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Shunt Active Filter Controlled by Fuzzy Logic

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Abstract. Harmonics contamination is a serious and a harmful problem in electric power systems. Active power filtering constitutes one of the most effective proposed solutions. A shunt active power filter that achieves low current total harmonic distortion THD, reactive power compensation, and power factor correction is presented. The topology is based on IGBT's voltage inverter, intended to damp harmonics produced by a diode rectifier. The main paper's contribution is the use of the notch filter method, consisting solely of two serial band-pass filters, for reference currents calculation, and the application of fuzzy logic for better active filter current control accuracy. The gating signals were generated through the carrier-based PWM strategy. Simulation works of the studied model, using SIMULINK under MATLAB software, revealed satisfying results in transient and steady states.

Keywords: Harmonics, Shunt active power filter, Band-pass filters, Fuzzy logic, PWM strategy.

Introduction

The wide use of power devices based on semi-conductor switches in power electronic applications (diode and thyristor rectifiers, electronic starters, UPS and HVDC systems, arc furnaces, etc…) induces the appearance of the dangerous phenomenon of harmonic currents flow in the electrical feeder networks, producing distortions in the current/voltage waveforms. As a result, harmful consequences occur: equipment overheating, malfunction of solid-state material, interferences with telecommunication systems, etc... Damping harmonics devices must be investigated when the distortion rate exceeds the thresholds fixed by the ICE 61000 and IEEE 519 standards. For a long time, tuned LC and high pass shunt passive filters were adopted as a viable harmonics cancellation solution [1]. However, insufficient passive filter characteristics or even resonant amplification of harmonics due to mistuned components on the one hand, and the decreasing costs of power electronics devices on the other hand, increased interest in two or multilevel shunt, series and hybrid active power filters (APF's), which besides their capability to cancel harmonics with minimum drawbacks, contribute in the reactive power compensation, power factor correction and DC voltage regulation [2-7]. Although series APF's offer reduced rated power capacity and filtering characteristics, they present the disadvantages of difficulty to protect against power system anomalies and the need to be connected to passive LC filters in order to operate correctly [2]. On the other hand, shunt APF's are not disturbed by power distribution anomalies and the compensation of the power factor as well as current harmonics can be easily implemented [3]. The notch filter is a very simple method allowing the APF's current reference extraction without need to active/reactive power or any complicated calculations. The design of a control able to pursue current peaks isn't straightforward. But, this difficulty has been overwhelmed by the introduction of fuzzy logic in power electronic field. In fact, with fuzzy logic it's possible to design a control system adjusting the control surface for very different working conditions, so the control can follow the reference current even when very high peaks occur. Besides, DC capacitor’s voltages can be maintained at constant levels with fuzzy control [8-10].

This paper deals with a shunt active power filter topology that achieves simultaneously harmonic current damping, reactive power compensation, and power factor correction. For the APF's reference current computation we use the notch filter method, and for gating signal generation we apply the carrier-based PWM modulation. The fuzzy control consists of converting classical LPF correctors to fuzzy ones, improving the system dynamic. Simulation studies were carried out using SIMULINK under MATLAB software.

Shunt Active Power Filter Modeling

Principle

An active power filter is a converter (inverter), placed between the power supply and the receiver, which absorbs the whole or part of the disturbances generated by the said receiver [11, p. 330]. If we denote i_{ca}, i_{cb}, i_{cc}, the receiver absorbed currents, and i_{sa}, i_{sb}, i_{sc}, the desired power supply currents, then the active filter must provide currents i_{fa}, i_{fb}, i_{fc}, given by:

$$i_{fa} = i_{ca} - i_{sa} \qquad i_{fb} = i_{cb} - i_{sb} \qquad i_{fc} = i_{cc} - i_{sc} \tag{1}$$

so that:

- The currents taken from the power supply are sinusoidal;
- The fundamentals of these currents are in phase with the supply voltages;
- The currents meet these two conditions simultaneously.

The example of harmonic load considered in this paper is a three-phase uncontrolled diode bridge rectifier as shown in Fig. 1.

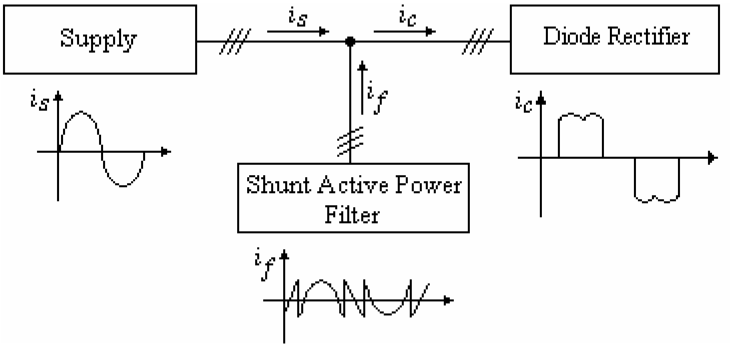

Fig. 1. Shunt active power filtering principle.

The shunt active power filter is intended to generate exactly the same harmonics contained in the polluting current i_c but with opposite phase.

Structure

The general structure of the active filter consists of several blocs as shown in Fig. 2.

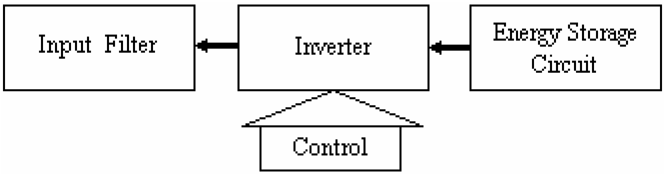

Fig. 2. The active filter general structure.

The equivalent circuit of the whole power supply-active filter-diode rectifier is presented in Fig. 3.

Mathematical model

According to the equivalent circuit shown in Figs. 3 and 1, the active power filter is described by the relation:

$$L \frac{di_f}{dt} = v_f - v_s \tag{2}$$

with

$$v_f = \gamma . E \tag{3}$$

γ is a switching state taking the values of either 1 or –1 corresponding to the two inverter levels $+E$ or $-E$. Equation (2) allows the dimensioning of the filter. Finally, the whole supply-active power filter-rectifier can be modelled by the following equations:

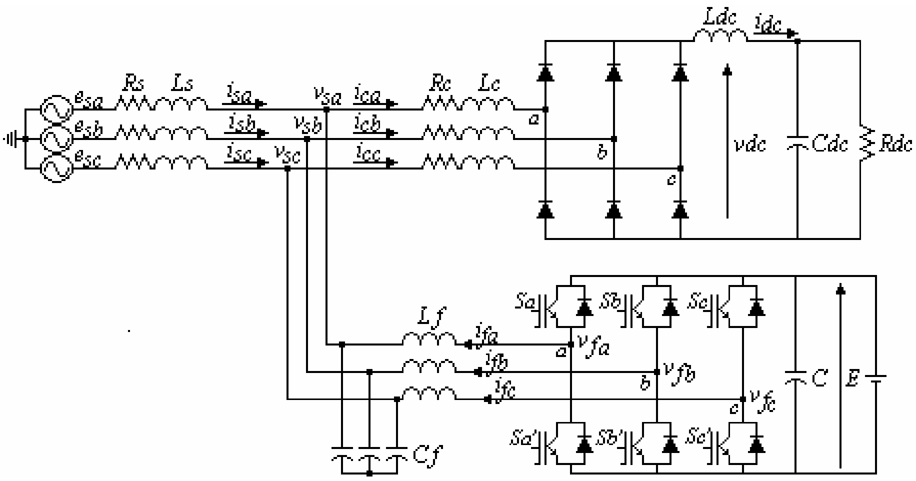

Fig. 3. Equivalent circuit of supply-active filter-rectifier.

$$\frac{d}{dt}\begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} = \begin{bmatrix} 1/L_f & 0 & 0 \\ 0 & 1/L_f & 0 \\ 0 & 0 & 1/L_f \end{bmatrix} . \begin{bmatrix} v_{fa} - v_{sa} \\ v_{fb} - v_{sb} \\ v_{fc} - v_{sc} \end{bmatrix} \tag{4}$$

$$\frac{d}{dt}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} -R_s/L_s & 0 & 0 \\ 0 & -R_s/L_s & 0 \\ 0 & 0 & -R_s/L_s \end{bmatrix} . \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} v_{sa} - e_{sa} \\ v_{sb} - e_{sb} \\ v_{sc} - e_{sc} \end{bmatrix} \tag{5}$$

Shunt Active Power Filter Control

Control circuit synoptic diagram

Figure 4 illustrates the active power filter control circuit synoptic diagram, where 'PI' is a Proportional-Integrator corrector.

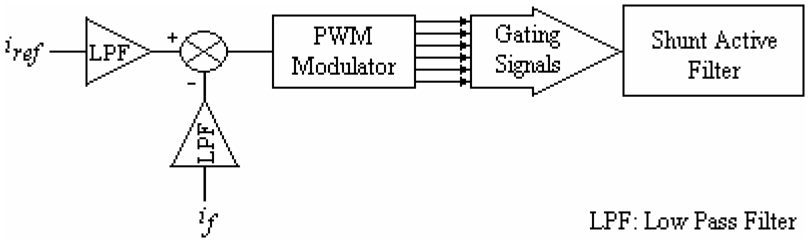

Fig. 4. Active filter's control circuit synoptic diagram.

A good and robustness control is a system which forces a signal to track closely its reference. The control strategy applied in this paper is the carrier-based PWM modulation, which will be described later.

Current reference i_{refi} Calculating

Several methods for calculating i_{refi} (i = a, b, c) are proposed. These methods are divided into two types: single-phase and three-phase. In the three-phase approach, the three phases operate simultaneously as in the case of real and imaginary instantaneous powers [12]. In the single-phase kind, each phase operates individually as used in the FFT and the notch filter methods [13]. In this study, we apply the method of notch filter which consists of two identical band-pass filters in series, as shown in Fig. 5.

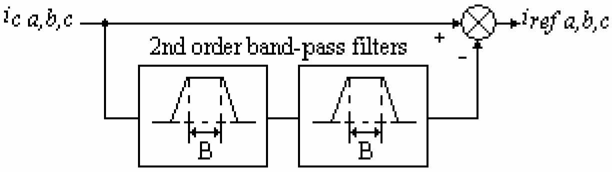

Fig. 5. Notch filter based on band-pass filters method.

The transfer function of this band-pass filter is given by:

$$TF = \frac{K.B.p}{p^2 + B.p + \omega_c^2} \tag{6}$$

where:

K is the gain, p is Laplace operator, B is an angular frequency equal to $2\pi f_b$, f_b is the width of the busy band and ω_c is the cutoff frequency.

Control strategy

As mentioned earlier, the applied control strategy is the carrier-based PWM modulation which follows the principle provided in Fig. 6 [14].

A carrier-based PWM modulator generates a composite signal that consists of a modulation signal and a carrier signal. In the linear mode, the peak of a modulation signal is less than or equal to the peak of the carrier signal. Figure 6 illustrates a two-level carrier-based PWM signal. As shown in Fig. 6, in the linear mode and for carrier-based two-level PWM modulators, we have:

$$\begin{cases} tk_{+} - tk_{-} = u_k.T_s \\ tk_{+} = 1/2.(1+u_k).T_s \\ tk- = 1/2.(1-u_k).T_s \end{cases} \tag{7}$$

where t_{k+} and t_{k-} are the positive and the negative pulse widths in the k^{th} sampling interval, respectively, u(k) is the normalized amplitude of the modulation signal in the k^{th} sampling interval ($|u(k)| \leq 1$), and the normalized peak value of the carrier signal is 1.

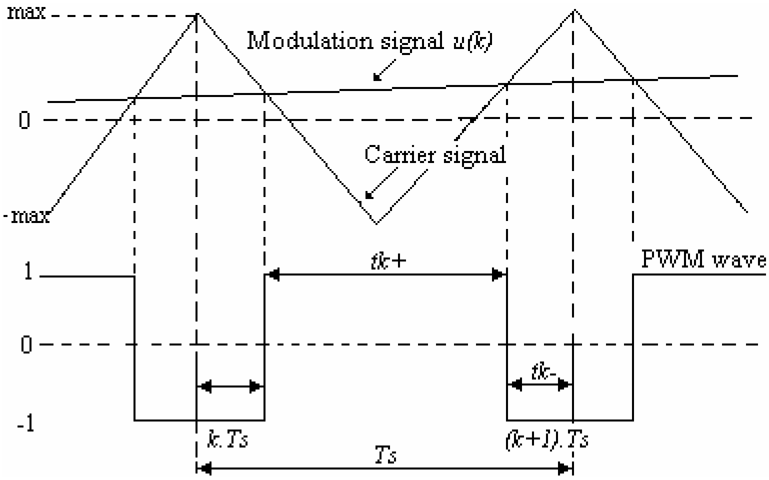

Fig. 6. Principle of two level carrier-based modulations.

The synoptic diagram of the applied PWM comparator is shown in Fig. 7. The difference between the active filter current and the reference current passes through a relay or a hysteresis comparator in order to determine the switches *Si, Si'* gating signals of each arm of the inverter.

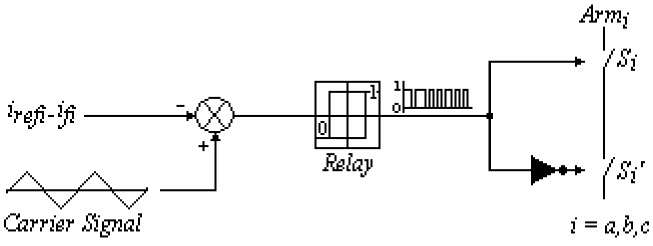

Fig. 7. PWM comparator synoptic diagram.

Fuzzy Control Application

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 [15, p. 16]. Figure 8 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*).

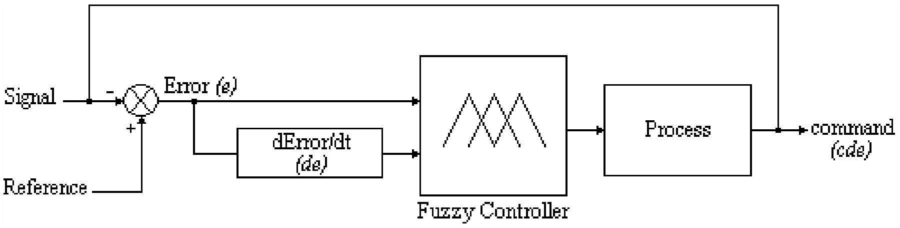

Fig. 8. Fuzzy controller synoptic diagram.

Figure 9 illustrates stages of fuzzy control in the considered base of rules and definitions: fuzzyfication, inference mechanism, and defuzzyfication.

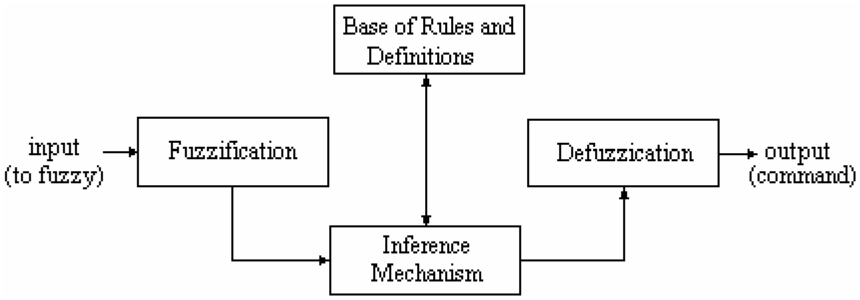

Fig. 9. Fuzzy control construction.

Fuzzy control of the active power filter's current

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.
- Defuzzyfication using the 'centroïd' method.

The establishment of the fuzzy rules is based on the error (*e*) sign and variation. As explained in Fig. 10, 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).

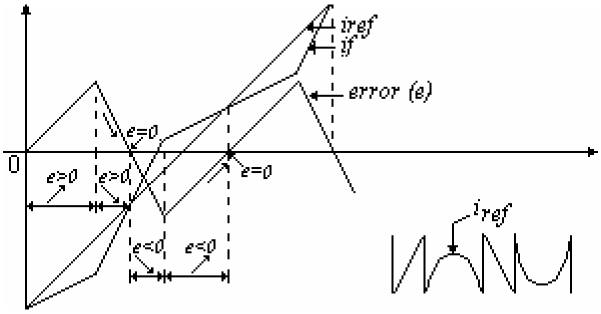

Fig. 10. Fuzzy rules establishment.

Simulation Results

Simulation software

For simulation studies, we used SIMULINK toolbox under MATLAB software in order to model and test the system under investigation.

Simulation parameters

The simulation parameters are summarized in Table 1.

Table1. Simulation parameters

Parameter	Value
Supply’s voltage e_s & frequency f_s	230 V (RMS), 50 Hz
Line’s inductance L_s & resistance R_s	0.03 mH, 0.1 Ω
Impedance upstream of the rectifier L_c and R_c	0.07 mH, 0.3 Ω
Inductance L_{DC}, capacitor C_{DC}, resistance R_{DC}	0.3 mH, 470 μF, 0.5 Ω
Active filter input DC supply: capacitor C, *E*	7μF, 700 V
Active filter output impedance L_f, C_f	1.25 mH, 21μF
if_{iref}’s calculating, band-pass filter: damping factor ξ	0.707
LPF corrector: gain *K*, time constant τ	1, $50e^{-6}$ s
PWM block:	10, 10 kHz
Carrier signal’s peak amplitude & frequency	18 kHz
Switching frequency	

Main results discussion

The simulation works of the above theoretical study shows an improvement in both harmonics filtering quality and system dynamic performance with the fuzzy correctors.

At first, let see in Figs. 11 and 12 the source current waveform and its harmonic spectrum before the application of classical shunt active power filtering. Important distortions are noticed in these figures with a THD of 15.83%.

After the application of shunt active power filtering based on low pass filters LPF correctors, we obtain the curves mentioned in Figs. 13 and 14 presenting the supply's current waveform and its harmonic spectrum in phase a (i_{sa}). It's clear that distortion was attenuated at a satisfying level seen that the THD decreased to 1.14%. Figure 15 shows the effectiveness of the control strategy which forced the APF current to follow its reference. Moreover, Fig. 16 proves that utility power factor was corrected by the fact that current and voltage are approximately in phase each other. As a result, power factor is near unity, and consequently reactive power consumed by the non-linear load devices is compensated. Figure 17 displays the DC-bus voltage *E* feeding the APF inverter through the capacitor *C*. We can say that *E* is regulated, because ripples are from ± 0.05 V, oscillating around a fixed value: 700 V. Figure 18 gives us an idea about the non-linear DC side current and voltage.

Now, after introducing the fuzzy logic correctors, a new improvement occurs in the supply’s current waveform (Fig. 19), especially in the first half period (10 ms). The signal in this interval becomes more nearest to the sinusoidal form than the previous one without fuzzy correctors. Besides, the harmonic spectrum, presented in Fig. 20, shows the rate of this new improvement carrying out a THD of 0.99%. The effectiveness of the fuzzy control strategy is illustrated in Fig. 21 mentioning the APF current pursuing its reference. Concerning power factor correction and reactive power compensation, we see similar results compared to those obtained with classical LPF correctors (Fig. 22). The same remarks can be said about the APF DC feeding voltage, oscillating around 699.88 V, with ripples of ± 0.04 V (Fig. 23). Finally, by regarding Fig. 24, we see no differences in the DC load current and voltage waveforms compared with the case of classical LPF correctors.

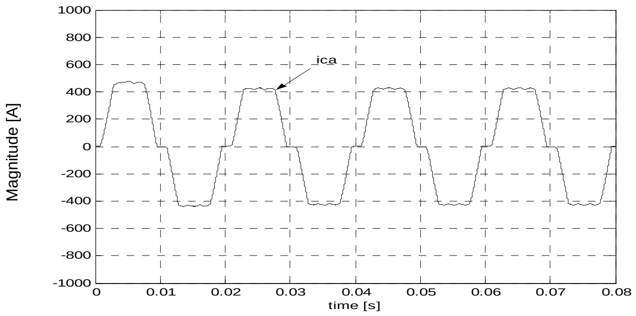

Fig. 11. Supply current i_{sa} waveform before applying classical APF.

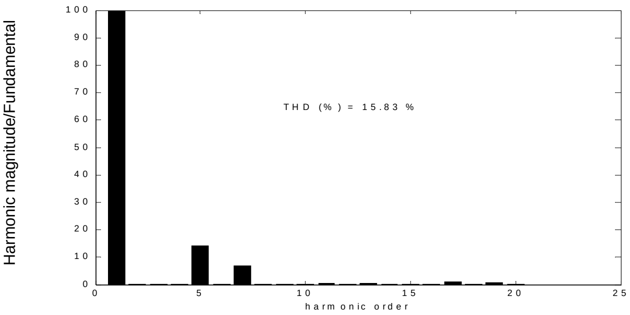

Fig. 12. Harmonic spectrum of i_{sa} before applying classical APF

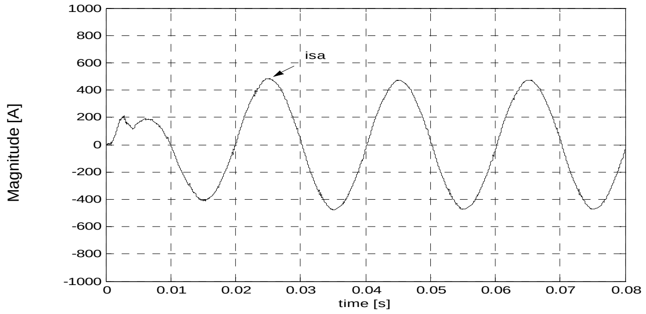

Fig. 13. Supply current i_{sa} waveform after applying classical APF.

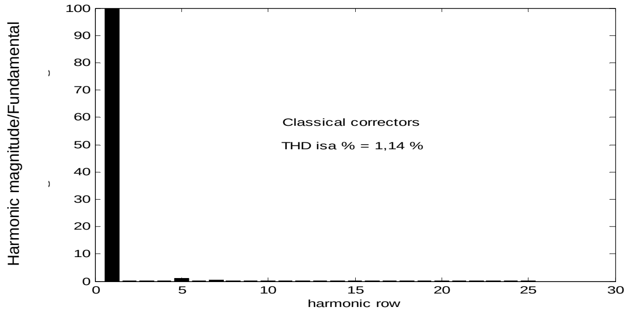

Fig. 14. Harmonic spectrum of i_{sa} after applying classical APF.

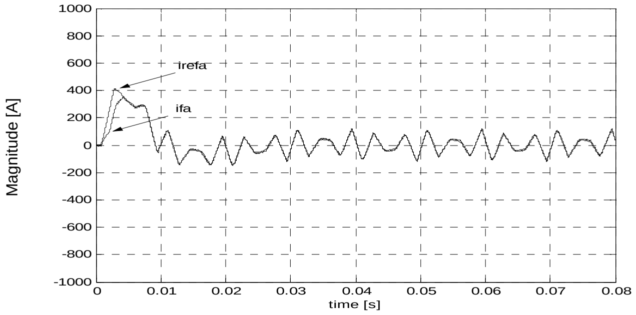

Fig. 15. APF current and its reference with classical correctors.

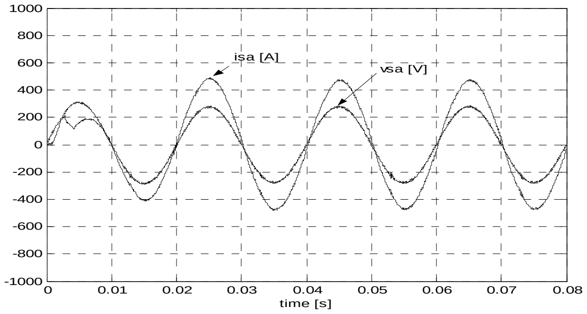

Fig. 16. Power factor correction after applying classical APF.

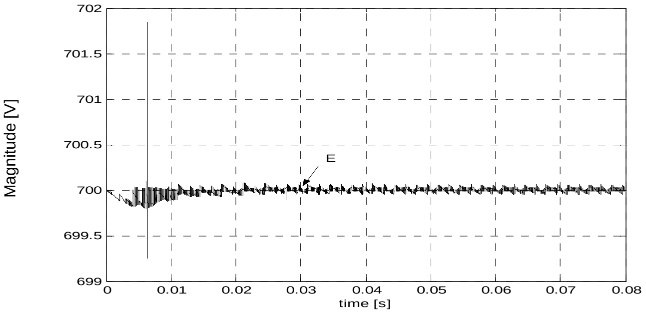

Fig. 17. DC voltage regulation after applying classical APF.

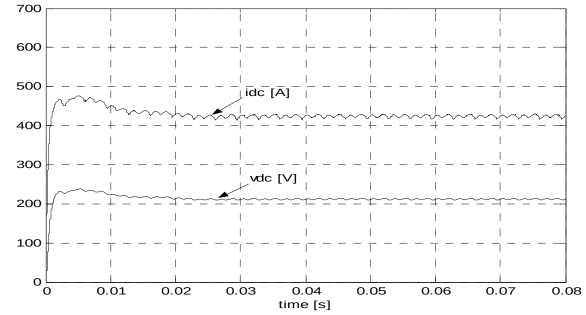

Fig. 18. Non-linear DC side current and voltage.

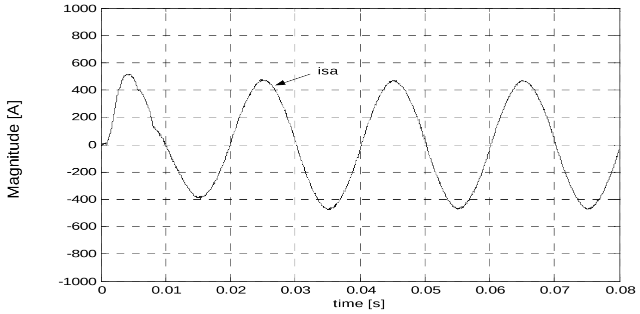

Fig. 19. Supply current i_{sa} waveform after applying fuzzy APF.

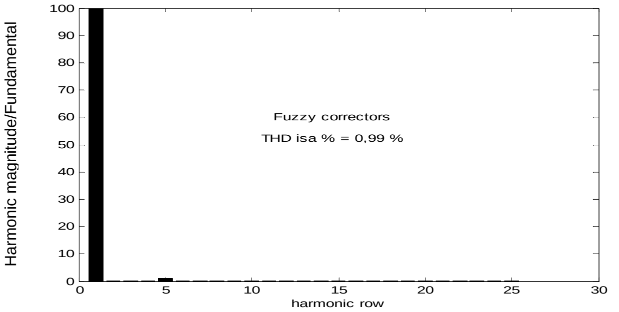

Fig. 20. Harmonic spectrum of i_{sa} before applying classical APF

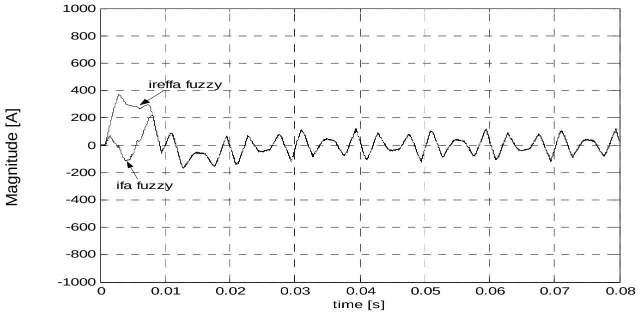

Fig. 21. APF current and its reference with fuzzy correctors.

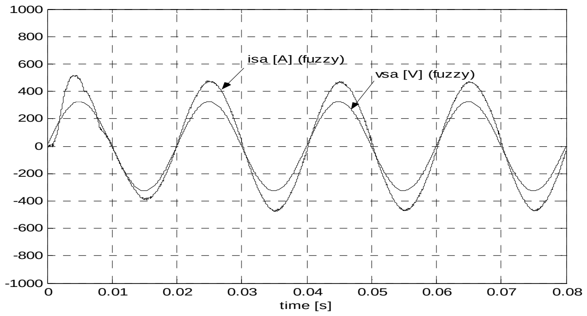

Fig. 22. Power factor correction after applying fuzzy APF.

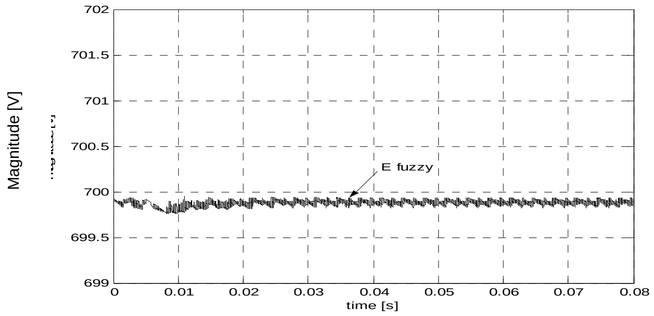

Fig. 23. DC voltage regulation after applying fuzzy APF.

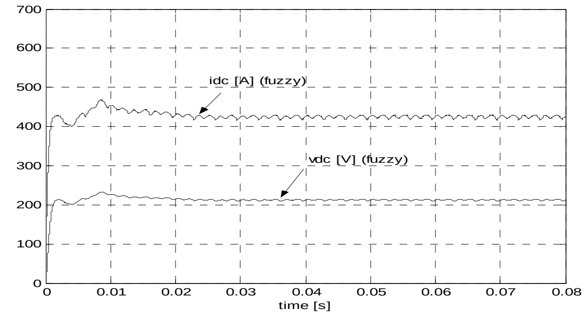

Fig. 24. Non-linear DC side current and voltage.

Conclusion

Throughout this work, we have shown the effectiveness of the shunt active power filtering especially with the application of fuzzy logic and with the application of the band-pass filter method for current references calculation. In fact, the distortion of the power supply current was diminished to a satisfactory level (THD = 0.99% in 80 ms with fuzzy correctors compared to 1.14% in 80 ms with classical correctors) and the power factor was corrected (power supply voltage and current became in phase).

For future work, we intend to extend our study to the hybrid structure of series and shunt active power filters and the application of the neural networks to these structures. Also, we intend to consider a polluting load with more than 15.83% of total harmonic distortion.

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التحكم في مرشح فعال ذي قدرة متوازية باستعمال المنطق الغامض

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قسنطينة، الجزائر

(قدم في ٢٩/٠١/٢٠٠٥م، وقبل للنشر في ١١/٠٢/٢٠٠٦م)

ملخص البحث. إنّ عدوى انتشار التيّارات المتناغمة في الأنظمة الكهربائيّة ذات القدرة قد تؤدّي إلى نتائج خطيرة ، والتّرشيح الفعّال ذو القدرة ما هو إلا واحد من أنجع الحلول المقترحة لمواجهة هذه الظاهرة. إن المرشّح الفعّال الأفضل هو الذي يعمل في نفس الوقت على خفض عامل الإلتواء التّناغمي الكلي THD ، ومراقبة تيار وجهد التغذية المستمرة للمموّج ، وتعويض أي نقص في القدرة الإرتكاسية وتحسين عامل الإستطاعة.

في هذه المقالة سنقوم بعرض دراسة لواحد من المرشحّات الفعّالة المتوازية معتمدا في تكوينه على مموّج جهد ثلاثي الأطوار ، وثنائي المستويات ، ومزوّد بترانزستورات IGBT ، مستعملا زوجا متسلسلا من المرشّحات تمرير نطاقي في حساب التيّارات المرجعيّة.

أما لجوؤنا للمنطق الغامض FUZZY LOGIC فكان بهد ف الحصول على إجابة أحسن للمرشّح عن طريق تحويل المصححّات الكلاسيكيّة LPF إلى مصححّات غامضة.

أخيرا ، قمنا بدراسة برمجيّة للدرّاسة النظريّة السّابقة ، قصد الإقتراب من التّصرف العملي للمرشّح ، باستعمال البرنامج MATLAB – SIMULINK. كانت النّتائج المتوصّل إليها مرضية في كلّ من حالتي العبور والإستقرار.