FIVE-LEVEL SHUNT ACTIVE FILTER BASED ON INSTANTANEOUS P-Q THEORY AND FUZZY LOGIC CONTROLLER CONNECTED TO A PHOTOVOLTAIC SOURCE

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Abstract: This paper presents the optimal controller design of fuzzy logic, a power controlled shunt active filter connected by a photovoltaic system for compensation of harmonics and Reactive Power injected by non-linear loads. The proposed system consists of a photovoltaic (PV) inverter in five levels in NPC structure connected to the network and a non-linear load constituted by a thyristor rectifier bridge feeding a resistive load in series with an inductor. In calculating the harmonic currents of reference, we use the algorithm P-Q and pulse generation, we use the intersective PWM. For flexibility and dynamics, we use fuzzy logic. The results give us clear that the rate of Harmonic Distortion issued by fuzzy logic is better than P-Q algorithm.

Key words: *Photovoltaic, Pulse Width Modulation (PWM), Fuzzy logic controller, P-Q Algorithm, Multilevel inverter, Active Power Filter Shunt (APFs).*

1. Introduction

The presence of non-linear loads and the progressive use of the static converters in the industry cause the consumption of reactive power and the injection of streams rich in harmonics in the network [1]. Distortion Harmonic is a form of pollution of the electricity network may create anomalies (temperature rise transformers, cables, motors, generators and capacitors, any triggering circuit breakers, control systems malfunction). Several solutions exist to remedy these drawbacks; the frequently applied is the parallel active filter. In fact, the primary role of active filtering, is to control the harmonic distortion in an active way by compensating the harmonics present in the power grid any point in time [2] [3] [4]. In applications of high power, the structure of multilevel converters is more suitable with respect to the conventional structure, since the voltages and output currents have a much lower harmonic content and the chopping frequency is lower [5] [6].

This paper presents the optimal controller design of fuzzy logic, a power controlled shunt active filter connected by a photovoltaic system for compensation of harmonics and Reactive Power injected by non-linear loads. The proposed system consists of a photovoltaic (PV) inverter in five levels

in NPC structure connected to the network and a non-linear load constituted by a thyristor rectifier bridge feeding a resistive load in series with an inductor. In calculating the harmonic currents of reference, we use the algorithm P-Q and pulse generation, we use the intersective PWM. For flexibility and dynamics, we use fuzzy logic. The results give us clear that the rate of Harmonic Distortion issued by fuzzy logic is better than P-Q algorithm.

2. Active Power Filter Shunt

Active Power Filter shunt (APFs) is a power electronics device based on the use of power electronics inverters (Fig.1). The shunt active power filter is connected in a common point connection between the source of power system and the load system which present the source of the polluting currents circulating in the power system lines. This insertion is realized via low pass filter such as, L, LC or LCL filters [6].
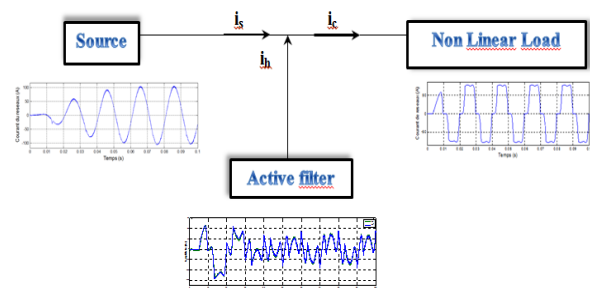

Fig.1. Active Power Filter shunt principle schematics

The most important objective of the APF is to compensate the harmonic currents and reactive power due to the non-linear load. Exactly to sense the load currents and extracts the harmonic component of the load current to produce a reference current as shown in Figure.2, The reference current consists of the harmonic components of the load current which the active filter must supply [3]

[13].This reference current is fed through a controller and then the switching signal is generated to switch the power switching devices of the active filter such that the active filter will indeed produce the harmonics required by the load. APFs are controlled to supply/extract compensating current to/from the utility Point Common Coupling (P_{CC}).
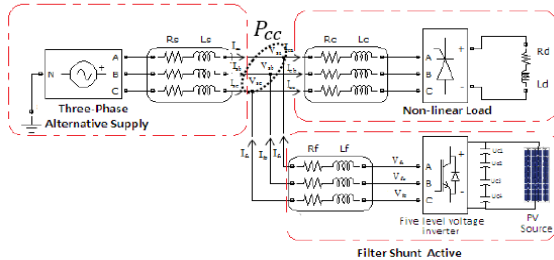

Fig.2.Equivalent schematic of APFs

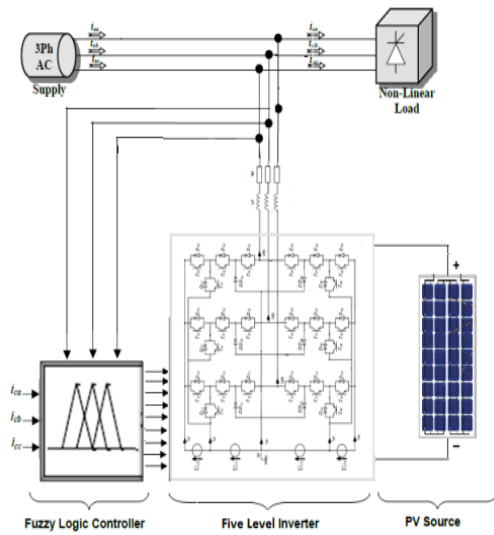Figure.3 shows the block diagram of the Shunt Active Filter powered by a photovoltaic source controlled by fuzzy logic.

Fig.3. Block diagram of an Active Power Filter Shunt controlled by Fuzzy Logic

3. APF Shunt Control Strategy

The control strategy permits to generate the gating signals to the APF switches. Mainly, we distinguish between two kinds of control techniques: The first one, commonly called the Sigma-Delta Modulation, is based on hysteresis comparators and is characterized by a non controllable switching frequency. The second one modulates the pulse width and controls the switching frequency: It is called the Pulse width Modulation (PWM). Several

PWM techniques exist [8], [9].

Particularly, we cite the carrier-based modulation, the calculated one, and the space vector one. In this paper we applied the carrier-based PWM having the control law described in Figure 4. As shown on Figure 4.a, the pulses (gating signals) are obtained by the intersections of the modulation signal (Δif in our case) and one or many carrier signals (generally triangular or saw-toothed signals). This can be realized by comparing the APF error current with the triangular carrier signal (Figure 4.b). After that, the output passes through a hysteresis comparator and is saturated between 0 and 1, corresponding to the two states of the switch. Then, if the saturated output is equal to 1, the leg upper switch is in the 'on' position; else, it's in the 'off' position. Concerning the lower switches, complementarities with the upper ones must be ensured (i.e. Si' = not (Si), i = a, b, c) in order to avoid the opening of voltage sources or the short-cuttin of current sources.

In this kind of PWM, the parameters that influence the switching frequency are mainly the modulation index (modulating wave magnitude/carrier signal magnitude) and the carrier frequency.
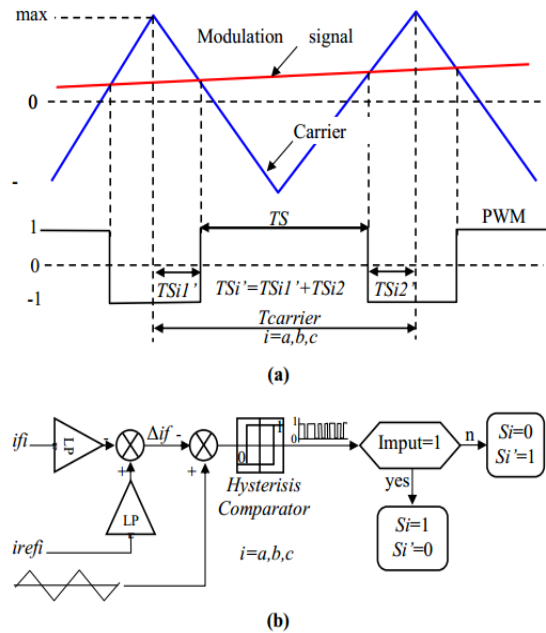

(a)

(b)

Fig.4.The Five-level shunt APF Control Law
(a) Carrier-based PWM principle
(b) Pulses generation

4. Algorithm "P-Q" Extraction of Current Harmonic

The diagram in Fig. 5 illustrates the steps for extracting the harmonic current components of non-linear load [10].
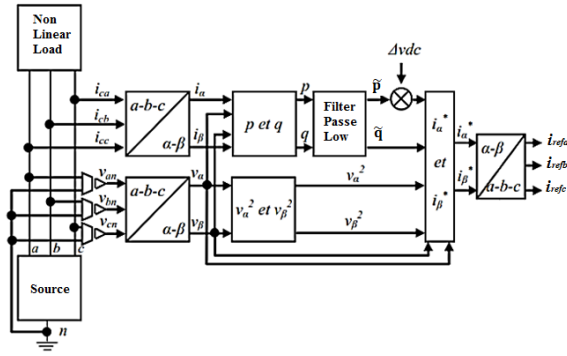
Fig.5.Algorithm P-Q extraction of harmonic currents

Theory P-Q presented before is valid only for the three-phase systems deprived of homopolar component. The extraction of the harmonic currents in single-phase applications cannot be achieved by this method. It is applicable in the case where tensions are distorted vsabc provided to filter the ripples made on the module of the vector.

5. Fuzzy Logic Controller

A. Constructing a Fuzzy Controller

Fuzzy logic serves to represent uncertain and imprecise knowledge of the system, whereas fuzzy control allows taking a decision even if we can't estimate inputs/outputs only from uncertain predicates [8], [9]. Figure 6 shows the synoptic scheme of fuzzy controller, which possesses two inputs: the error (e), (e= iref – if) and its derivative (de), and one output: the command (cde).
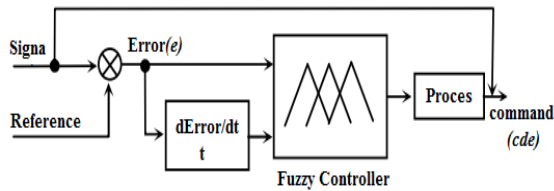
Fig.6. Fuzzy controller synoptic diagram

Figure 7 illustrates stages of fuzzy control in the considered base of rules and definitions: fuzzification, inference mechanism, and defuzzification.
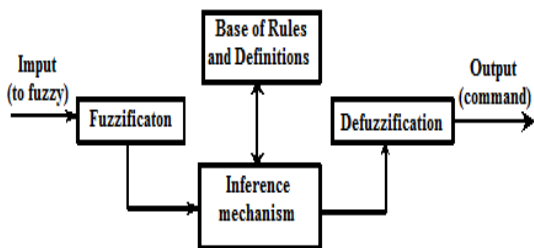
Fig.7. Fuzzy control construction

This step consists of transforming the classical low pass correctors (LPF) on fuzzy ones. The main characteristics of the fuzzy control are:
- Three fuzzy sets for each of the two inputs (e, de) with Gaussian membership functions.
- Five fuzzy sets for the output with triangular membership functions.
- Implications using the 'minimum' operator, inference mechanism based on fuzzy implication containing five fuzzy rules.
- Defuzzification using the 'centroïd' method.

The establishment of the fuzzy rules is based on the error (e) sign and variation. As explained in figure 8, and knowing that (e) is increasing if its derivative (de) is positive, constant if (de) is equal to zero, decreasing if (de) is negative, positive if (iref > if), zero if (iref = if), and negative if (iref < if), the command (cde) is:
- zero, if (e) is equal to zero,
- big positive (BP) if (e) is positive both in the increasing and the decreasing cases,
- big negative (BN) if (e) is negative both in the increasing and the decreasing cases,
- negative (N) if (e) is increasing towards zero,
- positive (P) if (e) is decreasing towards zero.

Finally, the fuzzy rules are summarized as follows:
1. If (e) is zero (ZE), then (cde) is zero (ZE).
2. If (e) is positive (P), then (cde) is big positive (BP).
3. If (e) is negative (N), then (cde) is big negative (BN).
4. If (e) is zero (ZE) and (de) is positive (P), then (cde) is negative (N).
5. If (e) is zero (ZE) and (de) is negative (N), then (cde) is positive (P).
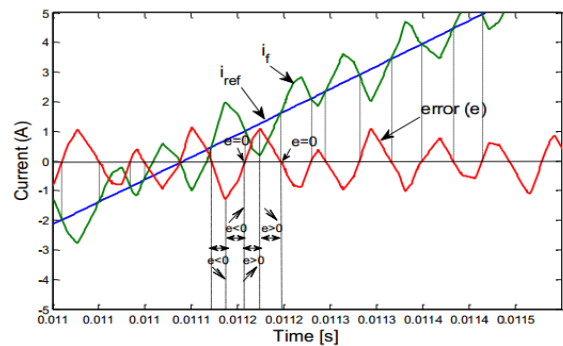

Fig.8. Fuzzy rules establishment.

The fuzzy inference mechanism used in this work is presented as following. The fuzzy rules are summarized in Table 1.

Table 1. Fuzzy Inference Rules

cde (t)		e (t)				
		NB	NS	Z	PS	PB
de (t)	NB	NB	NB	NS	NS	Z
	NS	NB	NS	NS	Z	PS
	Z	NS	NS	Z	PS	PS
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PS	PB	PB

6. Photovoltaic Array Generator

A. Solar Cell Parameter

To be able to develop a complete solar photovoltaic power electronic conversion system in simulation, it is necessary to define a circuit based simulation model for a PV cell in order to allow the interaction between a proposed converter (with its associated control arrangement) and the PV array to be studied. To do this it is necessary to approach the modeling process from the perspective of power electronics; that is to define the desired overall model in terms of the manner in which the electrical behavior of the cell changes with respect to the environmental parameters of temperature and irradiance. The authors cover the development of a general model which can be implemented on simulation platforms such as MATLAB, PSPICE or SABER and is designed to be of use to power electronics specialists. The model accepts irradiance and temperature as variable parameters and outputs the I/V characteristic for that particular cell for the above conditions.

B. Mathematical model for a photovoltaic cell

A mathematical description of the current/voltage (I/V) terminal characteristic for PV cells has been available for some time. The double-exponential equation I, which models a PV cell, is derived from the physics of the p-n junction and is generally accepted as reflecting the behaviour of such cells, especially those constructed from polycrystalline silicon [14] [15]. It is also suggested that cells constructed from amorphous silicon, usually using thick-film deposition techniques, do not exhibit as sharp a 'knee' in the curve as do the crystalline types, and therefore the current/voltage model of equation 1 provides a better fit to such cells. Equation 1 is in effect a subset of the double exponential equation effected by setting the second saturation current IS1 to zero. Both of these equations are implicit and nonlinear and therefore determination of an analytical solution is difficult.

$$ I = I_{ph} - I_{S1}\left[e^{\frac{q(V+IR_s)}{kT}} - 1 \right] - I_{s2}\left[e^{\frac{q(V+IR_S)}{AkT}} - 1 \right] - \frac{V+IR_s}{R_p} \tag{1} $$

$$ I = I_{ph} - I_S\left[e^{\frac{q(V+IR_s)}{kT}} - 1 \right] - \frac{V+IR_s}{R_p} \tag{2} $$

Or:
V: solar cell terminal voltage, Volt,
I: solar cell terminal current, Ampere,
I_{ph}: photogenerated current (linearwith irradiance), Ampere,
I_{S1}: saturation current due to diffusion mechanism, Ampere,
I_{S2}: saturation current due to recombination in space charge layer, Ampere,
A: 'diode quality'factor (variable with cell type for amorphous cells using the single exponential model, but for polycrystalline cells may be set constant to 2 across all cell types; approximation for Shockley-Read-Hall recombination in the space-charge layer),
R_S: cell series resistance, Ohm,
R_p: cell shunt resistance, Ohm,
e: electronic charge, 1.6 x 10-19 C,
k : Boltzmann's constant, 1.38 x 10-23 I/K,
T: ambient temperature, Kelvin.

Working backwards from the equations, an equivalent circuit can be easily determined, and this aids development of the simulation model. This equivalent circuit is shown in figure 9.
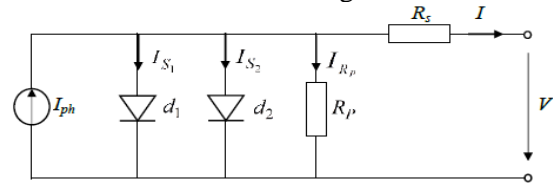

Fig.9. Electrical model of a solar cell with two diodes and a shunt resistor.

$$ I_{ph} = I_{sc} \tag{3} $$

$$ I_S = \frac{I_{ph}}{\left(\exp\left(\frac{V_{oc}}{0.25ec} \right) - 1 \right)} \tag{4} $$

The photovoltaic system includes:
- Nine photovoltaic modules (60 Watt of power each and 1000 W/m^2 of irradiation) ;
- PV array operates at MPP: $P_{PV} = 9*60 = 540\ W$;

- Maximum Power Point Tracking controller (MPPT);
- Boost converter (DC/DC) that steps-up a DC input voltage.

7. Simulation Result and Analysis

A. Photovoltaic system

Figure 10 shows the voltage value obtained by the photovoltaic array and feeds the dc/dc converter, or (V_{PV}= 193.5 V).
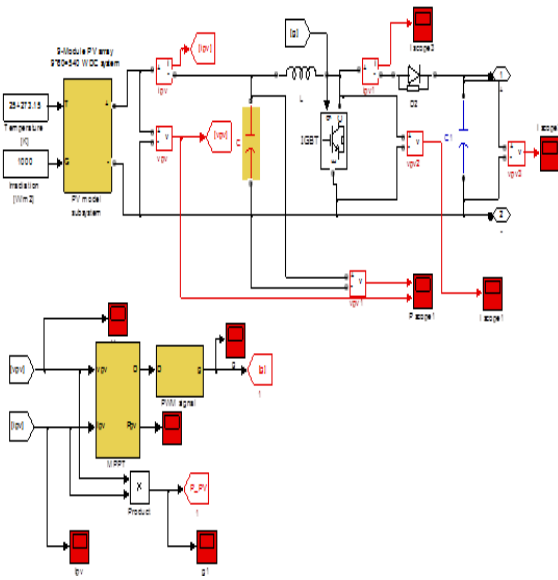
Fig.10. Photovoltaic system developed with Matlab/Simulink

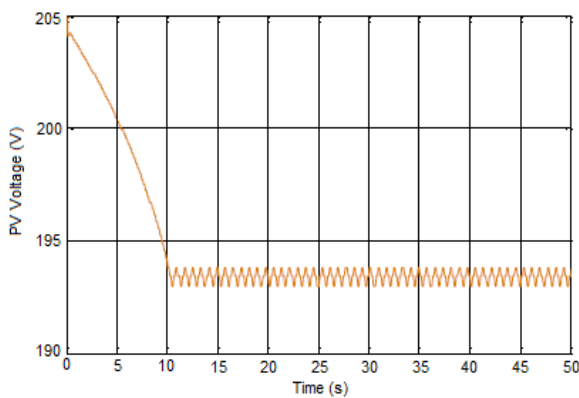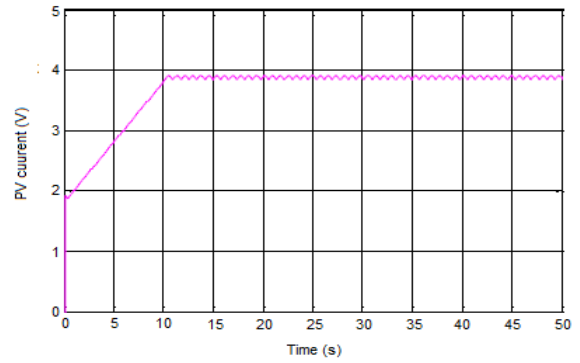Fig. 11. PV array voltage V_{PV}

Fig. 12. Shows PV array current ideally tracks the Boost input current reference, or (I_{PV} =I_{ref} =3.8 A)
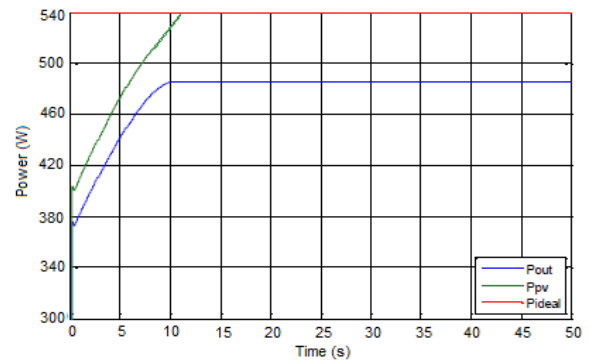
Fig. 13. PV array output power P_{PV} compared to ideal P_{ideal} and MPP P_{out}.

B. Active Power Filter shunt

The Simulink toolbox in the Matlab software in order to model and test the system using P-Q algorithm method then fuzzy logic controller. The system parameters values are summarized in Table 2.

Table 2.Simulation Parameters Common to the Applications Considered

Parameters	Numerical values
Supply's voltage	230 V
frequency	50Hz
Line's inductance L_s	19.4 µH
resistance R_s	0.25 mΩ
DC link's inductance L_{dc}	20 mH
resistance R_{dc}	6.5 Ω

Shunt active filter: DC supply voltage $U_{c1}=U_c/4$	**210 V**
inductance L_f	**1.5 mH**
I_{ref} calculation and Control bloc: 2nd order Band Pass Filter BPF, Cut-off frequency f_0 and Damping Factor Zeta ξ 1st order Low Pass Filter: i_f LPF, i_{ref} LPF, Carrier bipolar saw-toothed, signal magnitude and frequency, Switching frequency	**50 Hz, 0.707 K=1, τ = 50e-6 s K=1,τ = 2e-4 s 10, 20 kHz., 5 kHz**
inductance L_C	**1.5 mH**

C. Characteristics of the Current of Source before Active Filtering

The graphs of the load current before application of the active filter are shown in Fig. 14, 15. Symmetrical current distortion i_{ca} there is from the point of half period (see Fig. 14), which means that multiple harmonics 2 and 3 are absent in the spectrum of i_{ca} and only those of rank (6h ± 1) are present, this is confirmed by the spectrum of i_{ca} (see Figure 15) representing the first 30 harmonics more meaning, with a THD (i_{ca}) of 19.99% for an observation period of 0.1s.
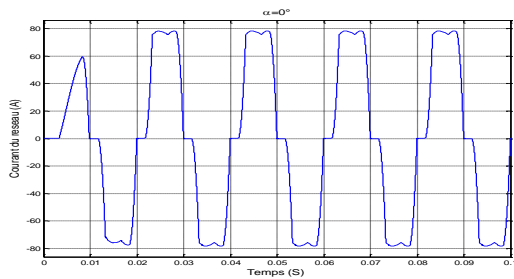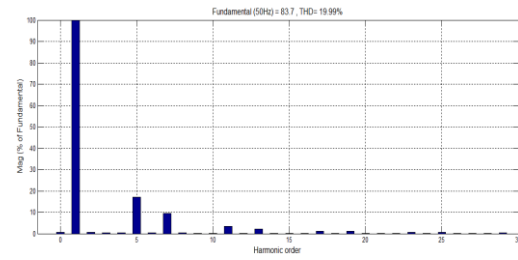

Fig. 14. Allure i_{ca} before active filtering

Fig. 15.Harmonic Spectrum i_{ca}

D. Characteristics of the Current of Source after Active Filtering Using P-Q control strategy
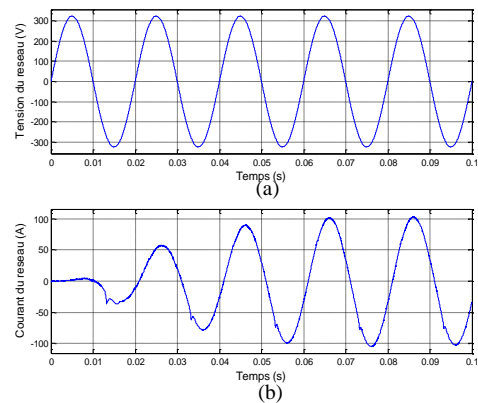

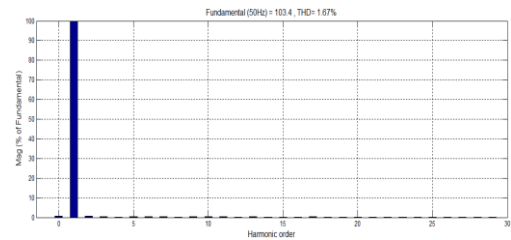Fig. 16. Allure v_{sa} and i_{sa} after filtering with *P-Q*

Fig.17.Spectrum harmonics i_{sa} after filtering with *P-Q*
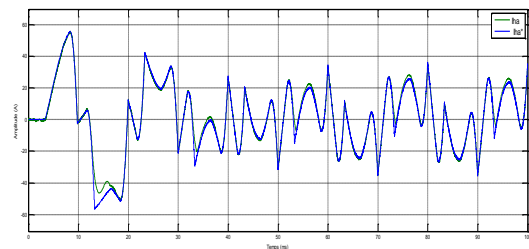

Fig.18. Current generated by the active filter i_{ha} and its reference i_{ha}* with *P-Q*
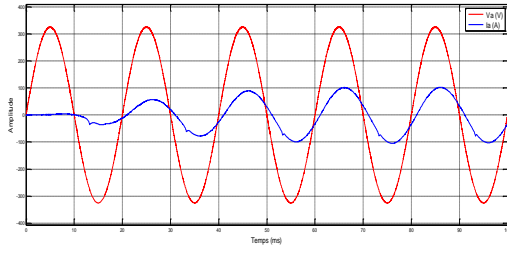
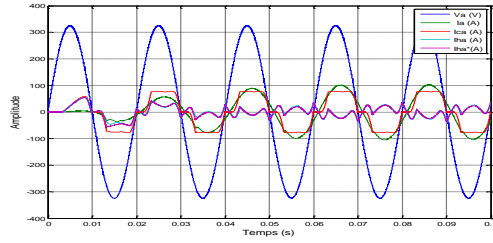Fig.19.Dephasing between the current i_{sa} and the voltage v_{sa} with *P-Q*

Fig. 20. Nonlinear load current i_{ca} , source i_{sa} and filter i_{ha} with *P-Q*

E. Characteristics of the Current of Source after Active Filtering Using Fuzzy Logic controller

Fig. 21. Allure v_{sa} and i_{sa} after filtering with fuzzy Logic controller

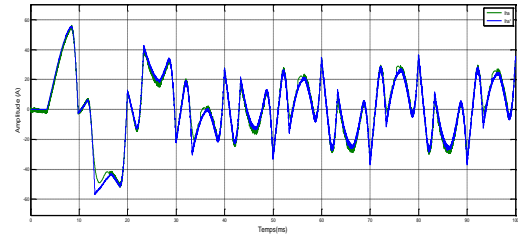Fig. 22. Spectrum harmonics i_{sa} after filtering with fuzzy logic controller

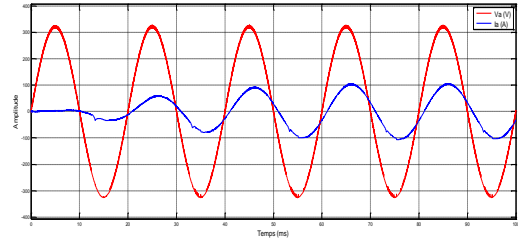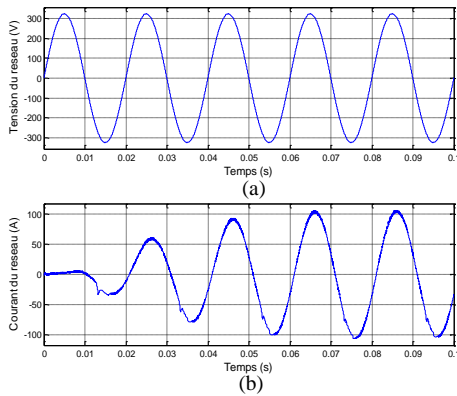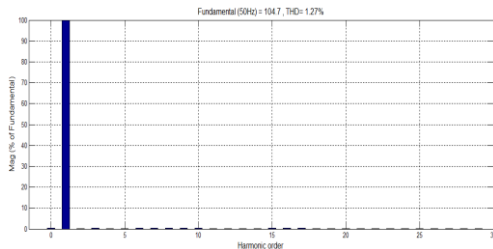Fig. 23. Current generated by the active filter i_{ha} and its reference $i_{ha}*$ with Fuzzy Logic controller

Fig. 24. Dephasing between the current i_{sa} and the voltage v_{sa} with Fuzzy Logic controller
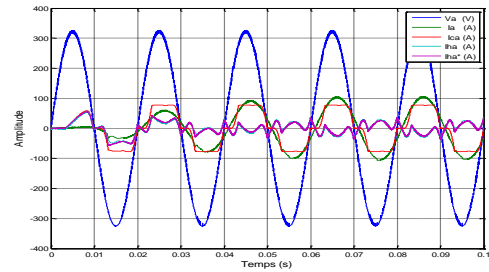
Fig. 25. Nonlinear load current i_{ca} , source i_{sa} and filter i_{ha} with Fuzzy Logic controller

Simulation in this section 3-phase 5-level shunt active power filter response shown here is voltage condition sinusoidal. Simulation is carried out for both instantaneous power theory P-Q and fuzzy logic controller. Fig. 16(a) and Fig. 21(a) shows the source peak line-to-neutral voltages of phases "a" as indicated in v_{sa}. Fig. 16(b) and Fig. 21(b) shows the source currents with P-Q method then fuzzy logic are shown in i_{sa} which shows a value for fuzzy controller a little less than the P-Q algorithm and a better sine wave form during the steady state. Fig. 18 and Fig. 22 show the compensating current injected into the system by the APFs is illustrated in i_{ha}. We see that the filter current i_{ha} well pursues its reference for fuzzy method that the P-Q algorithm. Fig. 17 and Fig. 23 illustrates the performance of Shunt active power filter under balanced sinusoidal voltage condition. THD for P-Q algorithm method is about 1.67% and THD for fuzzy logic controller is 1.27%.

8. Conclusion

The THD measure in the presence of a controlled Shunt Active Power Filter is within the IEEE-519 harmonics standard. The results obtained in this modest work allow us to visualize the effectiveness of an active power filter shunt (APFs) using a P-Q algorithm then a fuzzy controller. In fact, the harmonic distortion (THD) drops after using the parallel active filter from 19.99% to 1.67% for the P-Q algorithm method and to 1.27% for the fuzzy logic controller. Thus the power factor has been fixed, that is to say voltage and current became almost in phase. Summarizes that the Fuzzy Logic controlled based APFs demonstrates a better dynamic behavior than conventional algorithm method P-Q. It does not require any mathematical model of the system and can also work with imprecise inputs.

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