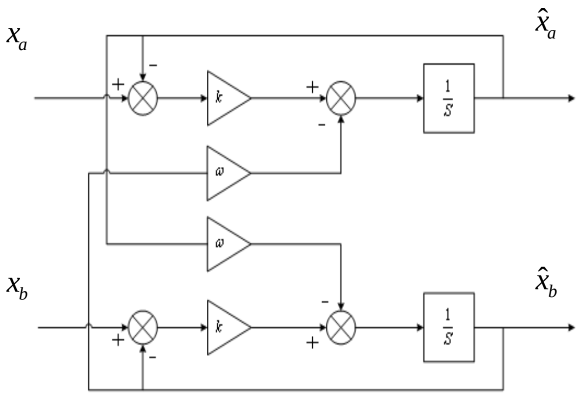


Fig 5. Self Tuning Filter tuned at the pulsation ω_c

The flow chart of the control algorithm in the DSP software is shown in Fig. 4.

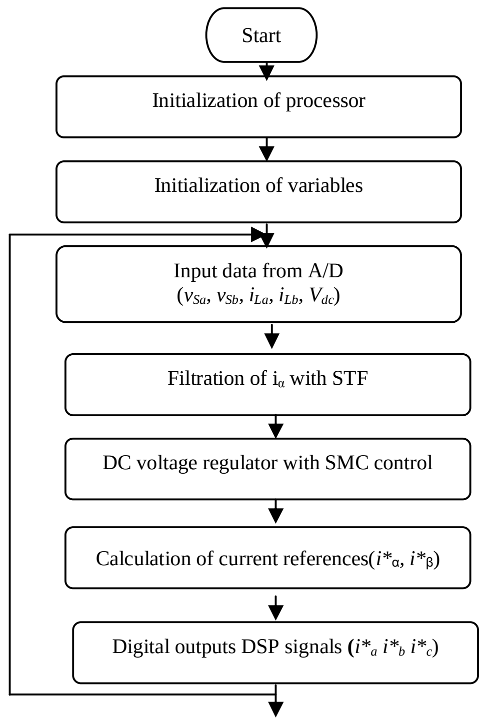


Fig. 4. The flow chart of the control algorithm in the DSP software

B- Further reference currents

The finality of the FAP is a command to control the output currents of the APF in order to nearest they follow their references. The principle of this lawsuit is based on the comparison between the current generated by the FAP and the reference current in order to deduce the control orders power switches. Hysteresis-band instantaneous current control PWM technique is popularly used because of its simplicity of implementation, fast current control response and inherent peak current limiting capability. This type of nonlinear control uses the error signal between the reference current and the current produced by the APF see Fig. 6. The error is compared to a template called hysteresis band. Once the error reaches the upper or lower band, a new control command is sent to the semiconductor so as to maintain the actual current within the strip. The only parameter intervening in regulating is the width of the hysteresis band. It determines, on the one hand the average switching frequency and on the other the error on the currents generated. The hysteresis current control is simple to implement and gives good results in regulation and gives good results in regulation because neither static error nor following error. The control is robust with respect to system parameters and exhibits good dynamic transient.

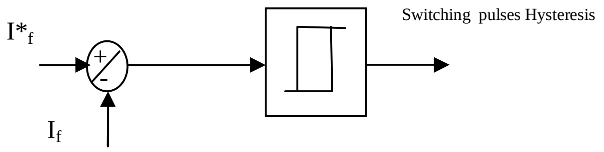


Fig.4 - Hysteresis band current controller

IV . Simulation results and discussions

Some simulation results using model in Matlab-Simulink and SimPower System Blockset are presented. The harmonic current and reactive power compensated by APF implemented in three- phase power systems with the utility power supply voltage of 100V and current source three- phase diode-bridge rectifier with R-L loads as the current compensation object. The design specifications and the circuit parameters used in the simulation are parameters are used for simulation: $V_S = 50$ V (rms), $R_S = 0.1\ \Omega$, $L_S = 0.566$ mH, $R_C = 0.01\ \Omega$, $L_C = 1$ mH, $R_{d1} = 26.25\ \Omega$ and $R_{d2} = 17\ \Omega$, $L_d = 1$ mH, $V_{dr} = 140$ V, $C = 1100\ \mu$F, *HB* (hysteresis band) =0.1

To study the performance of the APF, first simulation is done on fixed load (R_{L1} & L_L) and the filter is switched on at 0.12s.

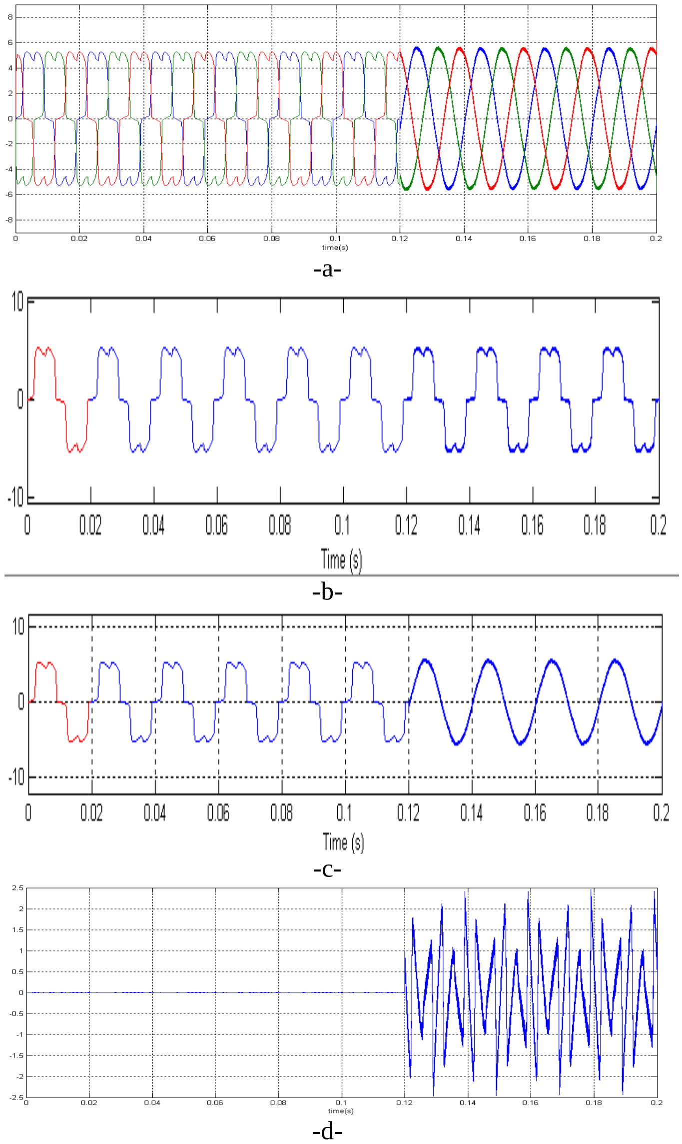


Fig 5 Three phase main current (b) load current; (c) Mains current; (d) compensating current waveform

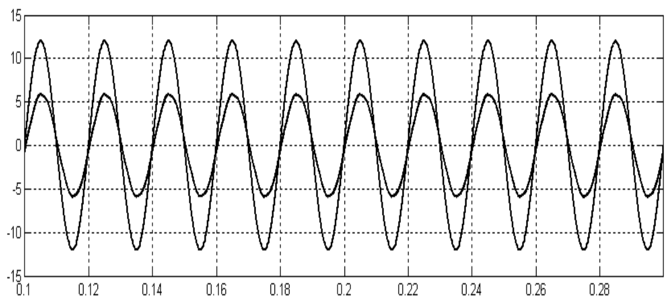
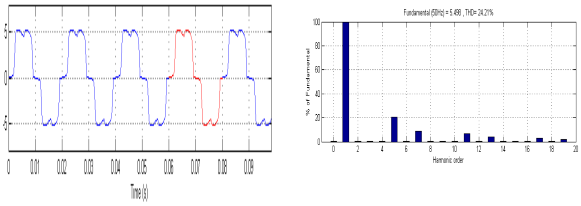
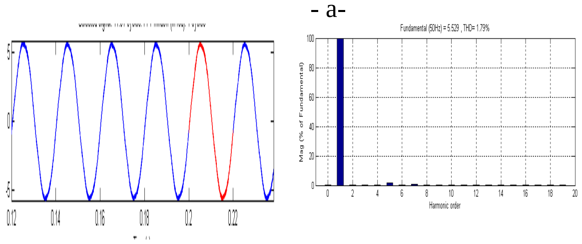


Fig 6. Power factor correction after applying PI controller.

We see that before the connection of the APF, the mains current has a same waveform of the load current. At 0.12s, the APF is connected. mains current will be sinusoidal and exactly in phase with source voltage.



- a-

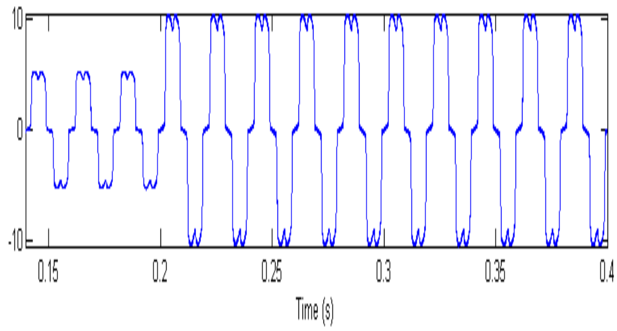


-b-

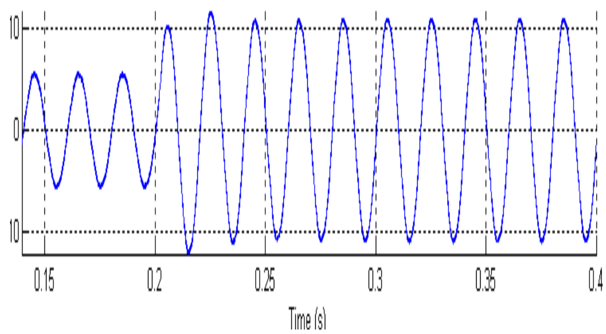
Fig 7 -Mains current waveform and its spectrum, (a) before filtering, (b) after filtering.

Still in Fig.7 a-b; a spectrum analysis shows that *Is* current which contained harmonics and a THD_i = 24.67%, will have one specter at fundamental frequency, all harmonics disappear and the THD_i = 2.3%.

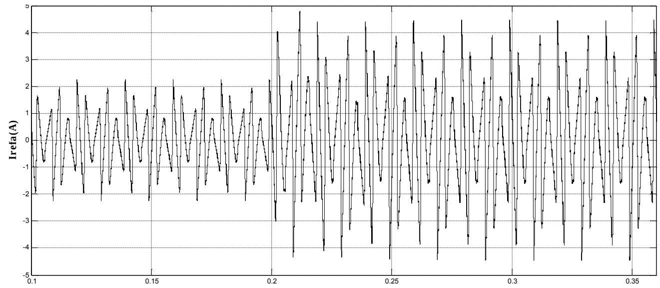
To observe the regulating process in PI control method in transient condition and the dynamics of the proposed APF, the DC side resistance is changed from Rd1 to Rd2 at 0.2s. It is clear from simulation results in Fig.8 that we obtain good transient performance of the source current, DC side capacitor voltage for the PI controller and the mains current maintains its sinusoidal waveform.



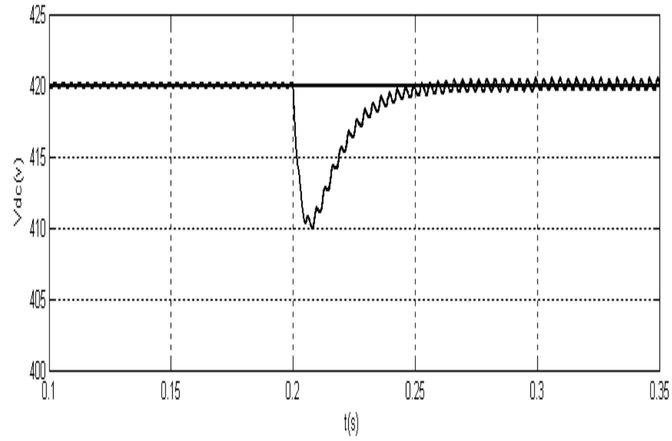
-a-



-b-



-c-



-d-

Fig 8 .Load perturbation response of PI controlled shunt APF. (a) load current; (b) Mains current; (c) compensating current waveform (d) dc voltage

V. EXPERIMENTAL RESULTS

The test bench used for the experiment was developed in LGEB laboratory. The input step-down transformer (10.60KVA) is connected to the mains (380 V line to line) and delivers a lumped voltage of 220 V. The three-phase parallel active filter is achieved with a voltage source inverter. This VSI contains a three-phase IGBT 1200V, 50A (SKM 50 GB 123D). To ensure the dead time of control signals and the insulation, developed cards based on the IXDP630 component and specialized circuits (SKHI 22) are used.

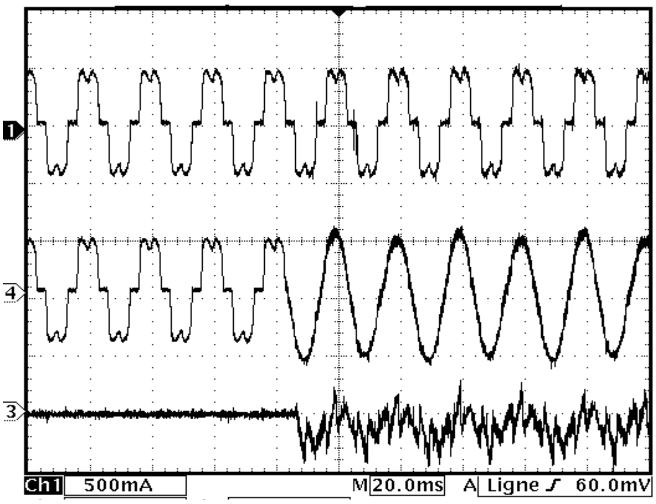


Fig. 9. Experimental APF results: load current i_L (A), filter current i_F (A) and source current i_S (A). Ch1 to Ch4 scale: 5 A/div. Time scale: 20 ms/div.

We see that before the connection of the APF, mains current has a same waveform of the load current. At 0.14s, the APF is connected. So, mains current will be sinusoidal

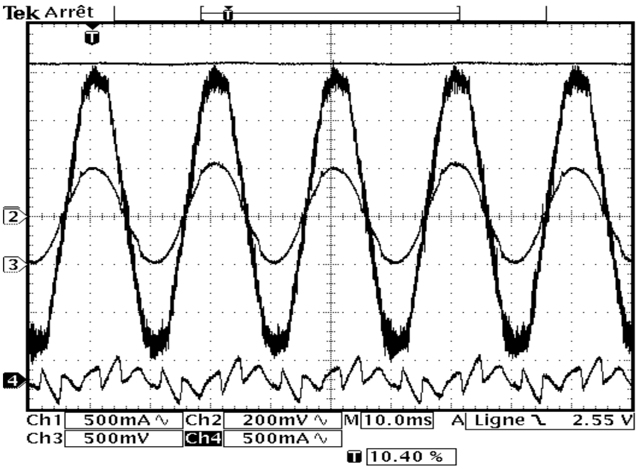


Fig. 10. Experimental APF results: load current i_L (A), filter current i_F (A), source current i_S (A) and source voltage Vs (V). Ch1 and Ch3 scale: 5 A/div; Ch2 scale: 100 V/div;Ch4 scale: 80 V/div; Time scale: 10 ms/div.

Figure 8 shows experimental results for the mains current has a sinusoidal form and in phase with supply voltage , which minimizes the reactive power consumed by the load . the DC bus voltage controller. The voltage Vdc on the DC side of the inverter is stable and regulated around its reference.

In Fig. 9 a spectrum analysis shows that i_S current which contained harmonics and a *THD* =26.42 % However, after filtering, this current have one specter at fundamental frequency, all harmonics disappear and the *THD* = 3.56%.(see Fig. 10).

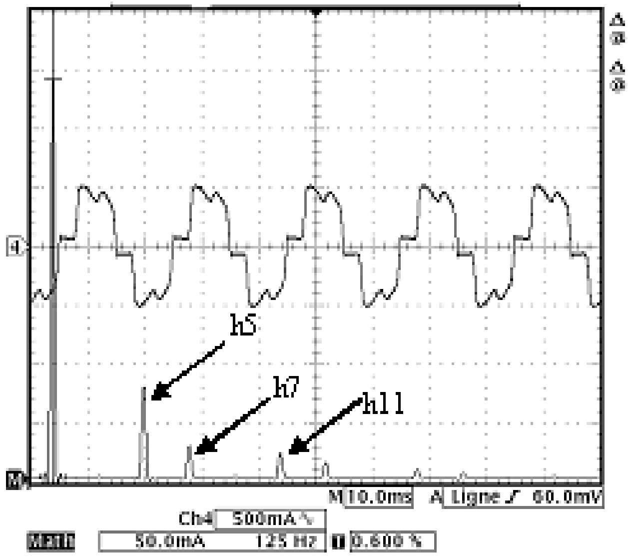


Fig.11. Experimental APF results : source current i_S and its spectrum before filtering

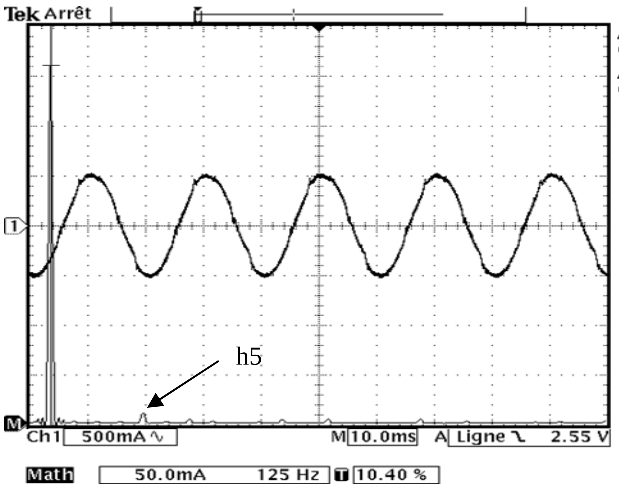


Fig12.Experimental APF results : source current i_S and its spectrum after filtering

Finally, to confirm the effectiveness of the proposed control, a double change of the reference is shown 420-320 and 420V. It can be noted that after a rapid transient response, the DC voltage follows its reference; there is no overshoot and the settling time is very small (see Fig. 12). Fig. 13 shows the corresponding results from the experimentation

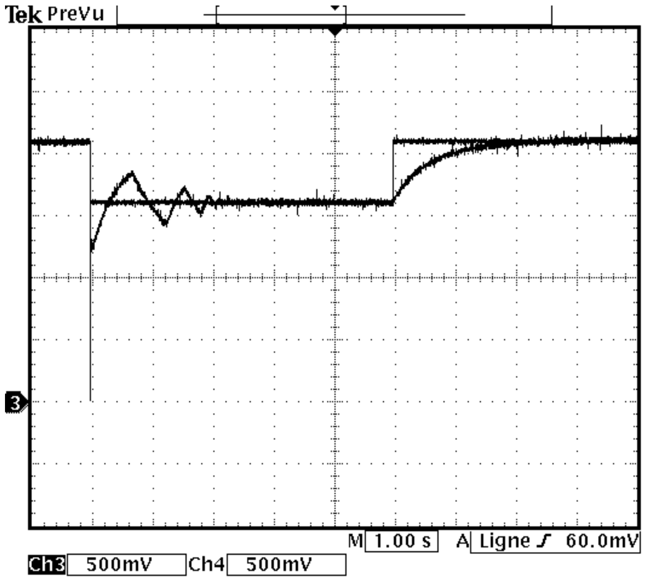


Fig.13. Experimental APF results: DC voltage V_{dc} (V) and DC reference voltage V^*_{dc} (V).Ch1 and Ch2 scale: 100 V/div. Time scale: 1s/div

VII. Conclusion

Experimental results and simulations show that the shunt active filter presents good dynamic and steady-state response. It can perform harmonic currents compensation, together with power factor correction. It can also

In this work, we have shown the effectiveness of the shunt active power filtering especially with the application of PI control and with the application of the instantaneous power based compensator .The THD of the source current and source voltage after compensation is well below 5%, the harmonics limit imposed by the IEEE-519 standard. Further studies will examine the opportunity of implementing a high frequency output filter with the three- phase inverter and the power factor was corrected (power supply voltage and current became in phase).

REFERENCES

[1] S.Beaulieu, M. Ouhrouche " real-time modelling and simulation of an active power filter " lASTED International Conference on Power and Energy Systems PES 2007, Clearwater, Florida, U.S.A.

[2] Mohamed Abdusalam, Philippe Poure and Shahrokh Saadate "Control of Hybrid Active Filter Without Phase Locked Loop in the Feedback and Feedforward Loops" ISIE, IEEE International Symposium on Industrial Electronics, Cambridge, UK, (2008).

[3] Mohamed Abdusalam, Philippe Poure and Shahrokh Saadate "Control of Hybrid Active Filter Without Phase Locked Loop in the Feedback et Feedforward Loops"

[4] Abdelmadjid Chaoui , Jean-Paul Gaubert Fateh Krim , Laurent Rambault "IP Controlled Three-Phase Shunt Active Power Filter for Power Improvement Quality " 1-4244-0136-4/06/ 2006 IEEE.

[5] Wenjin Dai , Baofu Wang , Youhui Xie " A Novel Fuzzy Logic Controller fro Active power Filter " CIMSA 2009 – International Conference computational intelligence for measurement systems and Applications .

[6] K. Hasan, and K. Osman, "Globally Stable Control of Three-Phase Three Wire Shunt Active Power Filters," Elec. Eng., vol. 89, no.5, 2007, pp. 411-418.

[7] Helder J. Azevedo, José M. Ferreira, António P. Martins, and Adriano S. Carvalho ''Direct current control of an active power filter for harmonic elimination, power factor correction and load unbalancing compensation,'' Proceedings of the 10th European Conference on Power Electronics and Applications, EPE'03,Toulouse, 2003, pp. 1-10.

[6] D. Casadi, U. Reggiani, and G. Grandi, ''Active power filters based on a single current measurement system,'' System Proceedings Symposium on Power Electronics, Electrical Drives Advanced Machines Power Quality (SPEEDAM'98), Italy, June 3-5, 1998.

[7] K. H. Yiauw, and M. S. Khanniche, ''A novel three-phase active power filter,'' Rev. Energ. Ren,: Power Engineering, 2001, pp. 77-84.

[8] S.Beaulieu, M. Ouhrouche " real-time modelling and simulation of an active power filter" ASTED International Conference on Power and Energy Systems PES 2007, Clearwater, Florida, U.S.A.

[9] M. Abdusalam, P. Poure and S. Saadate, '' Study and experimental validation of harmonic isolation based on Self-Tuning-Filter for three-phase active filter'', ISIE, IEEE International Symposium on Industrial Electronics, Cambridge, UK, (2008).