Contribution to the controling of the shunt active power filter to compensate for the harmonics, unbalanced currents and reactive power

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Abstract: - The present publication is articulated on the control strategy of the shunt active power filter in order to cleanse actively the electrical supply from the majority of the disturbing currents. This research treats a control strategy having a perfect robustness under a disturbed supply voltages and adaptability as for the evolution of the polluting loads. The performances of the strategy suggested are analyzed and compared, in simulation, with the strategy of the instantaneous power and the strategy of the synchronous detection which are adjusted to agree under more constraining conditions. The digital simulation results reveal a cleaning of the mains currents spectrum with a notable improvement of the electric power quality.

Key-words: - Shunt Active Power Filter, control strategy, disturbing currents, electric power quality.

1 Introduction

Following the liberalization of the electric power and the generalization of the generating equipment of electric disturbances, the supplier of the electric power and the customer must mobilize themselves to ensure the quality of the electric power. The active filter can be planned to ensure this quality. [6] [7]

This research project is interested in the robustness and the adaptability of the control strategy of the shunt active power filter (SAPF) to compensate for the great part of the disturbing currents for connection of various polluting loads in the industrial electric installations. [2] [3]

The originality of this strategy lies in its adaptability at the various disturbing loads and various network configurations even under strongly disturbed supply voltages.

The effectiveness of the strategy will be tested through a comparative study mixing the traditional control strategies with the example of the instantaneous power strategy and the synchronous detection strategy which are adjusted to agree under more constraining conditions.

2 System description

The studied system is composed from a three-phase supply feeding a three-phase SAPF and polluting load without neutral (Fig 1). [1] [2]

The polluting load is no linear and unbalanced with absorption of a reactive power. It consists of a rectifier controlled associated at DC loads (r_d, L_d). [6] [7]

The inductance (L_C,,r_C) represents the sum of the impedances of a possible transformer which is used to limit the derivative of the load currents.

The SAPF is based on an three-phase inverter with voltage structure, associated at passive filter. The three half bridges (T_1-T_4, T_2-T_5 and T_3-T_6) of inverter are based on IGBT. [5] [6]

The control strategy is composed from the calculation bloc of the disturbing currents and the regulation bloc of the SAPF currents. [6]

The switches states of T_1, T_2 and T_3 are respectively complementary to those of T_4, T_5 and T_6. One represents the switching states of T_1, T_2 and T_3 by the vector:

$$[C] = [C_1 \quad C_2 \quad C_3] \tag{1}$$

$[V_{Sabc}]$	The supply voltages
$[i_{Sabc}]$	The supply currents
$[i_{Chabc}]$	The polluting load currents.
$[i_{Fabc}]$	The SAPF currents.
$cos\varphi$	The Phase Displacement Factor
$\theta(t) = w_S t - \varphi$	The instantaneous phase of fundamental of $i_{Cha.}$

TABLE I - Nomenclature

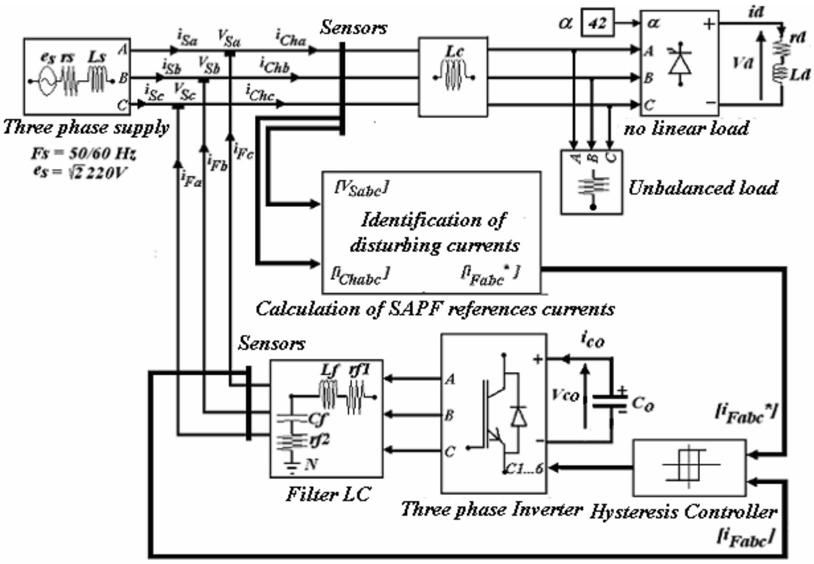

Fig. 1. Block diagram of the electric system studied

3 Control strategy of SAPF

On the basis of our research published [1], we are synthesized a control strategy of the SAPF to eliminate the disturbing currents. In order to make sure of the strategy effectiveness, the research objective is to detect its robustness and its adaptability under a voltage supply strongly disturbed.

With a same aim, a comparison is made with the strategy of the instantaneous power and the strategy of the synchronous detection which are revised and improved to agree under more constraining conditions.

3.1 Control strategy suggested

Our strategy consists, to determine the disturbing currents $[i_{Chabc\_p}]$, to eliminate the positive sequence at the fundamental frequency $[i_{Chabc\_f}]$ from the polluting load currents $[i_{Chabc}]$.

With an aim to obtain an energetic attenuation of the disturbing currents and to ensure a flexible correction of the reactive power, we considered two scenarios represented on the diagram of figure 2.

The First one is the compensation for the disturbing currents $[i_{Chabc\_p}]$ without the reactive power. Therefore, the SAPF reference currents must be clarified according to the relation:

$$[i_{Fabc}*] = C_{32}^{-1}\begin{bmatrix} i_{Ch\alpha} - i_{Ch\alpha\_f} \\ i_{Ch\beta} - i_{Ch\beta\_f} \end{bmatrix} \tag{2}$$

With:

$$\begin{bmatrix} i_{Ch\alpha\_f} \\ i_{Ch\beta\_f} \end{bmatrix} = I_{Ch1}.\sqrt{\frac{3}{2}}.\begin{bmatrix} \sin\theta \\ -\cos\theta \end{bmatrix} \tag{3}$$

Where I_{Ch1} represents the fundamental amplitude which is calculated with the relation:

$$I_{Ch1} = \sqrt{\frac{2}{3}}.\sqrt{< i_{Ch\alpha}^{\ 2} + i_{Ch\beta}^{\ 2} >} \tag{4}$$

For this case, we improve the form factor μ of the supply current, the power factor λ without touching the phase displacement factor $cos\varphi$.

The second proposes to compensate for the disturbing currents $[i_{Chabc\_p}]$ and the reactive power. Thereafter, the SAPF reference currents must check:

$$[i_{Fabc}*] = C_{32}^{-1}\begin{bmatrix} i_{Ch\alpha} - i_{Ch\alpha\_fa} \\ i_{Ch\beta} - i_{Ch\beta\_fa} \end{bmatrix} \tag{5}$$

With:

$$\begin{bmatrix} i_{Ch\alpha\_fa} \\ i_{Ch\beta\_fa} \end{bmatrix} = I_{Ch1a}\sqrt{\frac{3}{2}}.\begin{bmatrix} \sin\theta_S \\ -\cos\theta_S \end{bmatrix} \tag{6}$$

Where I_{Ch1a} represents the fundamental amplitude of the credit which is calculated with the relation:

$$I_{Ch1a} = \sqrt{2/3} < i_{Ch\alpha}.\sin\theta_S - i_{Ch\beta}.\cos\theta_S > \tag{7}$$

In this case, we make evolve positively at the same time the form factor ($\mu\uparrow$) of the supply current, the power factor $(\lambda\uparrow)$ and the phase displacement factor $(cos\varphi\uparrow)$.

The synchronization terms $(sin\theta_S, cos\theta_S)$ and $(sin\theta, cos\theta)$ are generated precisely by the phase synchronous detector (PSD) based on a numerical PLL [6] developed and proposed in other paper[1].

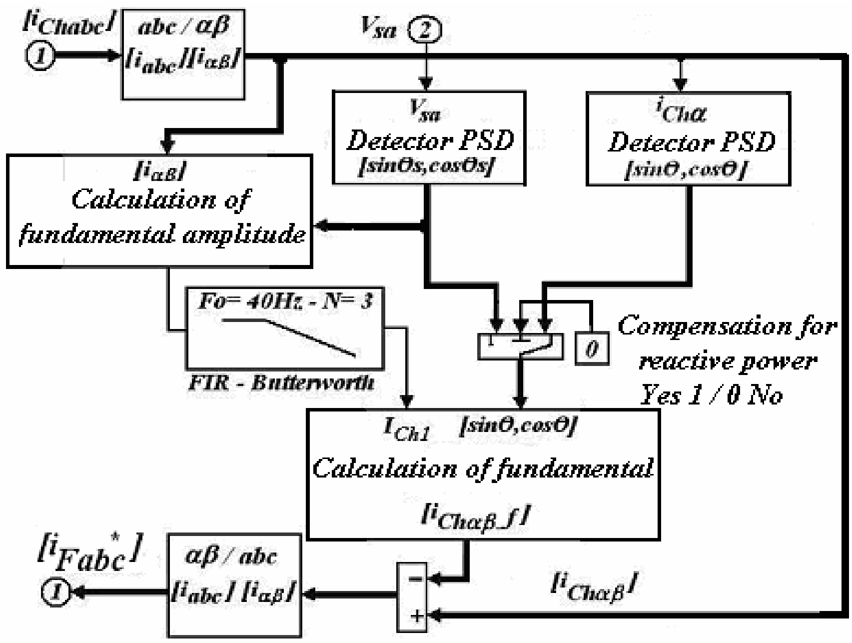

Fig. 2. Block diagram of the strategy suggested to calculate the SAPF references

3.2 The power strategy pq improved

The strategy of the instantaneous power, represented on figure (Fig 3), consists in calculating the instantaneous powers positive and negative sequence (p_{Ch}, q_{Ch}) consumed by the polluting load.

The instantaneous powers are written:

$$\begin{bmatrix} p_{Ch} \\ q_{Ch} \end{bmatrix} = \begin{bmatrix} \tilde{p}_{Ch} + P_{Ch} \\ \tilde{q}_{Ch} + Q_{Ch} \end{bmatrix} \tag{8}$$

(P_{Ch}, Q_{Ch}) are the DC powers related to the fundamental component of the current and the tension

$(\tilde{p}_{Ch}, \tilde{q}_{Ch})$ are the AC powers related to the sum of the disturbing currents and voltages.

It should be noted that in the presence of a supply voltage disturbances, the voltage harmonics and the current harmonics with same rank cause the deterioration of the DC instantaneous power.

This influences the identification in a precise way the disturbing currents. We make use of our synchronous phase detector (PSD) to detect the positive sequence at the fundamental frequency $[V_{Sabc\_f}]$ of the supply voltages $[V_{Sabc}]$. Then we calculate the instantaneous powers by:

$$\begin{bmatrix} p_{Ch} \\ q_{Ch} \end{bmatrix} = \begin{bmatrix} v_{S\alpha\_f} & v_{S\beta\_f} \\ -v_{S\beta\_f} & v_{S\alpha\_f} \end{bmatrix} . \begin{bmatrix} i_{Ch\alpha} \\ i_{Ch\beta} \end{bmatrix} \tag{9}$$

With:

$$\begin{bmatrix} v_{S\alpha\_f} \\ v_{S\beta\_f} \end{bmatrix} = V_{S1} . \sqrt{\frac{3}{2}} . \begin{bmatrix} \sin\theta_S \\ -\cos\theta_S \end{bmatrix} = C_{32} . \left[V_{Sabc\_f} \right] \tag{10}$$

Where V_{S1} represents the amplitude of positive sequence at the fundamental frequency which it's calculated with:

$$V_{S1} = \sqrt{\frac{2}{3}} . \sqrt{< v_{S\alpha}{}^2 + v_{S\beta}{}^2 >} \tag{11}$$

To calculate the reference currents of the SAPF, we proceeded by filtering the DC powers *(P_{Ch}, Q_{Ch})* through a digital filter of low-pass type *(FIR-Butterworth – NR = 4 or 5 – Fc=30Hz)*, then deducing the AC powers from them.

Thus to compensate for the harmonic currents, unbalanced currents and the reactive power, the reference currents of the SAPF $[i_{Fabc}]$ is clarified according to the relation:

$$\left[i^*_{Fabc} \right] = C_{32}{}^{-1} . \begin{bmatrix} i^*_{F\alpha} \\ i^*_{F\beta} \end{bmatrix} \tag{12}$$

With:

$$\begin{bmatrix} i^*_{F\alpha} \\ i^*_{F\beta} \end{bmatrix} = \frac{1}{v^2_{S\alpha\_f} + v^2_{S\beta\_f}} . \begin{bmatrix} v_{S\alpha\_f} & v_{S\beta\_f} \\ -v_{S\beta\_f} & v_{S\alpha\_f} \end{bmatrix} . \begin{bmatrix} \tilde{p}_{Ch} \\ q_{Ch} \pm Q_{Ch} \end{bmatrix} \tag{13}$$

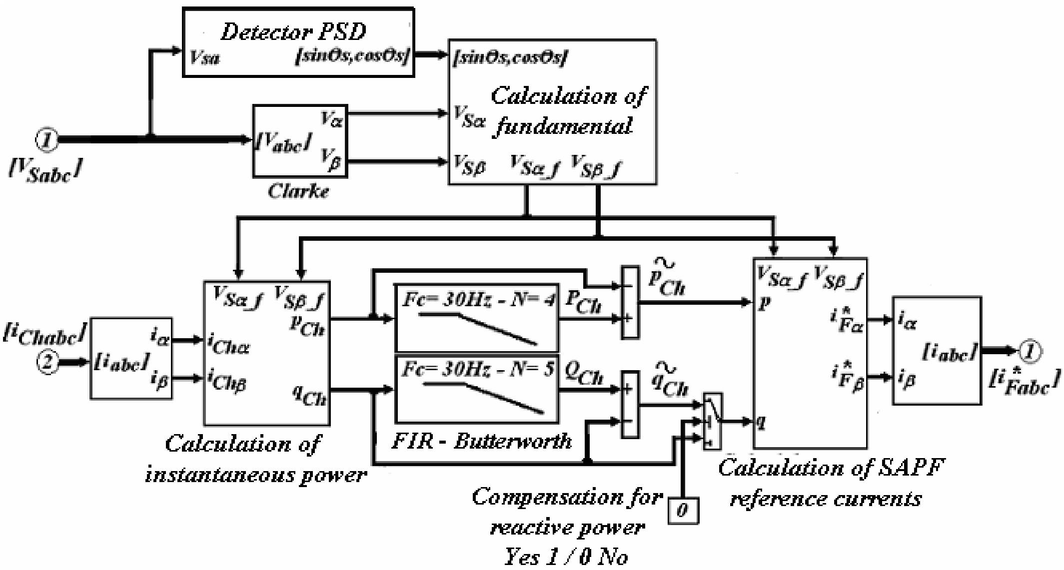

Fig. 3. Block diagram of the instantaneous power strategy improved to calculate the SAPF references

3.3 The synchronous strategy $i_d i_q$ improved

The method of synchronous detection (Fig 4) rests on the PARK transformation $P(\theta_S)$ to operate on the polluting load currents $[i_{Chanc}]$. This method requires a perfect precision of the calculation of the fundamental frequency.

Considering the presence of the frequency shifts and the disturbing voltage in the supply (harmonics, unbalance, off-peak…), we are benefited from our PSD based on the PLL to generate precisely the terms of synchronization $(\sin\theta_S,,\cos\theta_S)$. The PARK components of the load currents are written:

$$\begin{bmatrix} i_{Chd} \\ i_{Chq} \end{bmatrix} = \begin{bmatrix} I_{Chd} + \tilde{i}_{Chd} \\ I_{Chq} + \tilde{i}_{Chq} \end{bmatrix} = P(\theta_S).[i_{Chabc}] \quad (14)$$

- (I_{Chd}, I_{Chq}): DC components related to the fundamental currents.
- $(\tilde{i}_{Chd}, \tilde{i}_{Chq})$: AC components related to the sum of the disturbing currents.

We obtain the reference currents of the SAPF by eliminating the DC components on the currents (i_{Chd}, i_{Chq}) by the means of a digital filter of low-pass type *(FIR – Butterworth - Fc=40Hz - N=5)*.

The reference currents of the SAPF $[i_{Fabc}*]$ is clarified according to:

$$\left[i^*_{Fabc}\right] = P^{-1}(\theta_S).\begin{bmatrix} i^*_{Fd} \\ i^*_{Fq} \end{bmatrix} \quad (15)$$

With:

$$\begin{bmatrix} i^*_{Fd} \\ i^*_{Fq} \end{bmatrix} = \begin{bmatrix} \tilde{i}_{Chd} \\ i_{Chq} \pm I_{Chq} \end{bmatrix} \quad (16)$$

4 Simulation and results

The digital simulation is carried out in the environment *Matlab/Simulink – Power System Blockset*. The simulated block diagram is given to the figure (Fig. 1) with parameters on table (TABLE III).

The simulation of the control strategy suggested shows well an almost perfect identification of the positive sequence at the fundamental frequency and that its performances are slightly better compared to the conventional strategies which are improved (Fig. 5).

This is makes some with the difficulty in filtering (*Filter of order 5 or 6*) the DC components of the instantaneous powers and the components of PARK which know increasingly strong undulations in the presence of a supply voltage disturbed (Fig. 6 and 7).

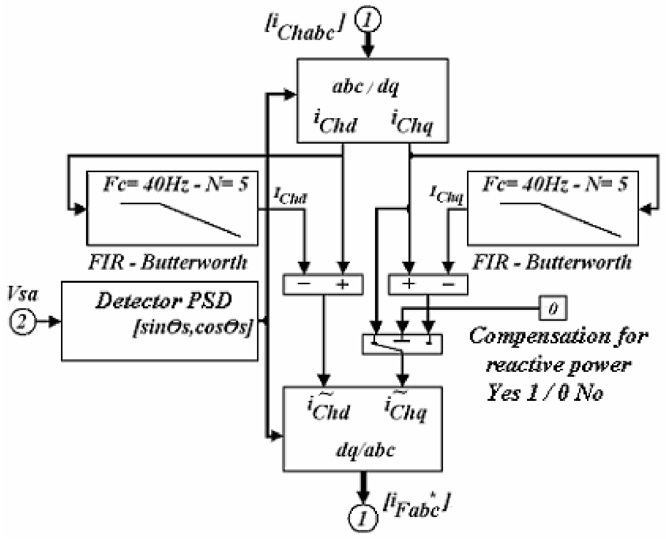

Fig. 4. Block diagram of the synchronous detection strategy improved to calculate the SAPF references

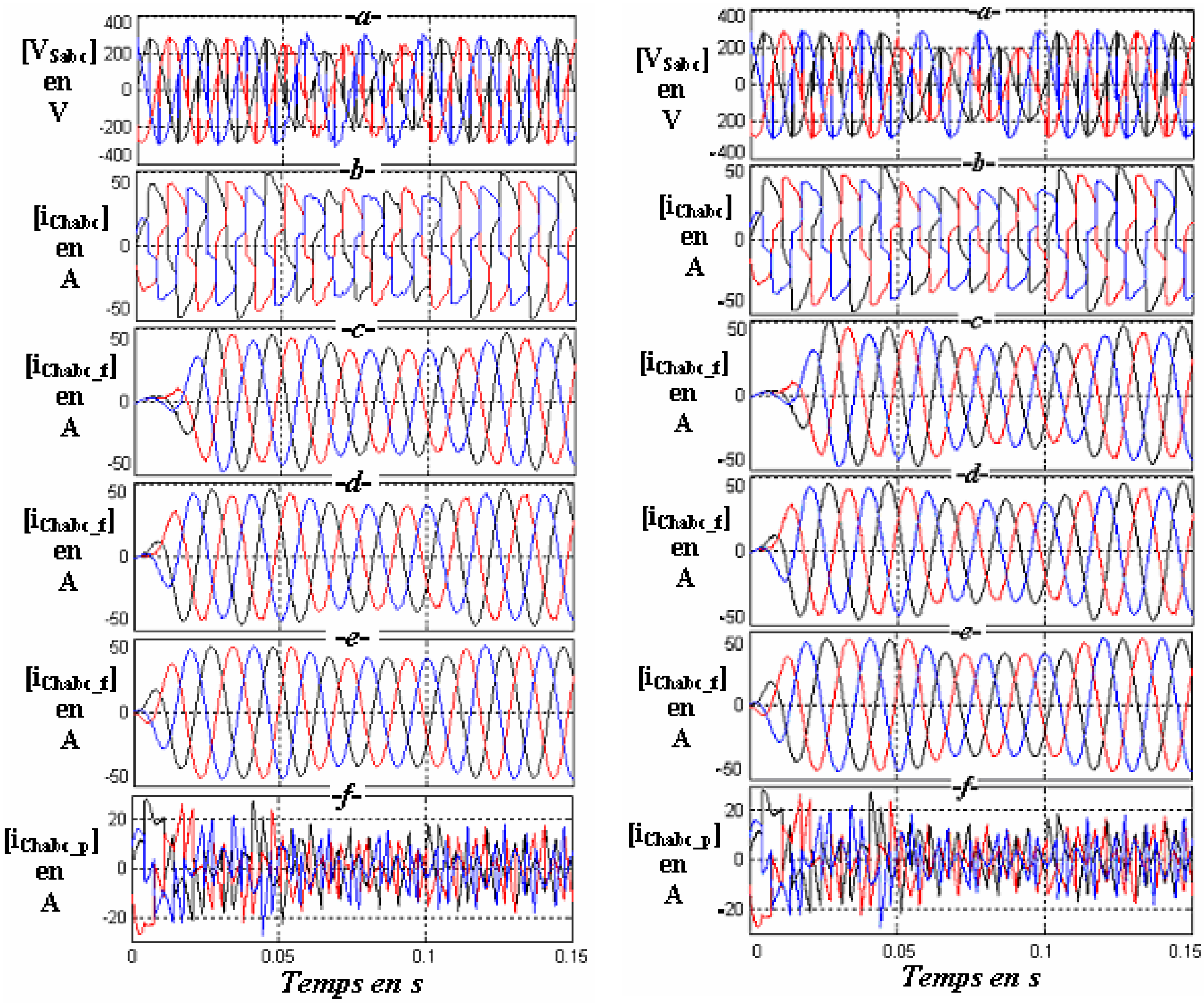

Fig. 5. Results of identification of the fundamental and the disturbing currents
a) The supply voltage b) The polluting load currents c) Fundamental calculated by the strategy suggested
d) by the strategy *pq* improved E) by the strategy $i_d i_q$ improved

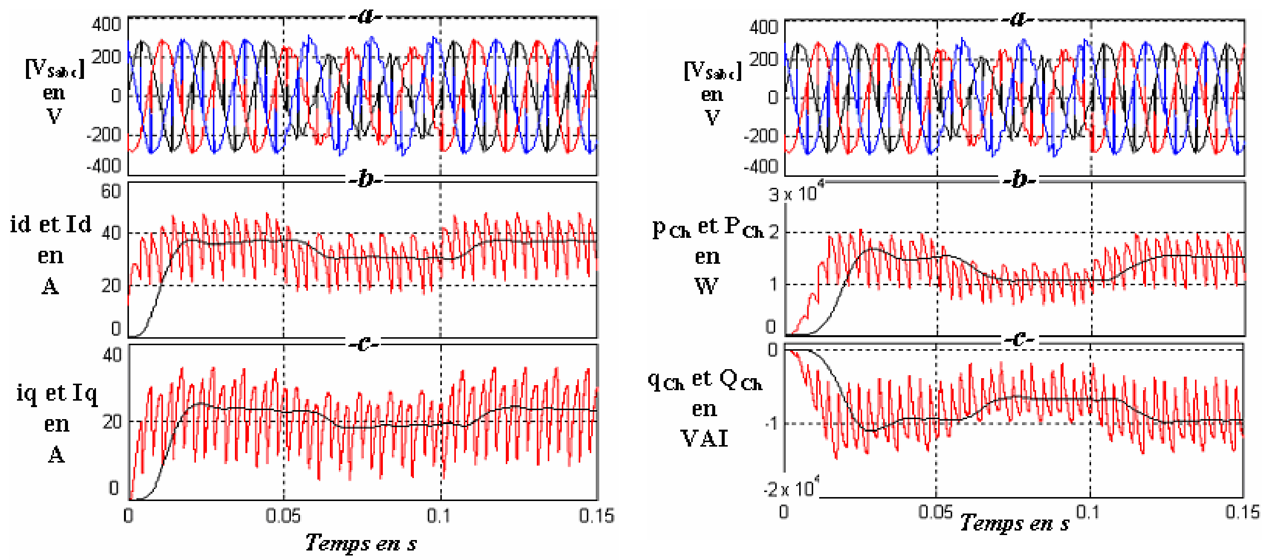

Fig. 6. Analyze PARK components (i_d and I_d, i_q and I_q) and instantaneous powers (p and P, q and Q) for a supply voltage distorted (THD_U=17%) and unbalanced (ΔU_i =23%)

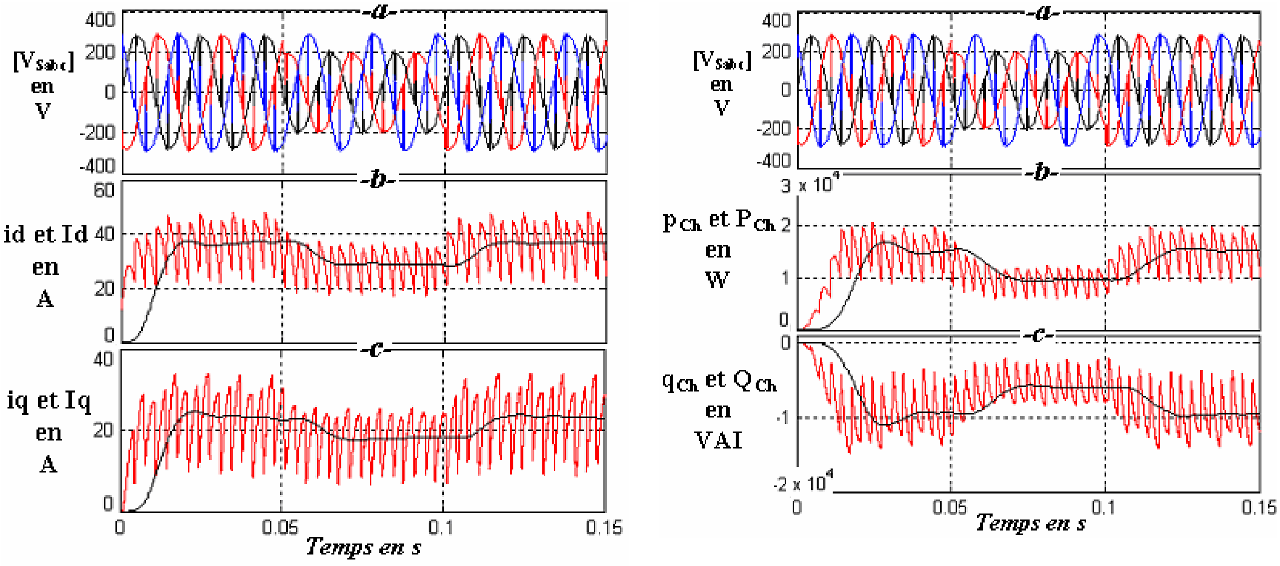

Fig. 7. Analyze PARK components (i_d and I_d, i_q and I_q)) and instantaneous powers (p and P, q and Q) for a supply voltage with a two phase off-peak $\Delta U/U_N = 30\%$

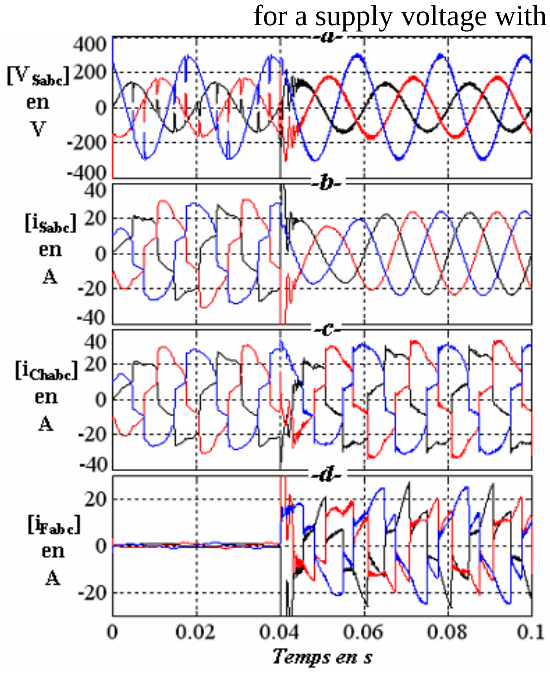

Fig. 8. Compensation for the distuyrbing currents and the reactive power at t=0.04 for a supply voltage with two phase off-peak ($\Delta U/U_N$ =35%) and unbalances (ΔU_i =20%)

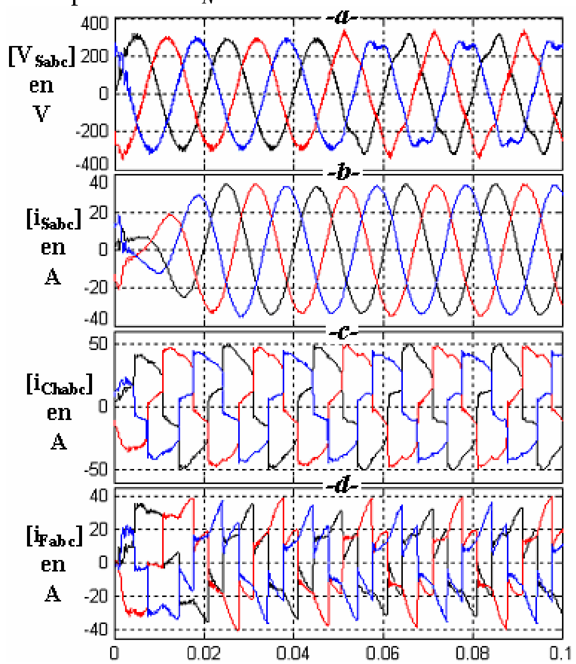

Fig. 9. Compensation for the disturbing currents and the reactive power for a supply voltage deformed at t=0.05s

The results of the temporal analysis (Fig. 8 and 9), shows a perfect compensation with a stable and fast dynamics (te <2ms). The table (TAB II) recapitulates these results before and after the insertion of the SAPF. Indeed, one notes a clear reduction of the harmonic distortion (*THDi*), unbalance degree (ΔIi) and form factor μ of the supply currents. Just as we note a clear improvement of the power factor λ and phase displacement factor $\cos\varphi$.

The results of the digital simulation reveal a perfect compensation of the disturbing currents and a robustness of the strategy developed like those improved in presence of a supply voltage disturbed. Moreover, we note the cleaning of the supply currents spectrum and the compensation of the reactive power.

Characteristic of disturbances	Without SAPF	With SAPF
Harmonic distorsion *THDi*	22.1%	0.49%
Unbalance degree ΔIi	6.15%	0.6%
Form factor μ	97.64%	99.98%
Displacement factor $\cos\varphi$	0.905	0.998
Power factor λ	88.36	99.78

TAB II – The results obtained by a strategy suggested

Supply voltage	e_S=220 V, f_S=50/60 Hz
Supply impedance	r_S= 500 mΩ - L_S=0.5 mH
Inductance L_C	L_C=50 mH - r_C =0.1Ω
DC load	L_d=50 mH - r_d= 10 Ω
Capacitance of the SAPF	V_{CO} = 540 V- C_O = 8.8 mF
Inductance of Filter (LC)	L_f=400 mH - r_{F1} =10 mΩ
Capacitance of Filter (LC)	C_f =5 mF - r_{f2}=0.5Ω

TABLE III – THE PARAMETERS OF THE SYSTEM SIMULATED

5 Conclusions and prospects

The first results of this research allowed the numerical validation under Matlab of the results obtained of the robust control strategies suggested for the SAPF.

Simulations enabled us to evaluate the performances of the control strategy studied by proving the effectiveness of the SAPF to compensate for overall all the disturbing currents generated by the disturbing loads.

The results show well the adaptability and the robustness of the control strategies under a strongly supply voltage disturbed with a light advantage of the strategy suggested compared to those conventional.

Consequently, this study contributes to universalize the shunt active filters with an aim of improving quality of electric power and increasing the reliability of the electric systems.

Appendix

The characteristic of the electric disturbances

$\Delta U/U_N = U\text{-}U_N/U_N$: the off-peak depth of the voltage with U_N nominal effective value.

$\Delta Y_i = |Y_{1i}|/|Y_{1d}|$: the unbalance degree of current or voltage .Y_{1d}, Y_{1i}: Effective value of the positive and negative sequence of the fundamental one.

Y_1, Y_n: the effective value of fundamental and the harmonic of row *n* (of current or voltage)

Hn %: Individual rate of harmonics. $H_n=100.Y_n/Y_1$

$THD_y = 100.\sqrt{\sum_{n=2}^{\infty} Y_n^2} / Y_1$: The Total Harmonic Distortion.

$\lambda = \cos\varphi.\mu$: The Power Factor With

$\mu = Y_1 / \sqrt{\sum_{n=1}^{\infty} Y_n}$: The Form Factor

$\cos\varphi$: The Phase Displacement Factor

The transformation of Clarke C_{32} and Park $P_{22}(\theta_S)$:

$$C^{-1}{}_{32} = \sqrt{\frac{2}{3}}.\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}^{-1}$$

$$= \sqrt{\frac{2}{3}}.\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}$$

$$P_{32}(\theta_S) = \begin{bmatrix} \sin\theta_S & -\cos\theta_S \\ \sin\theta_S - 2\pi/3 & -\cos\theta_S - 2\pi/3 \\ \sin\theta_S - 4\pi/3 & -\cos\theta_S - 4\pi/3 \end{bmatrix}^{-1}$$

$$= \frac{2}{3}.\begin{bmatrix} \sin\theta_S & \sin\theta_S - 2\pi/3 & \sin\theta_S - 4\pi/3 \\ -\cos\theta_S & -\cos\theta_S - 2\pi/3 & -\cos\theta_S - 4\pi/3 \end{bmatrix}$$

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