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Comparative Study between Classical P-Q Method and Modern Fuzzy Controller Method to Improve the Power Quality of an Electrical Network

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***Abstract*—**This article presents two methods for the compensation of harmonics generated by a nonlinear load. The first is the classic method P-Q. The second is the controller by modern method of artificial intelligence specifically fuzzy logic. Both methods are applied to a shunt Active Power Filter (sAPF) based on a three-phase voltage converter at five levels NPC topology. 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.

***Keywords*—**Fuzzy logic controller, P-Q method, Pulse Width Modulation (PWM), shunt Active Power Filter (sAPF), Total Harmonic Distortion (THD).

I. Introduction

THE increasing use of control systems based on power electronics in industry involves more and more disturbance problems in the level of the electrical power supply networks [1], [2]. Non-linear electronic components such as diode/thyristor rectifiers, switched mode power supplies, arc furnaces, incandescent lighting and motor drives are widely used in industrial and commercial applications. These non-linear loads create harmonic or distortion current problems in the transmission and distribution network. The harmonics induce malfunctions in sensitive equipment, over voltage by resonance and harmonic voltage drop across the network impedance that affect power quality [3].

Researchers around the world are developing a shunt Active Power Filter (sAPF) to improve the power quality without the disadvantages of passive filters described in [4], [5]. The power switching devices is driven with specific control strategy to produce current that is able to compensate for harmonic and poor power factor load.

In this work, we took the inverter supplied with four identical continuous sources that can replace by other sources like solar photovoltaic energy.

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II. Shunt Active Power Filter (sAPF)

Shunt Active Power Filter (sAPF) 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].

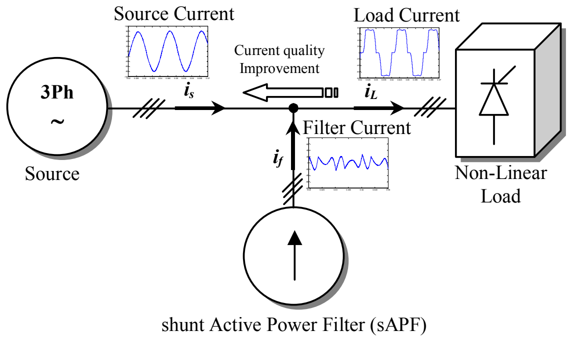


Fig. 1 Shunt Active Power Filter Principle Schematics

The most important objective of the APF is to compensate the harmonic currents 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 Fig. 2, The reference current consists of the harmonic components of the load current which the active filter must supply [7], [8]. sAPF is controlled to supply/extract compensating current to/from the utility Point Common Coupling (PCC).

III. Multilevel Inverter Illustration

A. Modeling of Three-Phase Inverter a Five-Level NPC Topology

The topology modeled in this study is the voltage inverter three phase five-level topology NPC (Neutral Point Clamp) [9], [10]. Fig. 3 shows the voltage three-phase five-level NPC topology inverter. The symmetry of three-phase five-level inverters can model them by leg [11]-[13].

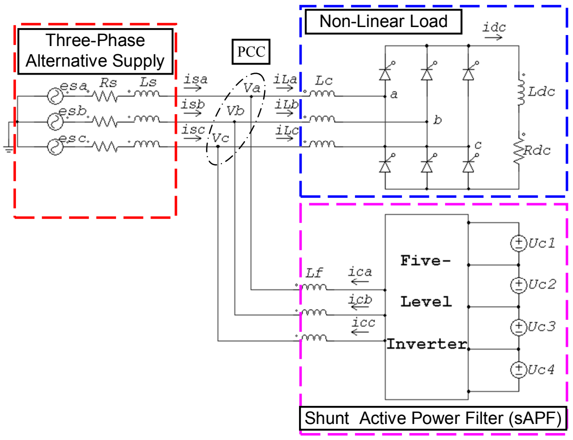


Fig. 2 Equivalent Schematic of sAPF Five Levels

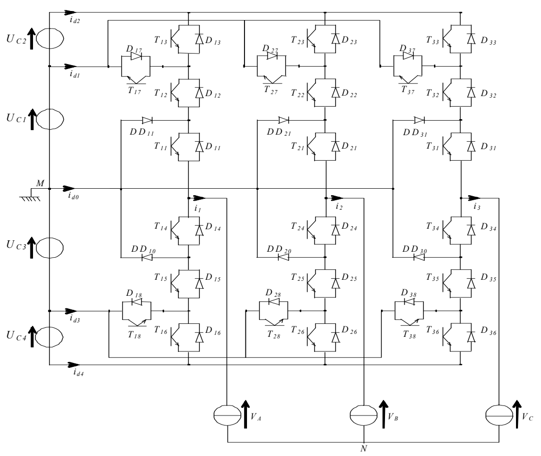


Fig. 3 Three-Phase Inverter a Five-Level NPC Topology

To avoid short-circuit voltage sources by conducting several switches, and the inverter is completely controllable, we adopt an additional control, the optimal control is defined as:

$$\begin{cases} F_{k4} = 1 - F_{k2} \\ F_{k5} = 1 - F_{k1} \\ F_{k6} = 1 - F_{k3} \end{cases}, \tag{1}$$

For the arm k, the connection functions of half arm expressed by means of connection functions of the switches as follows where $k = 1, 2, 3$:

$$\begin{cases} F^b_{k1} = F_{k1}.F_{k2}.F_{k3} \\ F^b_{k0} = F_{k4}.F_{k5}.F_{k6} \end{cases}, \tag{2}$$

Connect functions for switches in parallel are defined as:

$$\begin{cases} F_{k7} = F_{k1}F_{k2}(1 - F_{k3}) \\ F_{k8} = F_{k4}F_{k5}(1 - F_{k6}) \end{cases}, \tag{3}$$

Potentials of nodes A, B and C of Three phase five-level inverter relatively to the middle point M in the case $U_{C1} = U_{C2} = U_{C3} = U_{C4} = U$ are given by:

$$\begin{bmatrix} V_{AM} \\ V_{BM} \\ V_{CM} \end{bmatrix} = \begin{bmatrix} F_{17} + 2F^b_{11} - F_{18} - 2F^b_{10} \\ F_{27} + 2F^b_{21} - F_{28} - 2F^b_{20} \\ F_{37} + 2F^b_{31} - F_{38} - 2F^b_{30} \end{bmatrix} U_C, \tag{4}$$

The voltages across the load are given by the following system:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \left\{ \begin{bmatrix} F_{17} + 2F^b_{11} - F_{18} - 2F^b_{10} \\ F_{27} + 2F^b_{21} - F_{28} - 2F^b_{20} \\ F_{37} + 2F^b_{31} - F_{38} - 2F^b_{30} \end{bmatrix} U_C \right\}, \tag{5}$$

B. The Four Carriers Sinusoidal Pulse Width Modulation Strategy

In this section we will present the strategy triangulo-sinusoidal with four triangular bipolar carriers [13], [14] (Fig. 4) where we use four signals bipolar triangular (U_{p1}, U_{p2}, U_{p3}, U_{p4}) dephased one relative to another by one quarter of the period (Tp/4). As for the triangulo-sinusoidal command at a one carrier, this strategy is characterized by the modulation index m.

$$m = \frac{f_{pm}}{f_m}, \tag{6}$$

$$r = \frac{V_m}{U_{pm}}, \tag{7}$$

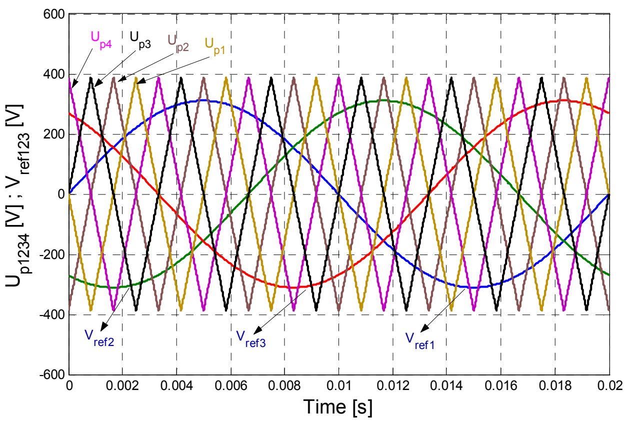


Fig. 4 Different signals for the four carriers sinusoidal pulse width modulation strategy (m = 6, r = 0.8)

IV. Method of Instantaneous Power

A. Instantaneous Active and Reactive Powers

This method of identification of harmonic currents, simpler is to eliminate the dc component of instantaneous active and reactive power which is relatively easy to achieve. Respectively denote the vectors of voltages at the connection point $[v_s]$ and load currents$[i_c]$ a balanced three-phase system by:

$$[v_s]=\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \text{and} [i_c]=\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix}, \tag{8}$$

The transformation of three-phase instantaneous values of voltage and current in the reference frame of coordinates is given by:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix}, \tag{9}$$

and currents:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix}, \tag{10}$$

The real and imaginary instantaneous power denoted p and q are defined by the following matrix relation:

$$\begin{bmatrix} p \\ q \end{bmatrix}=\begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ -v_{s\beta} & v_{s\alpha} \end{bmatrix}\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}, \tag{11}$$

By replacing the two-phase voltages and currents by their counterparts phase, we obtain:

$$p = v_{s\alpha}i_{c\alpha} + v_{s\beta}i_{c\beta} = v_{sa}i_{ca} + v_{sb}i_{cb} + v_{sc}i_{cc}\,, \tag{12}$$

Similarly, for the imaginary power we have:

$$q = v_{s\alpha}i_{c\beta} - v_{s\beta}i_{c\alpha} = -\frac{1}{\sqrt{3}}\left[(v_{sa}-v_{sb})i_{cc} + (v_{sb}-v_{sc})i_{ca} + (v_{sc}-v_{sa})i_{cb}\right], \tag{13}$$

From (11), asking:

$$\Delta = v_{s\alpha}^2 + v_{s\beta}^2$$

We have:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}=\frac{1}{\Delta}\left\{\begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix}\begin{bmatrix} p \\ q \end{bmatrix}\right\}, \tag{14}$$

or:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}=\frac{1}{\Delta}\left\{\begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix}\begin{bmatrix} p \\ 0 \end{bmatrix}+\begin{bmatrix} v_{s\alpha} & -v_{s\beta} \\ v_{s\beta} & v_{s\alpha} \end{bmatrix}\begin{bmatrix} 0 \\ q \end{bmatrix}\right\}=\begin{bmatrix} i_{c\alpha p} \\ i_{c\beta p} \end{bmatrix}+\begin{bmatrix} i_{c\alpha q} \\ i_{c\beta q} \end{bmatrix}, \tag{15}$$

with:

$$i_{c\alpha p} = \frac{v_{s\alpha}}{\Delta}p \quad i_{c\alpha q} = -\frac{v_{s\beta}}{\Delta}q\,, \tag{16}$$

$$i_{c\beta p} = \frac{v_{s\beta}}{\Delta}p \quad i_{c\beta p} = \frac{v_{s\alpha}}{\Delta}p\,, \tag{17}$$

The instantaneous power along the axes and can be written:

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix}=\begin{bmatrix} v_{s\alpha}i_{c\alpha} \\ v_{s\beta}i_{c\beta} \end{bmatrix}=\begin{bmatrix} v_{s\alpha}i_{c\alpha p} \\ v_{s\beta}i_{c\beta p} \end{bmatrix}+\begin{bmatrix} v_{s\alpha}i_{c\alpha q} \\ v_{s\beta}i_{c\beta q} \end{bmatrix}=\begin{bmatrix} p_{\alpha p} \\ p_{\beta p} \end{bmatrix}+\begin{bmatrix} p_{\alpha q} \\ p_{\beta q} \end{bmatrix}, \tag{18}$$

$$p_{\alpha p} = \frac{v_{s\alpha}^2}{\Delta}p \quad p_{\alpha q} = -\frac{v_{s\alpha}v_{s\beta}}{\Delta}q\,, \tag{19}$$

$$p_{\beta p} = \frac{v_{s\beta}^2}{\Delta}p \quad p_{\beta q} = \frac{v_{s\alpha}v_{s\beta}}{\Delta}q\,, \tag{20}$$

From (12), we can write:

$$p = p_{\alpha p} + p_{\beta p} + p_{\alpha q} + p_{\beta q} = p_{\alpha p} + p_{\beta p} \tag{21}$$

The instantaneous powers p and q are expressed as:

$$\begin{aligned} p &= \overline{p} + \widetilde{p} \\ q &= \overline{q} + \widetilde{q} \end{aligned}\,, \tag{22}$$

With: $\overline{p}$ and $\overline{q}$: Continuous power related to the active and reactive fundamental component of the current; $\widetilde{p}$ and $\widetilde{q}$: Power alternatives related to the sum of harmonic components of current [15].

$$\begin{bmatrix} i_{ha}^* \\ i_{hb}^* \\ i_{hc}^* \end{bmatrix}=\sqrt{\frac{2}{3}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \sqrt{\frac{3}{2}} \\ -\frac{1}{2} & -\sqrt{\frac{3}{2}} \end{bmatrix}}\begin{bmatrix} i_{h\alpha}^* \\ i_{h\beta}^* \end{bmatrix}, \tag{23}$$

Fig. 5 shows the steps for obtaining the current harmonic components of nonlinear load [16].

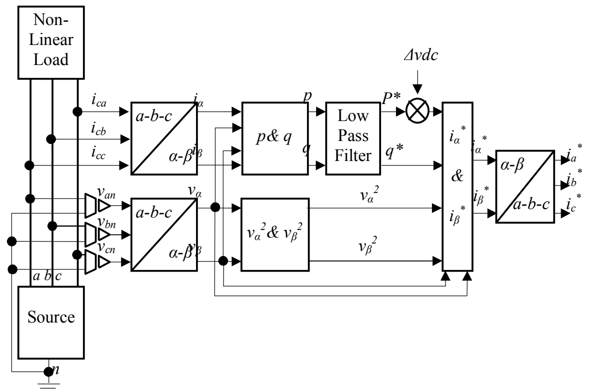


Fig. 5"P-Q" Algorithm Extraction of Harmonic Currents

B. Apparent Power, Reactive Power and Distortion Power

Steady deformed, it must amend the definition of power so that it reflects the current harmonic:

$$S = \sqrt{P^2 + Q^2 + D^2}\,, \tag{24}$$

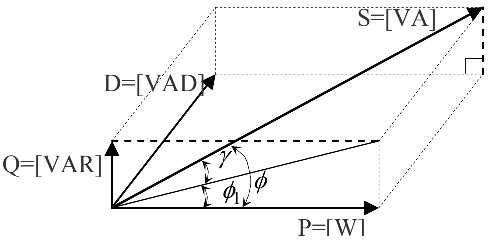


Fig. 6 Vector Representation of Apparent Power

In single phase, if the instantaneous voltage and current are expressed as:

$$v(t) = \sqrt{2}V_{eff}\sin(\omega t)$$
$$i(t) = \sum_{n=1}^{\infty}\sqrt{2}I_{n,eff}\sin(n\omega t + \phi_n) \quad (25)$$

This is the case for a strong network. Then we have:

$$P = VI_1\cos(\phi_1), \quad (26)$$

$$Q = V_{eff}I_{1,eff}\sin(\phi_1), \quad (27)$$

$$S = V_{eff}I_{eff}, \quad (28)$$

$$I_{eff} = \sqrt{I_{1,eff}^2 + I_{2,eff}^2 + I_{3,eff}^2 + ... + I_{n,eff}^2}, \quad (29)$$

$$D = V\sqrt{I_{2,eff}^2 + I_{32,eff}^2 + ... + I_{n,eff}^2}, \quad (30)$$

C. Total Harmonic Distortion (THD)

Our work focuses on using a parallel active filter, which means we need to calculate the Total Harmonic Distortion of current, as shown in:

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty}I_{n(rms)}^2}}{I_{1(rms)}}, \quad (31)$$

V. Fuzzy Logic Controller

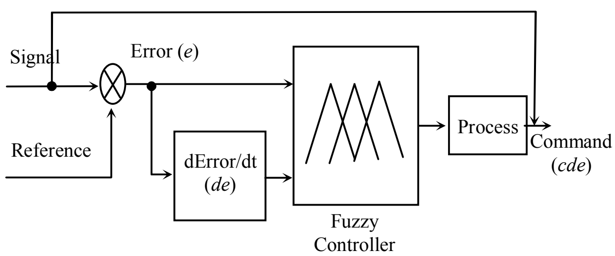


Fig. 7 Fuzzy Controller Synoptic Diagram

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 [17]. Fig. 7 shows the synoptic scheme of fuzzy controller, which possesses two inputs: the error (*e*), ($e = i_{ref} - i_f$) and its derivative (*de*), and one output: the command (*cde*).

Fig. 8 illustrates stages of fuzzy control in the considered base of rules and definitions: fuzzification, inference mechanism, and defuzzification.

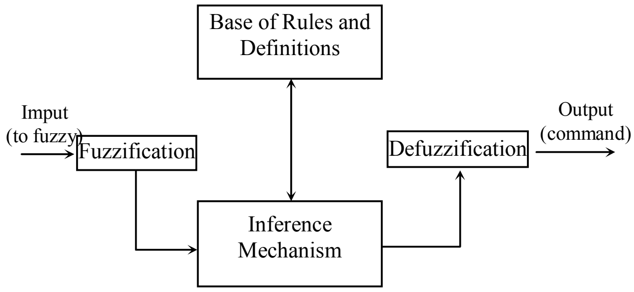


Fig. 8 Fuzzy Control Construction

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.

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).

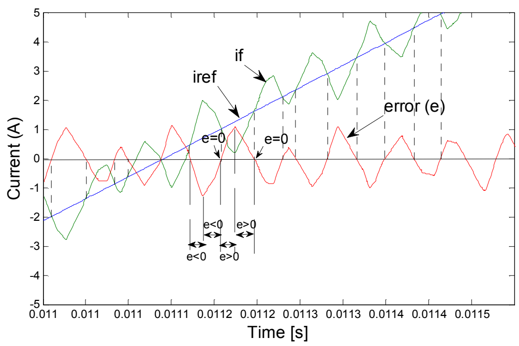


Fig. 9 Fuzzy Rules Establishment

The fuzzy inference mechanism used in this work is presented as following. The fuzzy rules are summarized in Table I [18].

Fig.10 shows surface file viewer fuzzy for the error and its derivative and the command signal respectively.

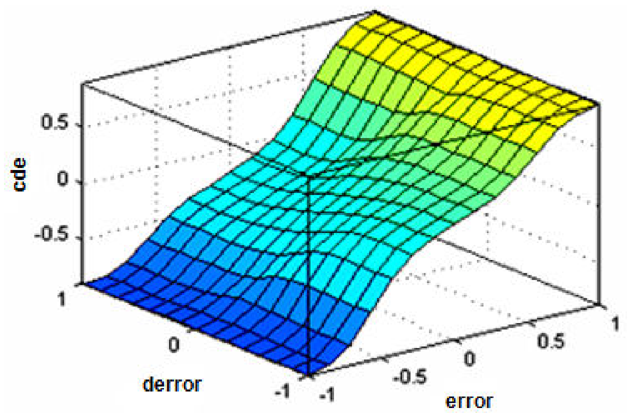


Fig. 10 Surface Viewer

VI. Simulation Results and Analysis

The system parameters values are summarized in Table I.

TABLE I
Simulation Parameters Common to the Applications Considered

Supply's voltage & frequency	220Vrms, 50 Hz
Line's inductance L_s& resistance R_s	19.4 µH, 0.25 mΩ
DC link's inductance L_{dc}& resistance R_{dc}	20 mH, 6.5 Ω
inductance L_C	1.8 mH
Shunt active power filter:	
DC supply voltage $U_{c1}=U_c/4$& inductance L_f	210 V,2.2 mH
i_{ref}calculation & Control bloc:	
2nd order Band Pass Filter BPF, Cut-off frequency f_0&	50 Hz,0.707
Damping Factor Zeta ξ	K=1, τ = 50e-6 s
1st order Low Pass Filter: i_fLPF, i_{ref}LPF,	K=1,τ = 2e-4s
Carrier bipolar saw-toothed, signal magnitude and	10, 20 kHz.,
frequency, Switching frequency	5 kHz.

Simulation in this section three-phase five-level shunt active power filter response shown here i_s voltage condition sinusoidal. Simulation is carried out for both instantaneous power theory P-Q and fuzzy logic controller.

Fig. 11 (a) shows the source peak line-to-neutral voltages of phases "a", "b" and "c" as indicated in v_{sabc}.

Fig. 11 (b) shows the distorted source or load currents due to the presence of the nonlinear load and when APFs is not connected as indicated in i_{La}.

Fig. 11(c) 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. 11(d) shows the compensating current injected into the system by the APFs is illustrated in i_{ca} and similar currents are injected into phases "b" and "c" for both methods.

We see that the filter current i_{ca} well pursues its reference for fuzzy method that the P-Q algorithm as indicated by the two figures in Fig. 11(e).

However, a THD_i is greater than 5 percent is unacceptable according to international standards [19]. Indeed, there are distortions in the current wave source. The latter are especially at intersections of i_{La} (current drawn by the nonlinear load) with i_{ca} for nonzero values of these two currents (as indicated in i_{La}, i_{sa} and i_{ca} curves), i.e. when i_{ca} changes direction of growth (up to down or down to up), (see Fig. 11(f), more precisely, it is at (di_{ca}/dt). Therefore, to reduce these distortions and make the THD_i is less than 5 percent, we must counter these (di_{ca}/dt).

Fig. 11(g) illustrates the performance of shunt active power filter under balanced sinusoidal voltage condition. THD for P-Q algorithm method is about 1.24% and THD for fuzzy logic controller is 0.80%.

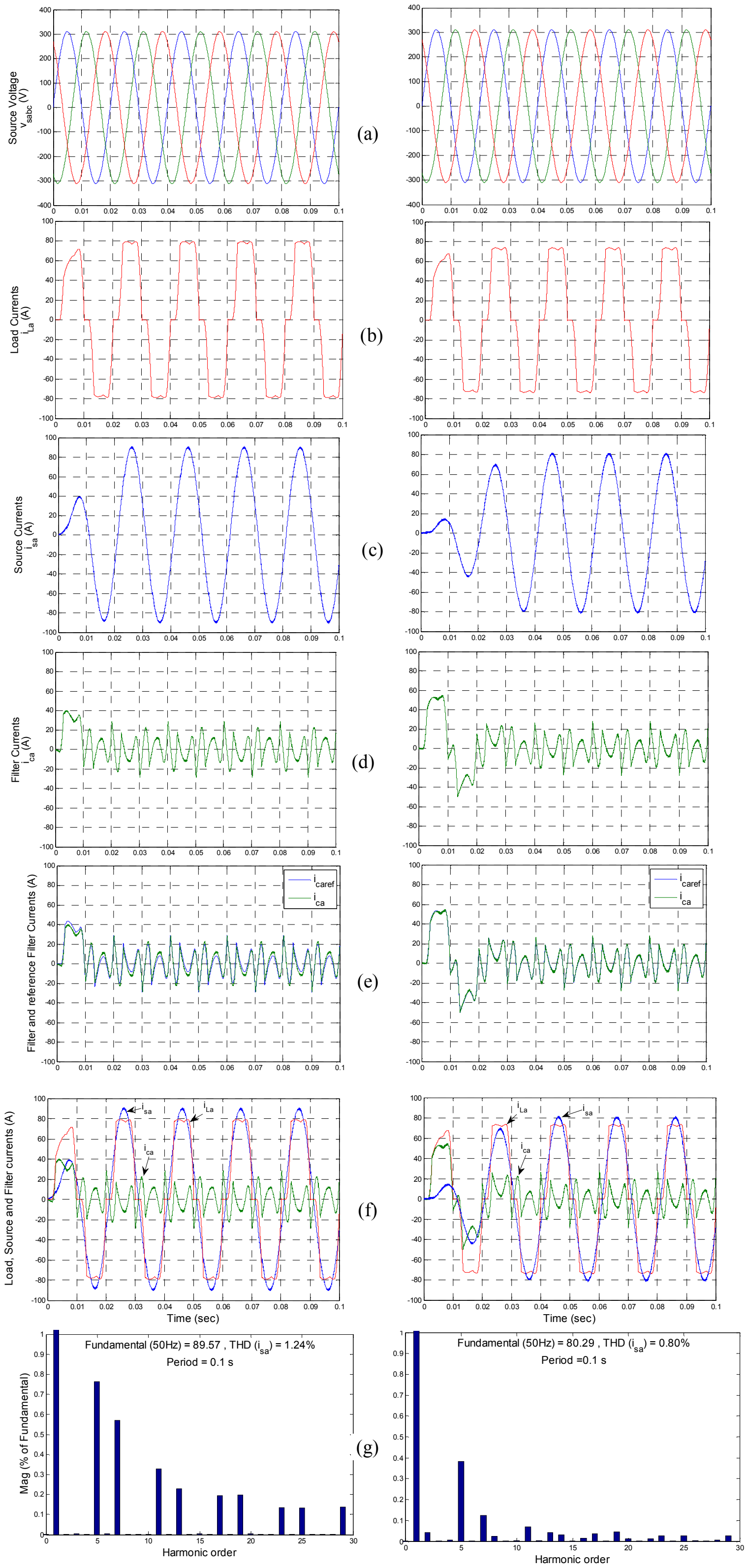
VII. Conclusion

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 a shunt active power filter (sAPF) using a P-Q algorithm then a fuzzy controller.

In fact, the harmonic distortion (THD) drops after using the parallel active filter from 19.20% to 1.24% for the P-Q algorithm method and to 0.80% for the fuzzy logic controller. Thus the power factor has been fixed, that is to say voltage and current became almostin 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.



Using P-Q control strategy *Using Fuzzy Logic controller*

Fig. 11 Comparison results between the P-Q method and the fuzzy controller for ashunt Active Power Filter 5-Level

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