Power quality enhancement using Fussy Logic Controller based Hybrid Active Power Filter

Mustapha SARRA

Department of Electronics
Faculty of Science and Technology
Mohamed El Bachir El Ibrahimi University, Bordj Bou Arréridj, Algeria
E.T.A Laboratory

Abstract- This paper presents a fuzzy logic controlled (FLC) transformerless shunt hybrid active power filter (SHAPF) used to improve the power quality by compensating harmonics and reactive power required by nonlinear load. The SHAPF is formed by a single seventh tuned LC filter per phase and a small-rated three-phase active filter, which are directly connected in series without any matching transformer. The required rating of the active filter is much smaller than that of a conventional standalone active filter be. To improve the dynamic of the system, a fuzzy logic based control is developed to regulate the dc-link voltage. All simulations are performed using Matlab-Simulink Power System Blockset and validated with an experimental test bench developed in the LIAS laboratory, University of Poitiers. Various simulation and experimental results of the proposed control algorithm are extensively tested for wide range of different loads under steady state and transient conditions with improved dynamic behavior of SHAPF to confirm his validity and effectiveness.

Keywords- Shunt Hybrid Active Power filter, Power quality improvement, Fuzzy logic controller (FLC).

I. INTRODUCTION

In recent years, power quality distortion has become serious problem in electrical power systems due to the increase use of nonlinear loads drawing non sinusoidal currents. They result in poor power factor, lower efficiency and interference to adjacent communication systems. Traditionally power passive filters (PPFs) have been used to eliminate the current harmonics and to improve the power factor. However, these PPFs present many disadvantages.

In order to overcome the above mentioned disadvantages inherent in PPFs, various kind of pure active power filters (APF) configuration have been researched and developed, however they also have some disadvantages [1]-[7].

As an alternative to mitigate the problems and to inherit advantages of PPFs and pure APFs, different topologies of hybrid active filters by connecting APFs and PPFs in series or parallel with various control strategies, have been proposed in recent years as lower cost alternatives to pure APFs used alone.

This paper describes a Transformerless SHAPF formed by a single LC filter per phase tuned to the seventh-harmonic frequency and a small-rated three-phase active filter based on a three-phase voltage-source PWM converter. The passive and active filters are directly connected in series. The dc voltage of the active filter is much lower than the supply line-to-line RMS voltage because no supply voltage is applied across the active filter. The supply voltage is applied across the capacitor of the passive filter. Moreover, no additional switching-ripple filter is required for the SHAPF because the LC filter operates not only as a harmonic filter but also as a switching-ripple. The reference current for the algorithm control applied to the SHAPF is based on advanced control algorithm consisting of synchronous reference frame (SRF) rotating at fundamental angular speed using a Multi-Variable Filters (MFV) combined with a robust PLL. [8]-[11].

To enhance the system dynamics, the current amplitude is commanded by a fuzzy logic controller, which adjusts the inverter DC-bus voltage and allows more flexibility and better dynamic response.

The advantage of fuzzy control is that, it does not require accurate mathematical model, can work with imprecise inputs, can handle nonlinearity, and are more robust than the conventional nonlinear controllers.

II- SHAPF TOPOLOGY AND COMPENSATION PRINCIPLE

Figure1 presents the power scheme of the SHAPF proposed in this paper and designed to reduce the total harmonic distortion (THD) of i_s below 5%. It consists of a three-phase three wire supply voltage, three phase six pulse rectifier, and the active filter which is directly connected to the system through the 7^{th} tuned LC filter. The active filter consists of a three-phase voltage-source PWM converter using six IGBTs, and a DC capacitor C_{dc}.

This hybrid topology allows the inverter to have a very weak DC-side voltage. The passive filter sinks the 7^{th} harmonic current, while the active filter compensates for the other harmonic currents produced by the diode rectifier (non linear load). The SHAPF compensate non linear load current harmonics by injecting equal but opposite harmonic compensating current, so it operates as a current source injecting the harmonic components but phase-shifted by 180°.

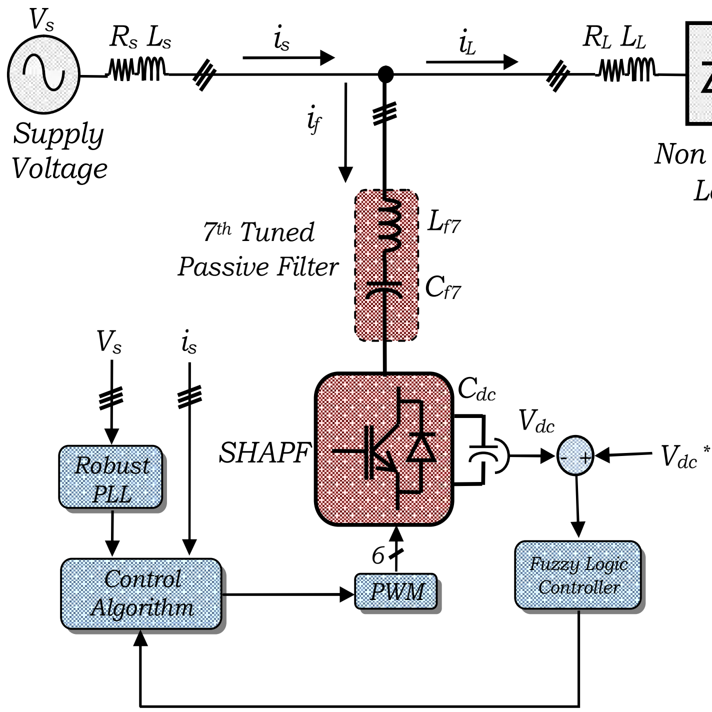


Figure 1. Power scheme of the SHAPF

III-SHAPF CONTROL METHOD

Figure 2 shows the proposed control circuit of SHAPF, which detects the three-phase supply currents Is_{abc} , three-phase voltage supply Vs_{abc} and the DC-bus voltage V_{dc} and then builds the reference voltages Vs_{abc}^{*} for the PWM voltage source inverter. First, the three-phase supply currents (I_{sa}, I_{sb}, and I_{sc}) are measured and transformed into the instantaneous active (I_d) reactive (I_q) components using synchronous reference frame (SRF) rotating at fundamental angular speed with the positive sequence of the system voltage (5).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\hat{\theta} & \cos\left(\hat{\theta}-\frac{2\pi}{3}\right) & \cos\left(\hat{\theta}+\frac{2\pi}{3}\right) \\ -\sin\hat{\theta} & -\sin\left(\hat{\theta}-\frac{2\pi}{3}\right) & -\sin\left(\hat{\theta}+\frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_{s_a} \\ i_{s_b} \\ i_{s_c} \end{bmatrix} \quad (1)$$

Where $\hat{\theta}$ is the phase of the positive sequence of the system voltage which is provided by the robust PLL proposed in this paper. The system under study is a three-wire system where the zero sequence may be neglected, so only i_d and i_q are considered.

The active and reactive currents can also be decomposed in their DC and AC components.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} i_{d_{DC}} + i_{d_{AC}} \\ i_{q_{DC}} + i_{q_{DC}} \end{bmatrix} \quad (2)$$

Where $(i_{d_{DC}}, i_{d_{qDC}})$ are respectively the d-axis and q-axis direct components which correspond respectively to the fundamental active and reactive components, and $(i_{d_{AC}}, i_{d_{qAC}})$ are respectively the d-axis and q-axis alternating components which correspond respectively to the harmonic active and reactive components.

It is hoped that the network supplies the DC values of the active current, while its AC components, as well as the reactive current, is supplied by the SHAPF. Concerning the reactive current, its DC value is provided by the passive filter, while the inverter provides an AC voltage to damp the harmonics. A second-order low-pass filter (LPF) with a cutoff frequency of 12 Hz extracts ac components $\tilde{i}_d$ from i_d. The obtained $\tilde{i}_d$ and i_q^* are then fed into the proportional plus integral (PI) regulators to generate the required voltage command for the inverter. A *dq* to *abc* transformation is applied to convert the inverter voltage command back to three-phase quantities. The sine/triangle modulation generates square wave switching commands to achieve harmonic isolation and dc-bus power balancing of the active filter inverter.

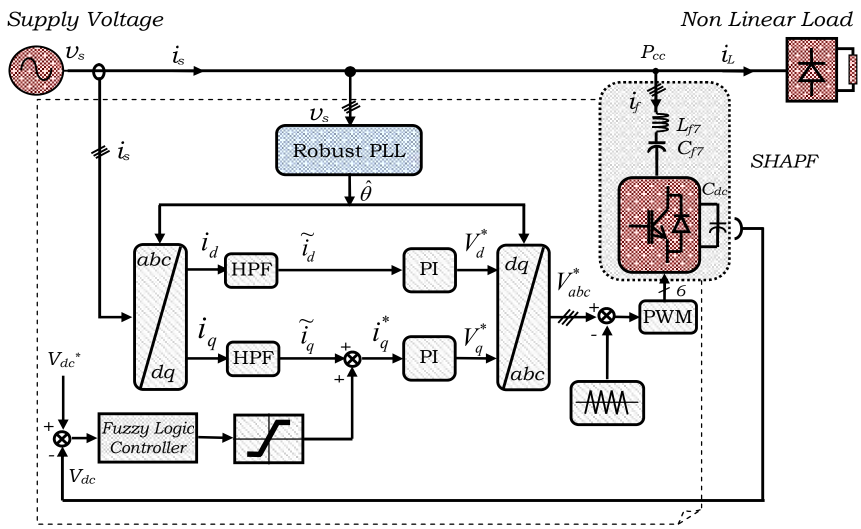


Figure. 2 Proposed control technique of the SHAPF

IV-DESIGN OF THE DC-BUS FUZZY LOGIC CONTROLLER

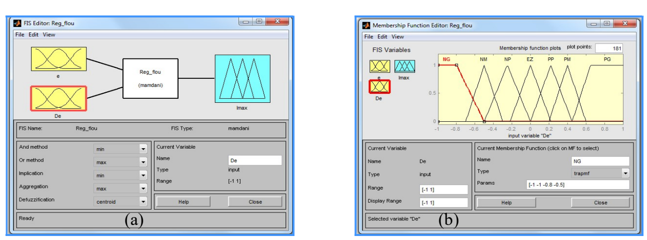
The SHAPF can build up and regulate the DC capacitor voltage by itself without any external power supply. The DC capacitor supplies a constant DC voltage and the real power needed to provide system losses. In the steady state, the real power delivered by the source must be equal to the load real power requirement and a small power to compensate the SHAPF losses.

Therefore, the DC capacitor voltage can be kept at a constant reference value. However, when the load state changes the real power balance between the network and the load will be disturbed. Thus, the DC capacitor must compensate this real power difference. A fuzzy logic controller is applied to maintain the constant voltage across the capacitor by minimizing the error between the capacitor voltage and the reference voltage. Therefore, the electrical quantity to be controlled in a DC voltage feedback loop is not ΔId but ΔIq as it is shown in Figure. 2 [12]-[19].

To design the fuzzy logic controller, variables which may represent the dynamic behavior of the controlled system must be chosen as the inputs of the controller. In the proposed FLC, the DC-bus voltage V_{dc} is sensed and compared with the reference set V_{dc}^*. The error obtained and its derivative are considered as the inputs of the FLC and the real power requirement for voltage regulation is taken as the output of the FLC. The DC-bus voltage is controlled by adjusting the active power by the proposed FLC.

The input and output variables are converted into linguistic variables. Seven fuzzy subsets , NL(Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive large) have been chosen both inputs; Seven sets for the output. Triangular membership functions are used for the input and output variables used here are shown in Figure.3.

Since both inputs have seven subsets, a fuzzy rule base expressed for the present application is given in Table 1.



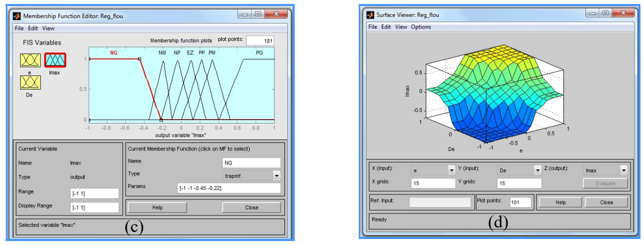


Figure 3. Triangular membership functions

TABLE1: Fuzzy control rules

e / De	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	EZ	PS	PM	PL	PL	PL	PL

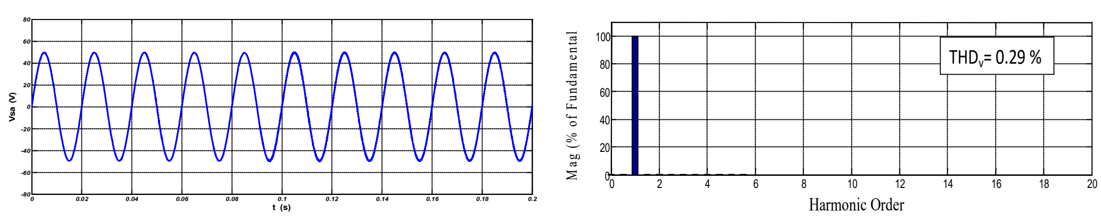
V- SYSTEM MODELING AND SIMULATION

To simulate the proposed control strategy of the SHAPF, a model is developed in Matlab/Simulink® environment using SimPower Systems Blockset. [19].
The complete active filter system is composed mainly of a three-phase source, a nonlinear load which is a three phase rectifier feeding an inductive load, a PWM voltage source inverter, and a control bloc. It should be noted that the simulation parameters are identical to those used for experimentation and are summarized in TABLE2.

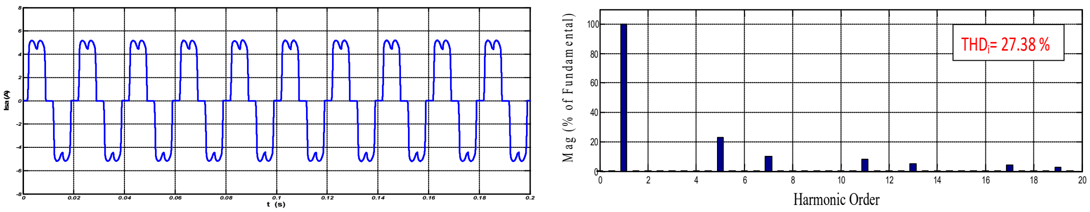
TABLE 2. SYSTEM COMPONENTS AND PARAMETERS VALUES

Supply Voltage	V_{Sabc} = 50V (rms)	Quality Factor Q	42
Line frequency	f =50 Hz	APF DC-capacitor	C_{dc} = 1100 µF
Supply line impedance	R_S =0.1 Ω , L_S =0.05 mH	APF DC-bus voltage	V_{dc}^* = 15 V
Nonlinear load components	R_L =0.1 Ω , L_L =0.05 mH R_{D1} =16.1 Ω , R_{D2} =30 Ω L_D =1 mH	Voltage regulator Parameters	K_{pv}=0.156, K_{iv}=11.1
		Current regulator Parameters	K_{pc}=0.156, K_{ic}=11.1
		Resonant frequency	350 Hz
7th tuned passive filter	L_{F7} =1.9 mH, L_{C7} =110µF	LPF Cut-off frequency	f_{LPF} = 12 Hz

Computer simulation verifies the viability and effectiveness of the proposed hybrid filter. At first, the results of simulation before connecting the filter to the network polluted by the nonlinear load are presented in Fig. 9. It can be noticed in Fig.9d that, without passive ore active filters in the system, the source current i_s presents a high harmonic distortion (THD_i=27,38%) caused by the presence of the nonlinear load. Otherwise, it can also be noted that the significant current generated by this nonlinear load, are 5th, 7th, 9th and 11th order, among them the biggest is the 5th. [19].



(a) (b)



(c) (d)

Figure. 4. Simulation waveforms before connecting the SHAPF

In the next section, the simulation results of the system are presented in steady and transient states. Fig. 5. presents the waveform of supply voltage V_{sa} *(V),* load current I_{ca} (A), supply current I_{sa} (A), the DC-bus voltage V_{dc} *(V)*.

When the SHAPF is applied to the system (switched on) at time t=0.08s, it can reduce the supply current THD_i from 27.38% to 2.71% so, it becomes almost sinusoidal waveform, which proves that the proposed SHAPF control strategy has the capability of compensating for current harmonics successfully. On the other hand, it can be observed how the SHAPF behaved under a first step change in the nonlinear load DC side at t=0.2s from R_{D2} to R_{D1} and from R_{D1} to R_{D2} at t=0.3s. After the nonlinear load changes occurred, the supply current was distorted for about one cycle (about 20ms), which would not produce any bad effect on external circuits and equipment, because the proposed SHAPF with its robust control strategy recovered from the transient state in one cycle. The DC-bus voltage V_{dc} was well regulated, even in the transient state, because of the use of the DC-voltage fuzzy logic controller. [19].

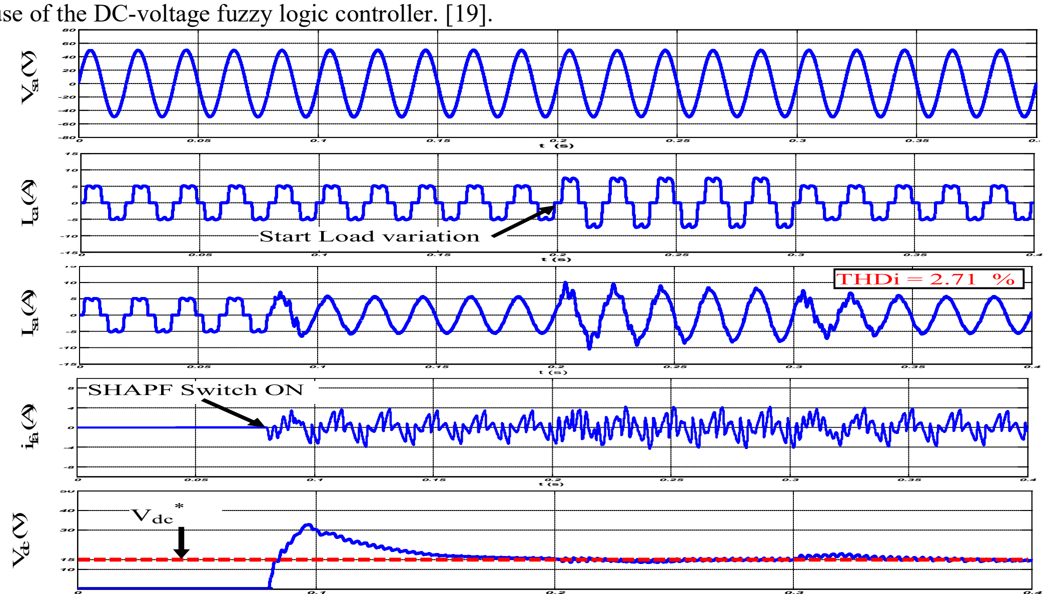


Figure 5. Simulation waveforms after connecting the SHAPF in transient state

VI- EXPERIMENTAL RESULTS

The experimentation of this work is done using the test bench which was developed in LAII laboratory, University of Poitiers (Figure.6). The input step-down transformer (20KVA, 400/230 V) is connected to the mains. The three-phase parallel active filter is achieved with a voltage source inverter of 20 KVA. This VSI contains a three-phase IGBT 1200 V, 50 A (SKM 50 GB 123D). To ensure the insulation and the dead time of control signals a developed card based on the IXDP630 component and a special driver circuit (SEMIKRON, SKHI 22) are used. The control strategy is implemented using a dSPACE card DS1104 developed under Matlab/Simulink^{TM} RTW environment. The sampling time using in practical tests for the proposed systems is 50 µs [17]-[19].

Fig. 7. presents the experimental results of the proposed robust PLL with unbalanced and polluted supply voltage and the perfect sinusoidal and balanced voltage generated by the proposed robust PLL. Like simulation results, these experimental results prove the effectiveness of the voltage harmonics filtering without generating any phase-shifting and eliminate the unbalance which can appear in the electric

network.

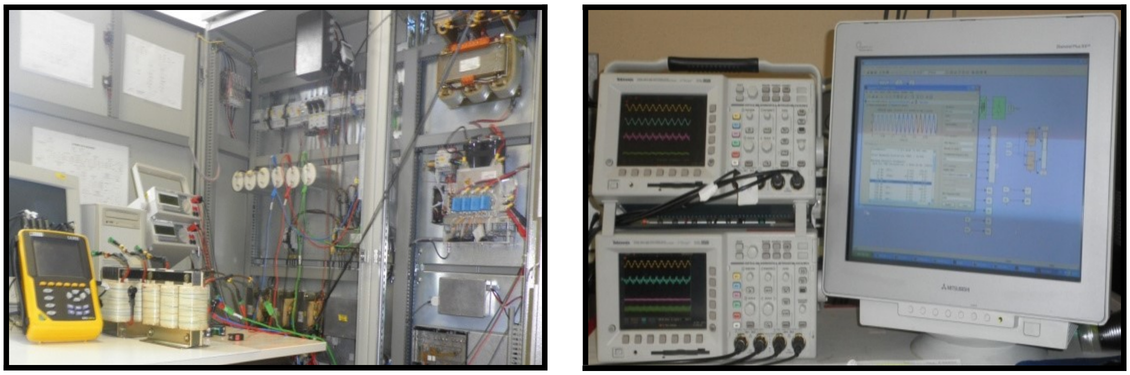


Figure 6. : Photography of the APF system prototype

The experimental results before connecting the filter to the network polluted by the nonlinear load are presented in Fig.7. Without passive or active filters connected to the system, the source current i_s presents a high harmonic distortion (THD_i = 23%) caused by the presence of the nonlinear load. Otherwise, it can also be noted that the significant current generated by this nonlinear load, are 5^{th}, 7^{th}, 9^{th} and 11^{th} order, among them the biggest is the 5^{th}, that confirm the simulation results. [19].

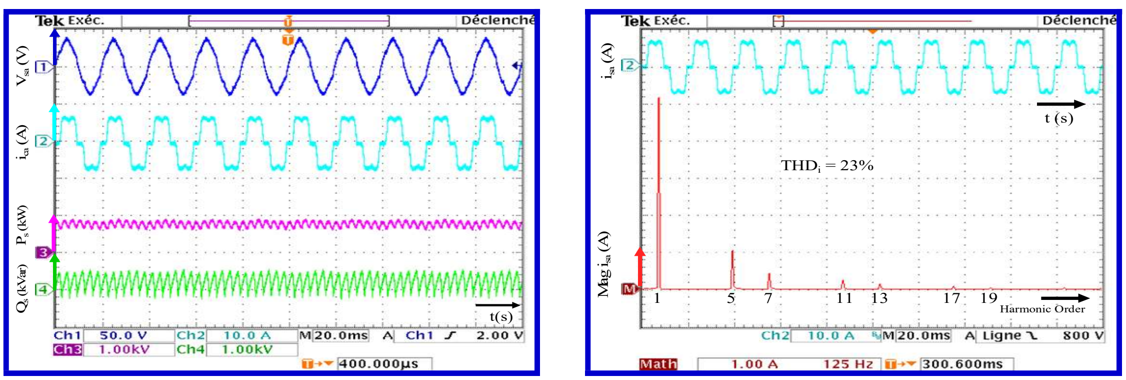
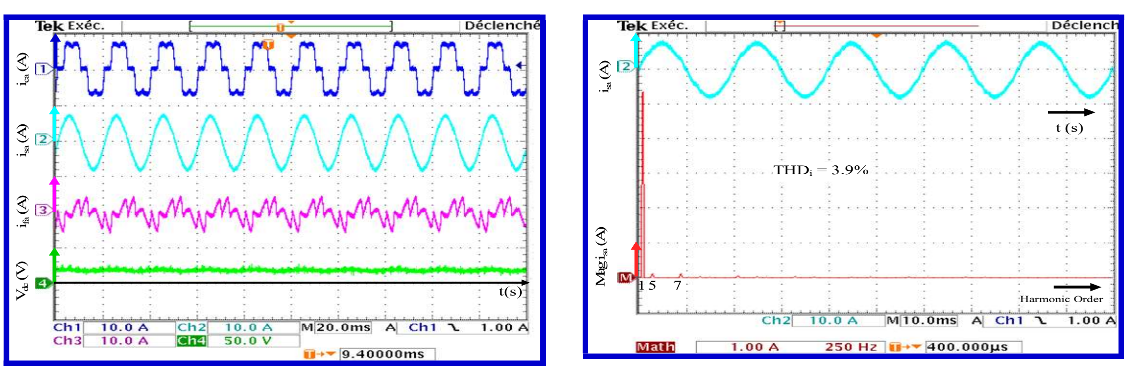


Fig. 7 Experimental waveform before connection of the SHAPF

The experimental results of the system in steady state are summarized in Fig.8. Fig.8a-b present the waveform of supply voltage V_{sa} *(V),* load current I_{ca} (A), supply current I_{sa} (A), the DC-bus voltage V_{dc} *(V)* stabilized at reference value V_{dc}^{*} fixed at 15V, the active power P (W) and the reactive power Q (VAR). When the SHAPF is applied to the system, it can reduce the supply current THD_i from 27.38% to 3.9% (2.7% in simulation) thus, it becomes almost sinusoidal waveform, which proves that the proposed SHAPF control strategy has the capability of compensating for current harmonics successfully. The DC-bus voltage V_{dc} was well regulated with the proposed FLC.



(a) (b)

Fig. 8. Experimental waveform after connection of the SHAPF

VII- CONCLUSION

A fuzzy logic controlled (FLC) applied to a transformerless shunt hybrid active power filter (SHAPF) to improve the power quality by compensating harmonics and reactive power required by nonlinear load has been presented in this paper. The SHAPF is formed by a single seventh tuned LC filter per phase and a small-rated three-phase active filter, which are directly connected in series without any matching transformer.

Finally, various simulations and experimental results of the proposed control algorithm based on a simple fuzzy logic controller (FLC) are presented under steady state and transient conditions to confirm his validity and effectiveness.

REFERENCES

[1] H. Akagi, "New trends in active filters for power conditioning," IEEE Trans. Ind. App., vol. 32, pp. 1312–1322, Nov./Dec. 1996.
[2] H. Akagi, Y. Kanazwa and N. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuit, IPEC'83-International Power Electronics Conference", Tokyo, Japan, pp. 1375–1386, 1983.
[3] F.Z. Peng, H. Akagi, and A. Nabae, "A study of active power filters using quad series voltage source PWM converters for harmonic compensation, IEEE Trans. Power Electronics, Vol. 5 no. , pp. 9-15, Jan. 1990.
[4] H. Fujita, H. Akagi," A Practical Approach to Harmonic Compensation in Power Systems-Series Connection of Passive and Active Filters", IEEE Trans. Ind. App.,vol.27, no.6, November/December 1991.
[5] H. Fujita and H. Akagi, "An approach to harmonic-free ac/dc power conversion for large industrial loads: The integration of a series active filter with a double-series diode rectifier," IEEE Trans. Ind. App., vol. 33, pp. 1233–1240, Sept./Oct. 1997.
[6] S. Bhattacharya, P. T. Cheng, and D. M. Divan, "Hybrid solutions for improving passive filter performance in high power applications," IEEE Trans. Ind. App., vol. 33, pp. 732–747, May/June 1997.
[7] H. Akagi, A. Nabae, and S. Atoh, "Control strategy of active power filters using multiple-voltage source PWM converters, IEEE Trans. Ind. App., Vol. 20 no. , pp. 460-465, May/Jun. 1986.
[8] W. Tangtheerajaroonwong, T. Hatada, K. Wada, and H. Akagi, "Design and Performance of a Transformerless Shunt Hybrid Filter Integrated Into a Three-Phase Diode Rectifier", IEEE Trans. Power Electronics, vol. 22, NO. 5, September 2007.
[9] S. Srianthumrong and H. Akagi, "A medium-voltage transformerless AC/DC power conversion system consisting of a diode rectifier and a shunt hybrid filter", IEEE Trans. Ind. App., vol. 39, NO. 3, May/June 2003.
[10] S. Srianthumrong, H. Fujita, and H. Akagi, "Stability analysis of a series active filter integrated with a double-series diode rectifier," IEEE Trans. Power Electron., vol. 17, pp. 117–124, Jan. 2002.
[11] B. R. Lin, B. R. Yang, H. R. Tsai," Analysis and operation of hybrid active filter for harmonic elimination," Electric Power Systems Research, vol. 62, pp. 191-200, 2002.
[12] S. G. Dan et al, "DSP control of line hybrid active filter", Proceedings of the IEEE International Symposium on Industrial Electronics, June 2005 Dubrovnik, Croatia2005.
[13] A Novel Shunt Hybrid Power Filter for Suppressing Harmonics", Proceedings of the IEEE International Symposium on Industrial Electronics, July 2006, Montreal, Canada.
[14] M. Sarra, K. Djazia, A. Chaoui, F. Krim, " Three-phase Active Power Filter with Proportional Integrator control", Journal of Electrical Systems, Special Issue no. 1, pp 79-84, Nov. 2009.
[15] A. Chaoui, J.P. Gaubert, F. Krim, G. Champenois : IP controlled three-phase shunt active power filter for power improvement quality, Electric Power Components and Systems, Vol. 35 no. 12, pp. 1331-1344, 2007.
[16] M.C. Benhabib, S. Saadate, "A new robust experimentally validated phase locked loop for power electronic control", EPE journal, vol.15, no3, pp.36-48, August 2005.
[17] A. Chaoui, J.P. Gaubert, F. Krim : Experimental Evaluation of a Simple Robust Control for Active Power Filtering Under Unfavorable Conditions", European Conference on Power Electronics and Applications, EPE 2009, Sep. 2009, Barcelona, Spain.
[18] M. Sarra, J.P. Gaubert, A. Chaoui, F. Krim," Experimental Validation of two Control Techniques Applied to a Three Phase Shunt Active Power Filter for Power Quality Improvement", International Review of Electrical Engineering Vol. 6. n. 6, pp. 2825-2836 (Special Issue), November 2011.
[19] Sarra C, Gaubert J.P, Chaoui A, Krim F. Control Strategy of a Transformerless Three Phase Shunt Hybrid Power Filter using a robust PLL. IECON 2012. 38th Annual conference on IEEE Industrial Electronics society. 2012 Canada. pp.1258-1267.