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Comparison of fuzzy logic and proportional controller of shunt active filter compensating current harmonics and power factor

L. ZELLOUMA[*1], S. SAAD[*2]

LEVRES Laboratory, University of El-Oued, Algeria
BP789 El-Oued, Email: zellouma13@yahoo.fr
SEM Laboratory, University of Badji Mokhtar-Annaba, Algeria
Email: saadsalah2006@yahoo.fr

Abstract – **This paper presents five-level inverter as a shunt active power filter (5APF) to compensate reactive power and suppresses harmonics drawn from a diode rectifier supplying RL load under distorted voltage conditions. The harmonic current extraction is based on the use of self tuning filter (STF) and fuzzy logic controller employed to control harmonic current and inverter DC voltage. The aim of the present work is to obtain a perfect compensation by extracting accurate harmonic currents to improve the performances of the five-levels active power filters.**

The proposed scheme is validated by computer simulation using MATLAB Fuzzy Logic Toolbox in order to show the effectiveness and ability of this method. The results have demonstrated that the proposed shunt active power filter with STF and Fuzzy Logic Controller (FLC) have produced a sinusoidal supply current with low harmonic distortion and in phase with the line voltage.

Keywords: **Shunt active power filter, Five-level inverter, Fuzzy logic control, self tuning filter, Harmonics, Reactive power compensation, PWM control.**

1. Introduction

The intensive use of static converters in the industry has lead to an increase in harmonic injection in the power system and a lower power factor. The harmonics causes problems in power systems and in consumer products such as equipment overheating, capacitor blowing, motor vibration, excessive neutral currents and low power factor.

Conventional active power filter was deeply explored and used to eliminate harmonics and compensate reactive power [1–3]. These active power filters are limited in medium power applications. Multilevel configuration were introduced and employed to achieve high power filters.

Actually, the use of multilevel inverters for high power drives and harmonic compensation [2-5] become a great issue. Multilevel pulse width modulation inverters can be used as active power filter for high power applications solving the problem of power semiconductor limitation.

The aim of the present work is to obtain a perfect compensation by extracting accurate harmonic currents to improve the performances of the five-levels active power filters.

The performances of different reference harmonic current extraction methods under balanced sinusoidal alternating current (AC) voltages conditions [6–11], such as the so-called *p–q* theory, Synchronous Reference Frame theory (SRF) and recently ADALINE neural network [6] provide similar performances. Differences appear when working under distorted and unbalanced AC sources. In real conditions, the voltage sources are distorted affecting greatly the filter performances [10].

In this paper, the reference current identification under distorted voltage conditions is based on using self tuning filter (STF). This filter is used to extract the fundamental component directly from the distorted voltage or/and current in α-β reference frame.

The controller is the main device of the active power filter operation and has been a subject of many works in recent years. In this paper, fuzzy logic controllers are used for harmonic current and inverter DC voltage control to improve the performances of the five levels shunt APF.

The advantages of fuzzy controller over conventional controllers, robustness, no need to accurate mathematical model, can work with imprecise inputs, and can handle non-linearity [12–22]. The performance of fuzzy controller and reference current identification using STF are evaluated through computer simulations under distorted voltage conditions. The obtained results showed that, the proposed active power filter scheme with STF and Fuzzy Logic Controller (FLC) has provided a sinusoidal supply current with low harmonic distortion and in phase with the line voltage.

2. Shunt APF configuration

The proposed shunt APF is employed to reduce harmonic currents and compensate reactive power. The topology presented in Fig.1 shows a three-phase five-level VSI used as shunt APF. In order to obtain an inverter (active filter) of N levels, N−1 capacitors are needed [23-24].

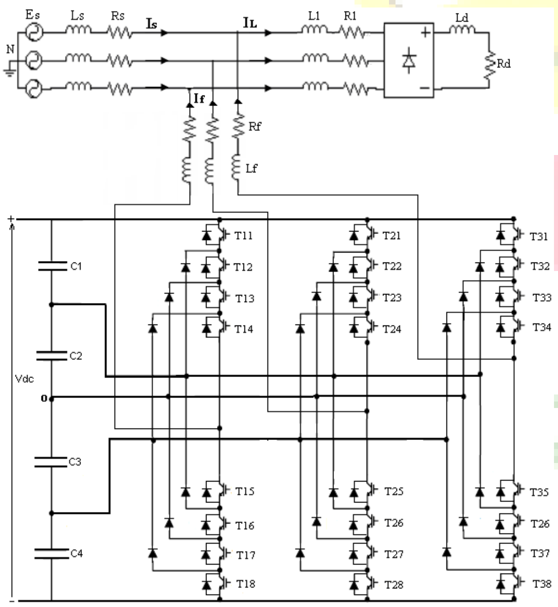

Fig.1. Active power filter operation

The voltage across each capacitor is equal to $V_{dc}/(N-1)$, V_{dc} is the total voltage of the dc source. Each couple of switches (S11, S15) form a cell of commutation, the two switches are ordered in a complementary way. The inverter produces five voltages according to the expression presented below:

$$V_{io} = k_i \frac{V_{dc}}{2} \qquad (1)$$

Where, V_{io} is the phase-to-middle fictive point voltage, K_i is the switching state variable (K_i =1, 1/2, 0, -1/2, −1), V_{dc} is the dc source voltage, and i is the phase index (i = a, b and c). The voltage values are presented in table 1 ($V_{dc}/2$, $V_{dc}/4$, 0, $-V_{dc}/2$, $-V_{dc}/4$) [23-24].

Table 1: Obtaining of five -level inverters.

K_i	T_{i1}	T_{i2}	T_{i3}	T_{i4}	T_{i5}	T_{i6}	T_{i7}	T_{i8}	V_{io}
1	1	1	1	1	0	0	0	0	$V_{dc}/2$
1/2	0	1	1	1	1	0	0	0	$V_{dc}/4$
0	0	0	1	1	1	1	0	0	0
-1/2	0	0	0	1	1	1	1	0	$-V_{dc}/4$
1	0	0	0	0	1	1	1	1	$-V_{dc}/2$

2. 1. Reference current calculation

A . Self tuning filter

M. Abdusalam et al [11] have presented in their work the principle, frequency and dynamic response of the STF under distorted conditions. Current or voltage signal, before and after filtering can be expressed by the following equation:

$$\hat{x}_\alpha(s) = \frac{k}{s}\left[x_\alpha(s) - \hat{x}_\alpha(s)\right] - \frac{w_c}{s}\hat{x}_\beta(s)$$

$$\hat{x}_\beta(s) = \frac{k}{s}\left[x_\beta(s) - \hat{x}_\beta(s)\right] + \frac{w_c}{s}\hat{x}_\alpha(s)$$

Where, $x_\alpha(s)$, $x_\beta(s)$, $\hat{x}_\alpha(s)$ and $\hat{x}_\beta(s)$ are a current or a voltage signal, respectively and w_c is the pulsation of STF.

The block diagram of the STF tuned at the pulsation w_c and the frequency response of the STF versus different values of the parameter *k* are given in [11]. It is observed that no displacement is introduced by this filter at the system pulsation. It has been also noticed that small value of *k* increases filter selectivity. Fig.2, shows the self-tuning filter tuned to the pulsation w_c.

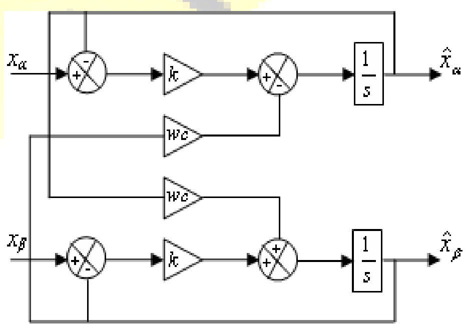

Fig. 2. Self-tuning filter tuned to the pulsation w_c.

B . Harmonic identification

Several methods [1-6] were proposed for harmonic currents identification. Mainly, methods based on the FFT (Fast Fourier Transformation) in the frequency domain and methods based on instantaneous power calculation in the time domain and recently artificial neural network method. The block diagram of the STF used with *p-q* theory to extract harmonic currents is illustrated in Fig. 3.

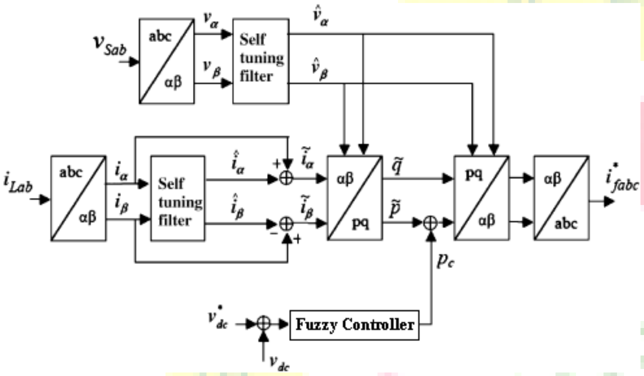

Fig. 3. Block diagram of the new STF-based harmonic isolator.

In this study, the *p–q* theory method is used enabling the compensation of harmonic currents, reactive power and unbalanced currents. The reference currents (harmonic currents) extraction is based on *α-β* transformation to obtain real and imaginary powers. The voltages (V_{Sa}, V_{Sb} and V_{Sc}) and currents (I_{La}, I_{Lb} and I_{Lc}) are transformed to bi-phase system according to the following equation:

$$\begin{bmatrix}x_\alpha\\ x_\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{pmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{pmatrix}\begin{bmatrix}x_a\\ x_b\\ x_c\end{bmatrix}$$

(2)

After that, the STF extracts the fundamental component at the pulsation w_c directly from the currents in the *α-β* axis. Then, the *α-β* harmonic components of the load currents are computed by subtracting the STF input signals from the corresponding outputs. The obtained signals are the AC components, □i_α and □i_β, which correspond to the harmonic components of the load currents I_{L1}, I_{L2} and I_{L3} in the stationary reference frame.

Then, self-tuning filter is applied to these *α-β* voltage components. This filter enables suppressing any harmonic component of the distorted mains voltages and as a result the harmonic extraction is improved. After computation of the fundamental component $\hat{v}_{\alpha\beta}$ and the harmonic currents $i_{\alpha\beta}$, the *p* and *q* powers are calculated as follows:

After computation of the fundamental component $\hat{v}_{\alpha\beta}$ and the harmonic currents $i_{\alpha\beta}$, we calculate the *p* and *q* powers as follows:

$$\begin{bmatrix}p\\ q\end{bmatrix}=\begin{pmatrix}\hat{v}_\alpha & \hat{v}_\beta\\ -\hat{v}_\beta & \hat{v}_\alpha\end{pmatrix}\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}$$

(3)

Instantaneous powers are composed from a constant part and a variable part corresponding to fundamental and harmonic currents respectively.

$$\begin{bmatrix}\tilde{i}_\alpha\\ \tilde{i}_\beta\end{bmatrix}=\frac{1}{\hat{v}_\alpha^{\,2}+\hat{v}_\beta^{\,2}}\begin{pmatrix}\hat{v}_\alpha & -\hat{v}_\beta\\ \hat{v}_\beta & \hat{v}_\alpha\end{pmatrix}\begin{bmatrix}\tilde{p}\\ \tilde{q}\end{bmatrix}$$

(4)

After adding the active power required for regulating DC bus voltage, p_c, to the alternative component of the instantaneous real power, $\tilde{p}$ (Fig. 3), the current references in the *α-β* reference frame are □$i^{*}_{\alpha\beta}$.

Then, the filter reference currents in the *a-b-c* coordinates are defined by:

$$\begin{bmatrix}\tilde{i}_{fa}\\ \tilde{i}_{fb}\\ \tilde{i}_{fc}\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0\\ \frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}\tilde{i}_\alpha\\ \tilde{i}_\beta\end{bmatrix} \qquad (5)$$

2.2. Inverter control strategy

This control uses a fuzzy logic controller which starts from the difference between the injected current (active filter current) and reference current (identified current) [2] that determines the reference voltage of the inverter (modulating wave). This standard reference voltage is compared with four carrier triangular identical waves.

These carrier waves have the same frequency and are arranged on top of each other, with no phase shift, so that they together vary from maximum output voltage to minimum output voltage . PWM synoptic block diagram of currents control is presented in Fig. 4.

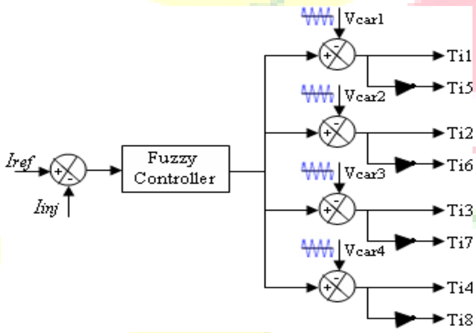

Fig. 4. PWM synoptic block diagram of currents control.

2. 3. *Fuzzy logic control application*

Fuzzy logic serves to represent uncertain and imprecise knowledge of the system, whereas fuzzy control enables taking a decision even if we can't estimate inputs/outputs only from uncertain predicates. The synoptic scheme of Fig.5 shows a fuzzy controller, which possesses two inputs and one output. The inputs are namely the error (e), which is the difference between the reference current (harmonic current) and the active filter current (injected current) (e = $i_{ref} - i_f$) and its derivative (de) while the output is the command (cde).

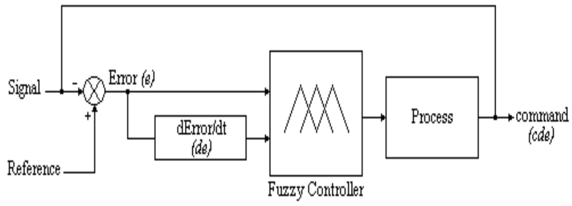

Fig.5. Fuzzy controller synoptic diagram

2. 4. *Active power filter current control*

The purpose of current control is to obtain sinusoidal source currents in phase with the supply voltages. The conventional PI controllers are replaced by fuzzy logic controllers [12-21] and their characteristics and fuzzy rules are given in [2].

2. 5 *DC capacitor voltage control*

Several power filter controllers were studied and used such as IP, RST, hysteresis, adaptive control and fuzzy logic controller.

In the present work fuzzy logic control algorithm is implemented to control the DC capacitor inverter voltage based on DC voltage error $e(t)$ and its variation $\Delta e(t)$ in order to improve the dynamic performance of APF and reduce the total harmonic source current distortion. The fuzzy logic rules are summarized in [2].

3. Computer simulation

The described fuzzy logic controller and STF have been tested on a distorted wave produced by a diode bridge rectifier with RL load and five levels PWM inverter used as shunt APF. The simulation is conducted using parameters illustrated in Table 3. The obtained switching signals of the three-phase five-level inverter are presented in Fig. 6. The load current before connecting shunt active power filter is illustrated in Fig. 7. This current is highly distorted and its THD is equal to 15.66% and its spectrum is shown in Fig. 8.

Table.3. Simulation parameters.

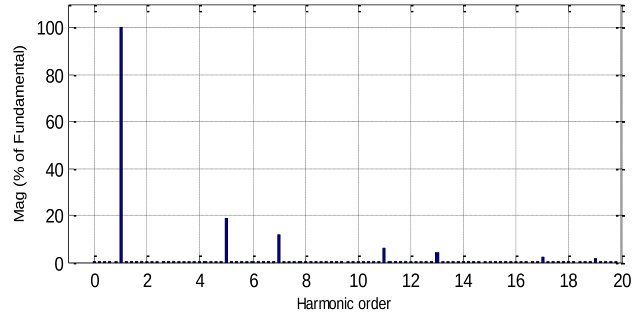

Fig. 8. Source current spectrum without filter.

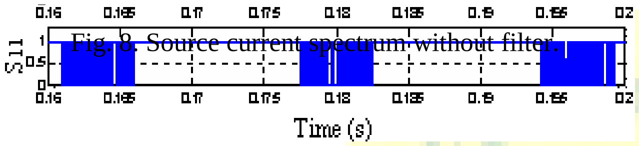

Fig. 6. Switching pulses of APF arms (S11, S12, S13, S14).

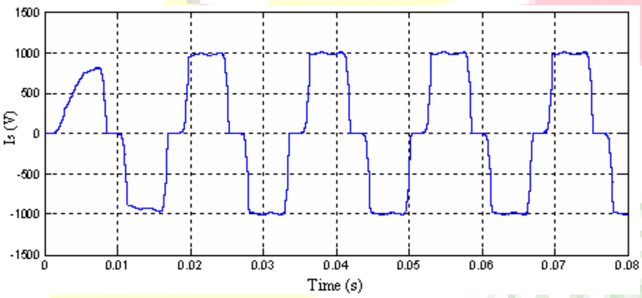

Fig. 7. Supply current *Is* waveform without filtering

Supply: *Vs*, R_s, L_s	220 V, 0.01Ω, 0.1 mH
System frequency	60 Hz
DC Load: R_d, L_d	0.5Ω, 0.3 mH.
Active Filter: V_{dc}, L_f, R_f , C_1=C_2 =C_3=C_4	800 V, 0.2mH, 0.005Ω, 30mF
Switching frequency	10 K Hz

4. Results and discussions

The obtained results are given to show the active power filter performances using fuzzy control schemes and self tuning filter (STF). Five-level shunt active power filter performances depend on current references quality, *p–q* theory and STF are used for harmonic currents extraction, the obtained current is shown in Fig. 9. This control method enables harmonic currents and reactive power compensation simultaneously; the obtained current and voltage waveforms are in phase as illustrated in Fig. 10.

It can be deduced that five level shunt APF contains less harmonic as presented in Fig. 11 with a THD of source current equal to 0.85% after compensation which is below the limit of 5%. The five-level voltages are (*Vao*): 400*V*, 200*V*, 0*V*, -400*V* and -200*V*, corresponding respectively to $V_{dc}/2$, $V_{dc}/4$, 0, -$V_{dc}/4$ and -$V_{dc}/2$, the DC voltage source (V_{dc}) is 800 V.

The output voltages V_{ao} and V_{an} are shown in Figs. 12 and 13. The five level active filter with fuzzy logic controllers and STF has imposed a sinusoidal source current waveform as illustrated in Fig. 10 and a constant and ripple free DC voltage as illustrated in Fig. 14.

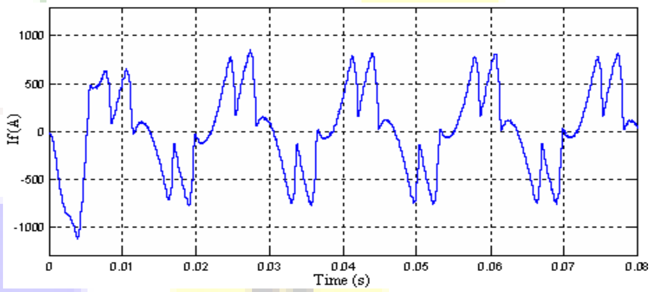

Fig. 9. Active filter current I_f.

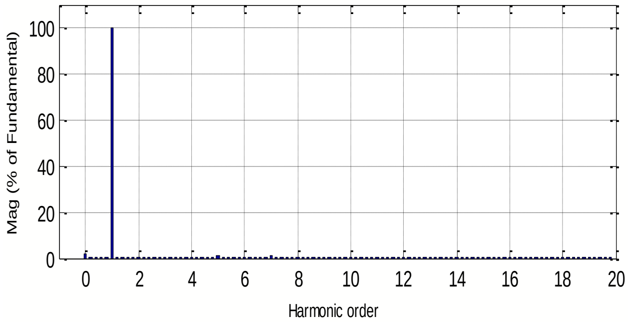

Fig. 11. Source current spectrum with filter.

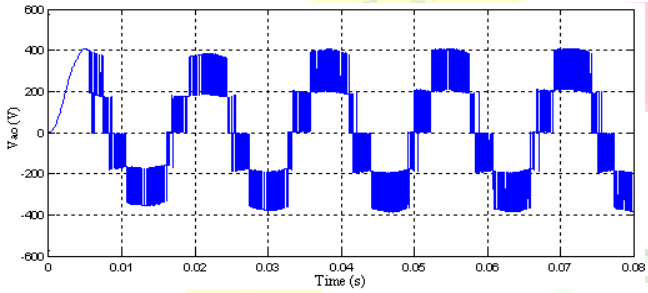

Fig. 12. APF output voltage V_{ao}.

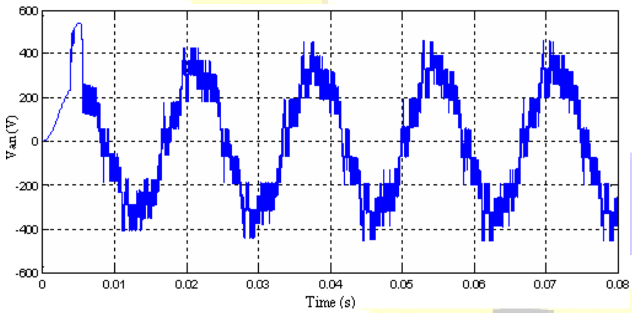

Fig. 13. APF output voltage V_{an}.

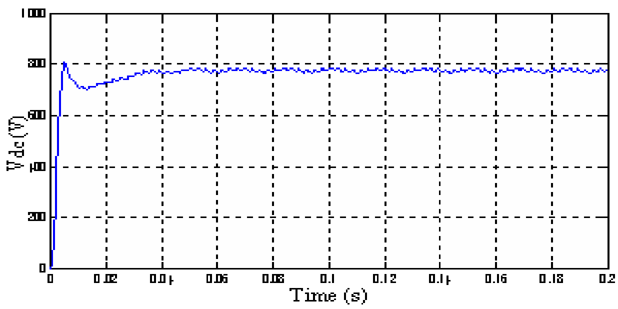

Fig. 14. DC voltage of the condenser

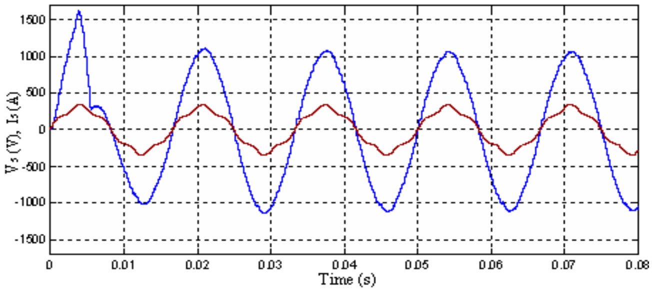

Fig. 10. Power factor correction (V_s, I_s).

5. Conclusion

In the present paper theoretical study with simulation of a fuzzy logic controller with SFT and five level shunt active power filter based on *p–q* theory to extract reference currents and PWM to generate switching signals have shown high shunt APF performances in reducing harmonics, and power factor correction. The results have proved that DC capacitor voltage and the harmonic currents control using FLC and STF are very important. This type of controller and filter are adapted easily to severe conditions such as distorted voltage conditions.

The three phase five level shunt active power filter is simulated and the THD measured verifies the reduction of harmonics to a low level when the fuzzy logic control is employed. The five level APF with FLC and STF provide numerous advantages such as perfect and accurate harmonic currents extraction, improvement of the supply current waveform, less harmonic distortion and its use in high power/medium voltage with a lower maximum device rating.

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