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Three -phase Active Power Filter Based on Fuzzy Logic Controller

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ABSTRACT. *Among the various available power filter controllers, such as IP, RST, and with adaptive control, the fuzzy controller, which is used to design controllers with complex dynamics, has been applied on three phase shunt Active Power Filter (APF). In our application, the fuzzy control algorithm is used to control the dc side capacitor voltage in order to improve the APF dynamics, to reduce the source current total harmonic distortion and to produce a high power quality.*

RÉSUME. *Parmi les divers régulateurs disponibles de filtre de puissance, tels que l'IP, le RST, et avec commande adaptative, le régulateur flou, utilisé dans la conception des contrôleurs à dynamique complexe, a été appliqué au filtre actif de puissance shunt (APF) triphasé. Dans notre application, l'algorithme commande floue sert à réguler la tension continue du condensateur de régulation dans le but d'améliorer la dynamique de l'APF, réduire la distorsion harmonique globale du courant de source et produire une bonne qualité de l'énergie.*

KEYWORDS. Shunt active power filter, fuzzy logic controller, hysteresis control, power quality.

MOTS-CLES. Filtre actif de puissance shunt, régulateur à logique floue, commande à hystérésis, qualité de l'énergie.

1. Introduction

A large number of low-power-electronic-based appliances are nonlinear loads that generate considerable disturbance in AC mains. The proliferation of nonlinear loads still continues with the increasing domestic and industrial needs. This results in deterioration of voltage waveforms quality, harmonic distortion, power losses and equipment damage risk.

To avoid these undesirable effects, traditional solutions using passive LC filters have been used, but they are ineffective due to their inability to adapt to network characteristic variation. Therefore, recent progress in switching devices has resulted in the formulation of several active filter topologies. [1, 2]

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Since recent years, APFs have been studied to compensate for reactive power, harmonics and flicker in industrial power systems [3]. Active filters may be put in series or in parallel with polluting loads just as with passive filters. Active and passive filters may be combined to form the so called hybrid filters [1], [3]. The objective of the active filters is to generate currents that are equal but opposite to the harmonic currents. The active shunt filter is connected in parallel with the load. The current produced by the active filter is the following:

$$i_f = i_L - i_s \tag{1}$$

Where i_L is the distorted load current, and i_s is the fundamental current, delivered by the mains supply. Therefore only the fundamental current would be delivered by the mains supply. The performance of active filters is based on the inverter parameters, the control method and the current reference synthesis method. These active filters are then used to reduce harmonics and to get a power factor close to the unity.

In this paper, dealing with a shunt APF topology that achieves simultaneously harmonic current damping, and power factor correction, the extended description of the application of this new approach for the APF's reference current computation is presented. For pulses generation, the hysteresis control has been employed.

The theoretical study is validated through simulations with Matlab-Simulink© package. The remainder of the paper is organized as follows: section (2) focuses on describing the shunt APF principle, topology and modeling. Section (3) emphasizes on the proposed control scheme. Section (4) presents the control strategy. Finally, a summary of the main simulation results and comments is presented.

2. Shunt APF principle and topology description

2.1. Principle

An APF is capable of solving many problems occurring in the electrical power feeder [4], [5]:

1- Harmonic distortion (of any phase sequence),
2- Fundamental-frequency reactive power (non-unity displacement factor),
3- Negative-sequence fundamental components (unbalance components),
4- Zero-sequence fundamental components (neutral line current),

To achieve these goals, especially in shunt configurations, source currents must be in phase with the positive sequence fundamental source voltage component.

Here, the role of the shunt active power filter is mainly to generate exactly the same harmonics contained in the polluting current but with opposite phase [3].

2.2. Topology Description

Fig.1 describes the structure of the considered topology. The proposed APF is based on a three-phase voltage inverter. Each arm contains two pairs of isolated gate bipolar transistors (IGBT) with anti-paralleling diodes. The polluting load is modelled by a bridge of a diode rectifier.

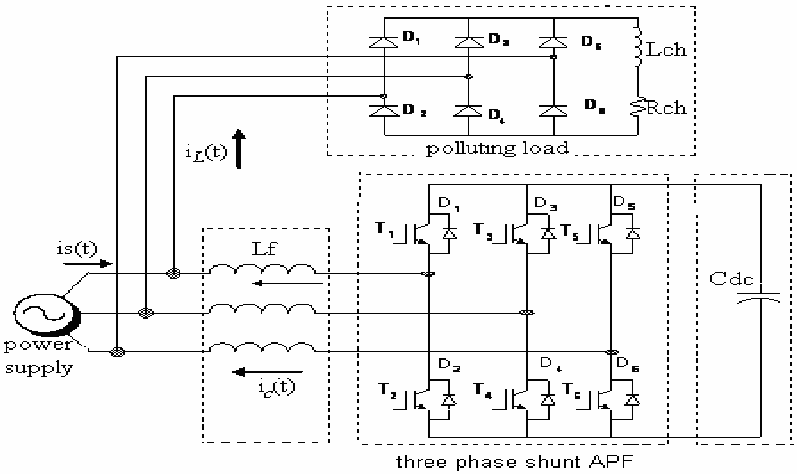


Fig. 1. Shunt active power filter topology.

Fig.1 shows the block diagram of the shunt APF under study. The active filter is composed of a three phase voltage source inverter with an ac inductor (L_f) and a dc bus capacitor (C_{dc}) to provide a constant dc voltage and the real power necessary to cover the losses of the system. A three-phase ac supply system $(v_{sa}, v_{sb}$ *and* $v_{sc})$ with line impedance (R_s and L_s).

The APF performance depends on power semiconductor devices design, switches modulation control technique and coupling elements design [5].

In this paper, global current harmonics compensation is studied. To compensate harmonics and fundamental reactive power, two equivalent current control methods can be considered, according to whether the regulated variables are the line currents (i_s) or the active power filter currents (i_f) [5]. Our algorithm focuses on directly calculating and controlling the mains currents. The objective is to get sinusoidal line currents in phase with the supply voltages at the common coupling point. The peak detector method is used to determine the current references [6]. The supply voltages at the common coupling point are considered to be sinusoidal and balanced.

The goal of this research work is to optimize the hysteresis technique using fuzzy logic controllers as well as the passive parameters of the active filter by using appropriate robust voltage controller.

2.3 Estimation of reference source current

The instantaneous reference lines- currents ($i_{saref}, i_{sbref}, i_{scref}$) *are* calculated from the multiplication of the three unity current vectors ($\sin(wt), \sin(wt - \frac{2\pi}{3})$, $\sin(wt + \frac{2\pi}{3})$) by the peak value of line-current $I_{s\max}$.

From the peak detector method; V_{smax} is obtained from the equation:

$$V_{smax} = \sqrt{2/3(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \quad (2)$$

2.4 Design of DC side Capacitor (C_{dc})

The determination of the energy-storage capacitor value is made either on the instantaneous released/stored capacitor energy to support the step increase/reduction in the power consumed by the load, using the energy-balance concept [7].

In such approach, the capacitor may have to supply the real power demand of the load during one cycle of the utility voltage in the worst case of transient. Hence, the capacitor value equation based on the energy-balance concept is:

$$\begin{aligned} \frac{1}{2} C_{dc}(V_{dcref}^2 - V_{dc}^2(t)) &= \Delta E_c(t) \\ &= \frac{1}{2} V_{s\max} \Delta I_L T \end{aligned} \quad (3)$$

Therefore, three capacitor voltage values are obtain on the basis of the following three situations:

- Step increase of the real fundamental component of the load current (C_{dc1}) :

$$\frac{1}{2} C_{dc1}(V_{dcref}^2 - V_{dc,\min}^2) = \frac{1}{2} V_{s\max} \Delta I_{L1} T \quad (4)$$

Where,

$V_{dc,\min}$: The pre-set lower limit of the energy storage capacitor voltage.

$V_{s,\max}$: The maximum voltage of the utility source.

T: is the period of the utility voltage source.

- Step reduction of the real fundamental component of the load current (C_{dc2}) :

$$\frac{1}{2} C_{dc2}(V_{dc,\max}^2 - V_{dcref}^2) = \frac{1}{2} V_{s\max} \Delta I_{L2} T \quad (5)$$

$V_{dc,\max}$: The pre-set upper limit of the energy storage capacitor voltage.

- Reactive and harmonic components of the load current during steady state (C_{dc3}):

$$\frac{1}{2}C_{dc3}\,(V_{dc,\Delta}^{2}-V_{dcref}^{2})=\frac{1}{2}V_{s\max}\Delta I_{L3}T \qquad (6)$$

The largest value of $(C_{dc1}, C_{dc2}\ et\ C_{dc3})$ is selected, if the sinusoidal current waveform during the transient is to be preserved. Otherwise ; (C_{dc3}) is the chosen capacitor value [7].

3. Proposed control scheme

The APF dc bus voltage V_{dc} is used in the control design loop and should be regulated at a set value V_{dcref} .

Fig.2 shows the bloc diagram of the proposed control scheme of shunt APF. The dc side capacitor voltage is sensed; then compared with a reference value. The signal error of comparison between the sensed voltage (V_{dc}) and its reference (V_{dcref}) is the input signal of the fuzzy regulator. The output of this regulator is considered as the peak value of line-current ($I_{s\max}$). This current takes into account both the active power demand of the load and the losses in the system.

The switching signals for the hysteresis converter are obtained in two steps:

First: by subtracting the actual load currents $(i_{La}, i_{Lb}\ and\ i_{Lc})$ from the reference current template ($i_{saref}, i_{sbref}, i_{scref}$), so; we get the instantaneous reference current of the APF $(i_{faref}, i_{fbref}\ and\ i_{fcref})$.

Second: by subtracting $(i_{faref}, i_{fbref}\ and\ i_{fcref})$ from the actual compensating current line, so; we get the gating pulses for voltage source inverter APF bridge.

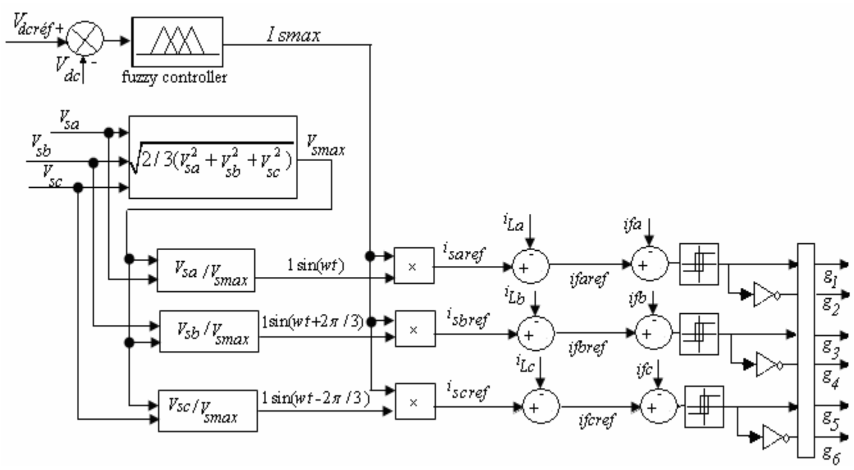


Fig. 2. Bloc diagram of direct current control

3.1 Proposed fuzzy control scheme

Fuzzy logic controller is becoming an increasing area of research in power electronics, this controller is based on the fuzzy set theory which takes its fundamentals from human thinking.

In order to implement the control algorithm of a shunt APF in closed loop, the dc side capacitor voltage is sensed and then compared with a reference value. The obtained error $(e = V_{dcref} - V_{dc})$ and change of error signal $ce(n) = e(n) - e(n-1)$ at the nth sampling instant are used as input for the fuzzy processing. The output of the fuzzy controller after a limit is considered as the amplitude of the reference current $I_{S\max}$ (Fig.3).

A fuzzy controller consists of stages: fuzzification, knowledge base, inference mechanisms, and defuzzification. The knowledge base is composed of a data base and a rule base, and is designed to obtain good dynamic response under uncertainty in process parameters and external disturbances. The data base, consisting of input and output membership functions, provides information for the appropriate fuzzification operations, the inference mechanism, and defuzzification. The inference mechanism uses a collection of linguistic rules to convert the input conditions into a fuzzified output. Finally, defuzzification is used to convert the fuzzy outputs into control signals [7, 8].

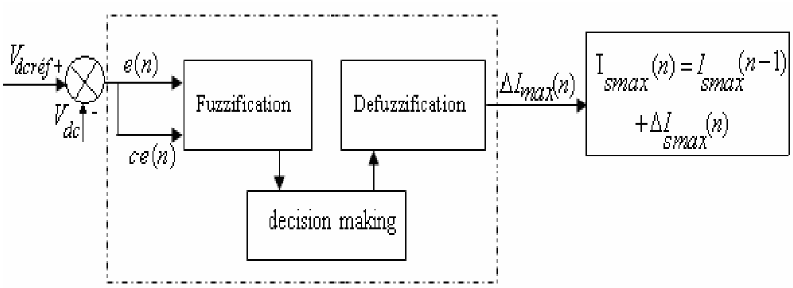


Fig. 3. Internal structure of fuzzy logic controller

3.2 Basic fuzzy algorithm

The fuzzy controller is characterized as follows:

1- Seven fuzzy sets for each input and outputs: NB (negative big) NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PB (positive big).

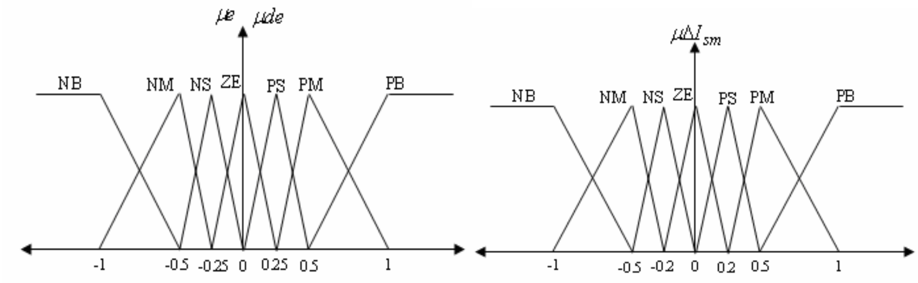
2- Triangular membership functions for simplicity.

3- Fuzzification using continuous universe of discourse.

4- Implication using Mamdani's 'min' operator.

5- Defuzzification using the 'height' method.

Fig.4 shows the normalized triangular membership functions used in fuzzification; Fig.4 (a) for e and ce and Fig.4 (b) for $\delta I_{\max}$:



-a- error and change in error -b- change in reference current

Fig. 4. Normalized triangular membership functions used in fuzzification.

3.3 Design of control rules

The fuzzy control rule design involves defining rules that relate the input variables to the output model properties.

For better control performance finer fuzzy partitioned subspaces are used and summarized in table 1:

		error (e)						
		NB	NM	NS	ZE	PS	PM	PB
change in error c(e)	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NP	NB	NB	NM	NS	ZE	PS	PM
	EZ	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

Table 1. Control rule table

The elements of table.1 are determined based on the theory that in the transient state, large error need coarse control, which requires coarse input/output variables; in the steady state, however, small errors need fine control, which requires fine input/output variables. Based on this, the elements of the rule table are obtained from an understanding of filter behaviour and modified by simulation performance [8, 9].

3.4 Hysteresis current control

The hysteresis current control with fixed band can be implemented to generate the switching pattern in order to get precise and quick response. The hysteresis band current control technique has proven to be most suitable for all applications of current controlled voltage source inverters in APF [7].

This strategy of control drives the inverter switching signals from the comparison of the current error to keep the current within the hysteresis band.

The error signals are operated by the hysteresis current control to generate the firing pulses which activate the inverter power switches in a manner that reduces the current error.

4. 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 indicated in table 2:

Fundamental frequency	$50Hz$
AC supply voltage	$V_S = 100V$
AC supply load	$R_S = 0.1\Omega$ $L_S = 0.15mH$
Rectifier load	$R_L = 6.7\Omega$ $L_L = 20mH$
APF inductor	$Lf = 0.66mH$
APF C_{dc} link capacitor	$Cdc = 2200\mu F$
APF dc link voltage reference	$V_{dcref} = 220V$

Table 2. Design specifications and circuit parameters

4.1 Case one: Steady state operation

The source current waveform in a-phase is shown in Fig.5 (a) and demonstrates that controller can exactly keep track the current component. Fig.5 (b) and Fig.5 (c) shows respectively the load and compensating currents.

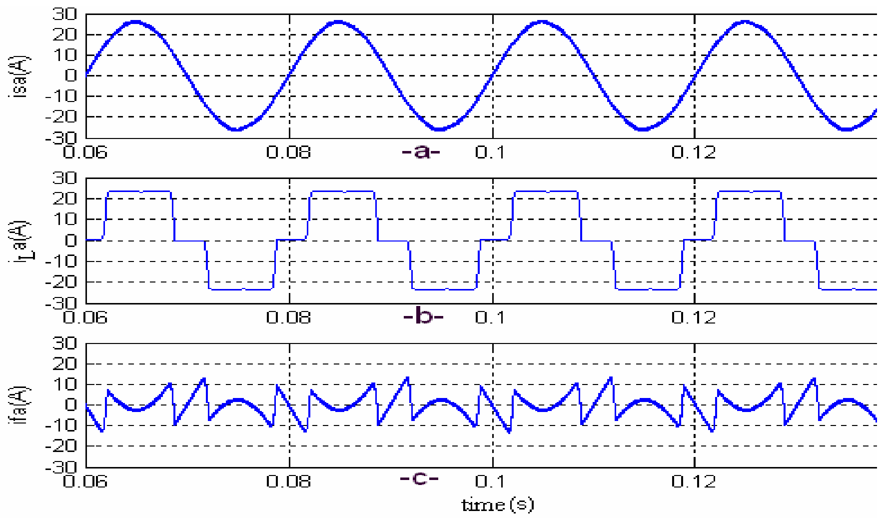


Fig. 5. (a) Supply current; (b) load current; (c) compensating current waveform after harmonic compensation

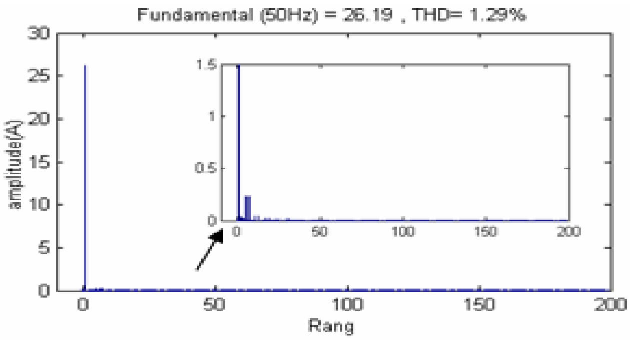


Fig. 6. Harmonics spectra of line-current

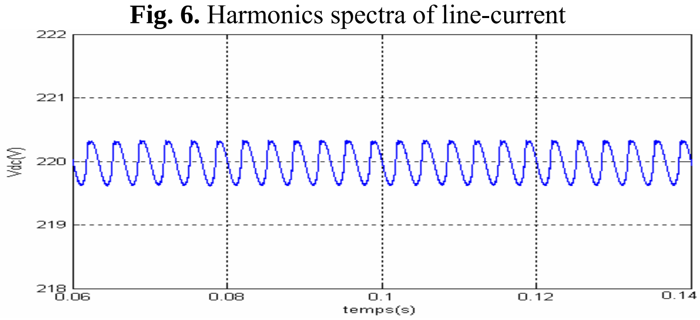


Fig. 7. Capacitor voltage.

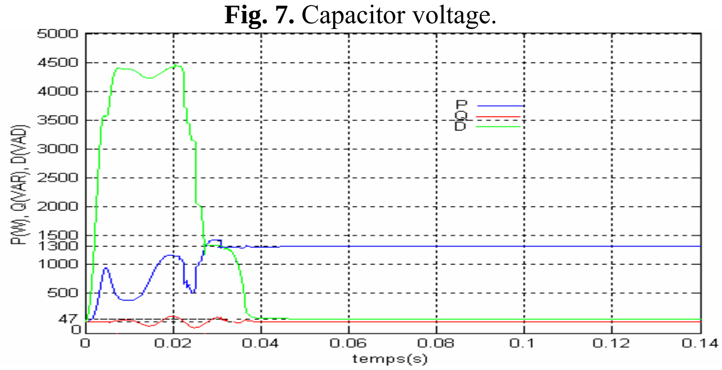


Fig. 8. Active, reactive and distortion powers.

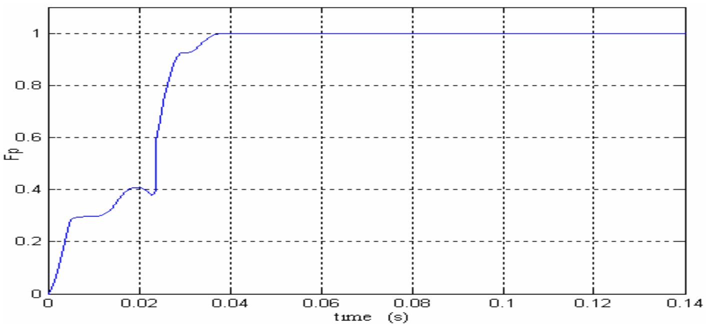


Fig. 9. Power factor

The capacitor voltage is shown in Fig.7, we can observe that its value follows up its reference, that is the objective of the fuzzy controller.
It is observed that the *THD* is improved from 28.20% before harmonic compensation to 1.29 % when using fuzzy control with shunt APF. Fig.8 shows the evolution of the active, reactive and distorting powers We can note that the proposed system becomes an active system with zero reactive power (Q = 0 VAR) with low distorting power. As well as, the power factor (Fig.9) is close to unity, this is the goal of the shunt APF.

4.2 Case two: Step change in load

To observe the regulating process in fuzzy control method in transient condition and the dynamics of the proposed APF, the dc side resistance is increased from 6.7Ω to 10Ω at t = 0.08s. As a result, the load current is reduced from 26.19A to 17.5A.

The simulation has been studied under the step change of the nonlinear load current. Fig.10 (a) shows the source current, Fig.10 (b) and Fig.10 (c) show respectively the load and the compensation currents.

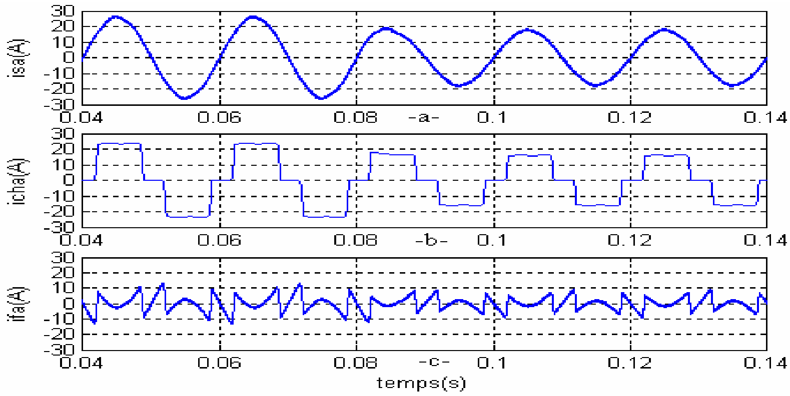


Fig. 10. (a) supply current; (b) load current; (c) compensating current waveform after harmonic compensation

The capacitor voltage is shown in Fig.11. Once the time interval of transient is over the dc capacitor voltage can be recovered to the reference value. Fig.12 shows the variation of the source current peak value.

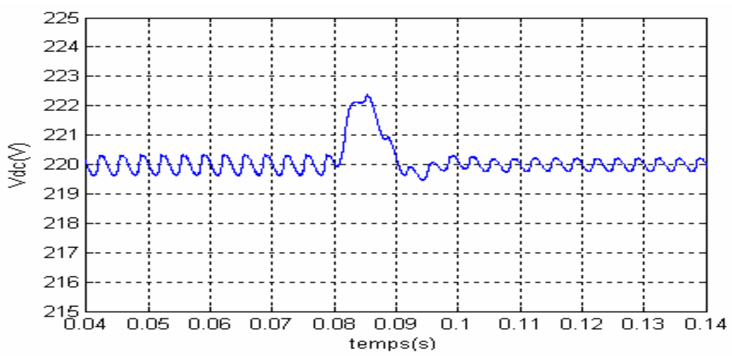


Fig. 11. Capacitor voltage

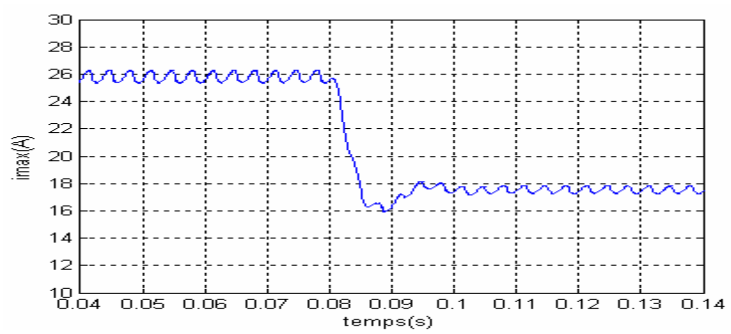


Fig. 12. Magnitude of current reference

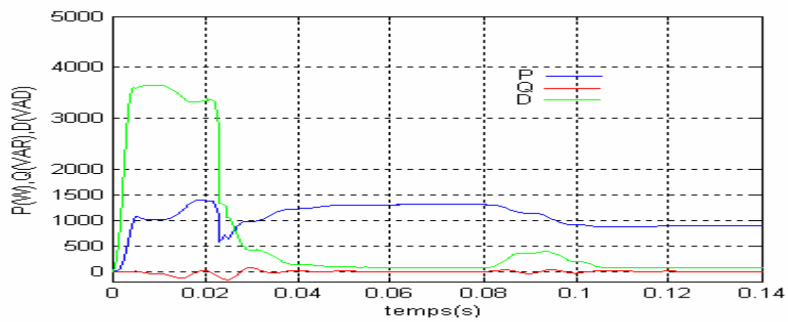


Fig. 13. Active, reactive and distorting powers

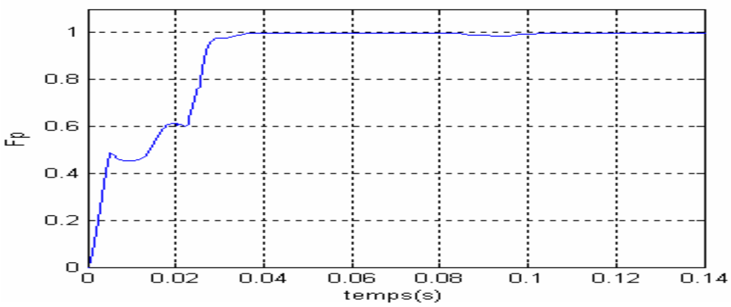


Fig. 14. Power factor

It is clear from simulation results that the mains current maintains its sinusoidal waveform and the transient performance of the source and the dc side capacitor voltage is better for the fuzzy controller during the load variations.

Also, the settling time required by the fuzzy controller is 20 ms (better than other controller, 30 ms if PI controller is used). These results confirm the good dynamical performance of the APF when using the fuzzy controller.

5. Conclusion

Due to the nonlinear load characteristics of much electronic equipment, the utility power system is polluted by harmonics and the power factor is reduced. In this paper, an active filtering approach using shunt APF based on a fuzzy controller to compensate all the harmonics is presented.

The simulations are performed using Matlab- Simulink© tool. It has been shown that the proposed fuzzy active filter exhibits better dynamic, in term of time response, and static performance, in terms of THD and input power factor close to unity, than conventional active filtering.

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