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Diagnostic and Active Filtering of Harmonics Generated by Compact Fluorescent Lamps

Samir Moulahoum *, Hamza Houassine * and Nadir Kabache *

Abstract – Use of nonlinear loads, such as power converters, fluorescent lamps and adjustable speed motor drives, is expected to grow rapidly. All of these loads inject harmonic currents. This paper presents the active filtering of the harmonic distortion generated by the compact fluorescent lamps (CFL). The Instantaneous active and reactive power theory (the p-q Theory) is used to design the control of parallel active filter. The control scheme has been verified using Matlab/Simulink with SimPower Systems through a set of simulation tests under different load conditions. Also, the tuning of the active power filter is performed to improve the quality of the electrical power supply.

Keywords: Active filter, CFL, Harmonics, Power Quality, THD

1. Introduction

Power system harmonics are integer multiples of the fundamental power system frequency. Power system harmonics are created by non-linear devices connected to the power system. High levels of power system harmonics can create voltage distortion and power quality problems. Harmonics in power systems result in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors [1-2].

When a sinusoidal voltage is applied to a certain type of load, the current drawn by the load is determined by the voltage and impedance and follows the voltage waveform. These loads are referred to as linear loads. However, some loads cause the current to vary disproportionately with the voltage during each cyclic period. These are classified as nonlinear loads, and the current taken by them has a non-sinusoidal waveform.

Waveform distortion can be mathematically analyzed to show that it is equivalent to superimposing additional frequency components into a pure sine wave. These frequencies are harmonics (integer multiples) of the fundamental frequency, and can sometimes propagate outwards from nonlinear loads, causing problems elsewhere on the power system. Examples of nonlinear loads are battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies.

One of the obvious ways to use electricity more efficiently is by using energy efficient lighting such as Compact Fluorescent Lamps (CFL) to replace conventional incandescent lamps. The electronic ballasts of CFLs are nonlinear, and hence a current waveform that is rich in harmonics is drawn. This harmonic current flowing in the network causes a power quality issue as these harmonic currents flowing through the system will distort the voltage waveform.

In the past the harmonics injected into the network by CFLs has been ignored as each CFL's injection is very small. The combined effect however, of the widespread adoption of CFLs can be just as detrimental as one large harmonic source.

In this paper, the perturbation generated by the electronic ballasts on the distribution power system was studied based on theoretic models of the Compact Fluorescent Lights and various experimental manipulations was discussed.

Traditionally, passive filters have been used to reduce line current harmonics, to compensate the reactive power and improve the power factor. However, passive filters are bulky, load dependent and can also cause resonance problems to the system. In order to solve these problems, Active power filters APFs have been considered as a possible solution for reducing current harmonics and also minimizing of power loses while transmission of energy from source to load [3-6].

Active filters use a switch mode power electronic converter to supply harmonic currents equal to those in the load currents. Different active power filters topologies have been presented in the technical literature [8-9]. Moreover, the active power filter can also compensate the load power

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* Research Laboratory on Electrical Engineering and Automatic LREA, University of Médéa, Algeria, Tel/Fax: +21325599986. (samir.moulahoum@gmail.com,hamza_houassine@yahoo.fr, nadir.kabache@gmail.com)

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factor. In this way, the power distribution system sees the non-linear load and the active power filter as an ideal resistor [10]

The control strategy applied in this paper is based on the instantaneous power in the α-β-0 reference frame (p-q theory), proposed by Akagi et al. [11]. In literature, several works can be found on control strategies for active power filters based on instantaneous power theory [12-13].

This paper presents experimental and simulation results that evaluate the harmonic distortion and the performance of the shunt active power filter with nonlinear Load CFLs.

2. Compact Fluorescent Lights Presentation

A compact fluorescent lamp (CFL), also called compact fluorescent light, energy-saving light, and compact fluorescent tube, is a fluorescent lamp designed to replace an incandescent lamp. The lamps use a tube which is curved or folded to fit into the space of an incandescent bulb, and compact electronic ballast in the base of the lamp.

Compared to incandescent lamps giving the same amount of visible light, CFLs use less power (one fifth to one third) and have a longer rated life (eight to fifteen times). In most countries, a CFL has a higher purchase price than an incandescent lamp, but can save over five times its purchase price in electricity costs over the lamp's lifetime.

CFLs radiate a light spectrum that is different from that of incandescent lamps. Improved phosphor formulations have improved the perceived color of the light emitted by CFLs, such that some sources rate the best "soft white" CFLs as subjectively similar in color to standard incandescent lamps.

3. Harmonics Generated By the CFLs

In this section we present the simulation of a lamp’s model (CFL) on a single phase (230V-50Hz), and three phase (380V-50Hz). The model, shown in Fig.1, is identified from the electronic ballast of the lamp. We use the harmonic analyzer to validate CFL electronic ballast block and to diagnostic the harmonic generated by the CFLs. A harmonic analyzer is used to obtain data in terms of electrical parameters for any point we are interested in for the application of harmonic filters. This device not only shows data on the spot but can also store data digitally which can later be retrieved using computer and a software provided by the harmonic analyzer manufacturer.

The experimental bench is illustrated in Fig.2.

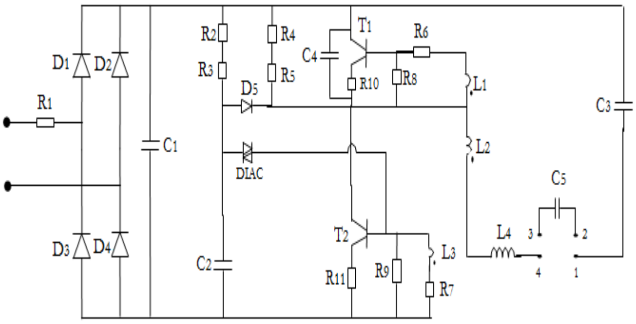

Fig. 1. CFL electronic ballast block diagram

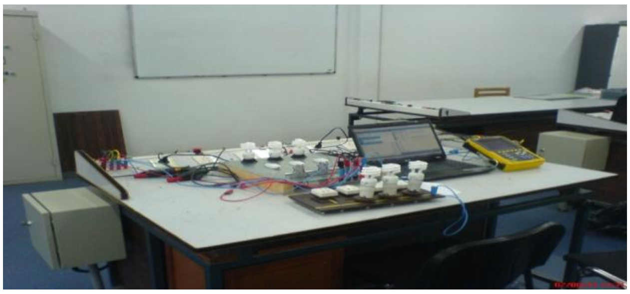

Fig.2. Experimental bench

3.1 CFLs under Single Phase Supply

The applied voltage is similar to that used in experimental tests, the THD is 4.9%. The current of the lamp with its harmonic spectrum is shown in the Fig.3 and Fig.4. Comparing the simulation results and the experimental tests, we conclude that the model adopted for the lamp is validated.

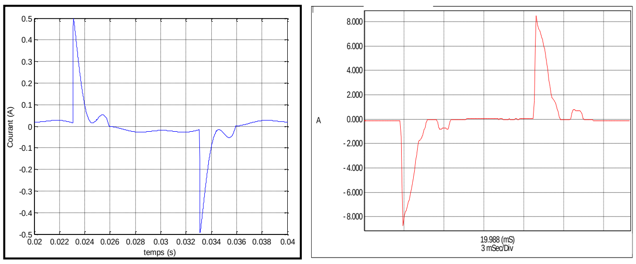

Fig.3. Source current: simulation (left) measure (right) current scale (*0.05)

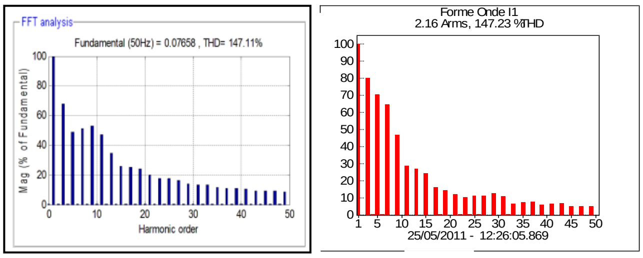

Fig.4. Harmonic spectrum of source current Simulation (left) Measure (right)

3.2 CFLs under Three Phase Supply

In this section we study the effect of CFLs on a three-phase balanced source. The current of the lamp in each phase is shown in the Fig. 5. The current record in the neutral and its harmonic analysis are given in Fig. 6 and Fig.7 respectively.

Comparing the simulation results and the experimental ones, we can confirm that:

– The current in three phases are identical, but distorted.

– The neutral current is with frequencies multiple of the frequency of 3rd harmonic.

– The model adopted for the lamps is validated.

After modeling and testing the CFLs, we concluded that these lamps are harmonic generator (non-linear loads), if used in large numbers, can affect the distribution network.

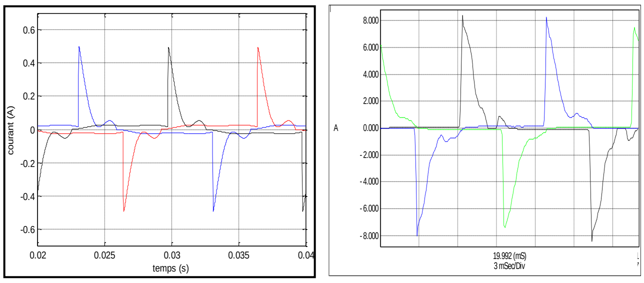

Fig.5. Three phase CFLs current: (left) Simulation, (right) Experimentation with current scale (*0.05)

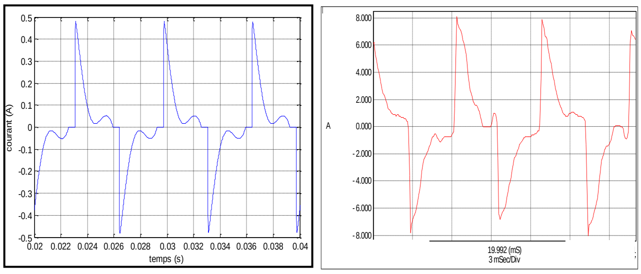

Fig.6. Current in neural conductor (left) Simulation, (right) Experimentation with current scale (*0.05)

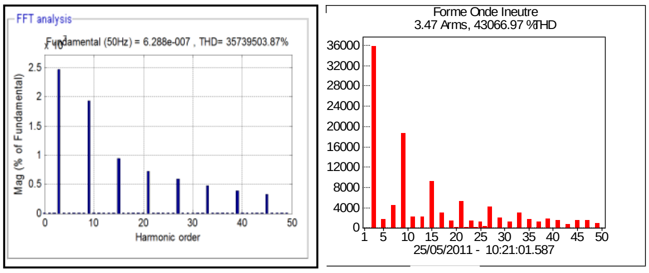

Fig.7. Harmonic analysis neural current (left) Simulation, (right) Experimentation

4. Shunt Active Power Filter

The shunt active power filter acts as a current generator that compensated the load current, in such a way that the source current drained from the network will become sinusoidal and in phase with the voltage.

Figure 8 shows a block diagram of SAPF. The shunt active filter generates the reference current i_f that compensates the load current i_L in order to guarantee sinusoidal current i_S drawn from the network. Therefore, shunt active power filter injects an equal-but-opposite harmonic compensating current i_f to cancel the harmonic contents of the line current i_S. So, the current i_S is the result of summing the load current i_L and the opposite filter current i_f:

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

Instantaneous reactive power theory, developed by Akagi et al [11], is used to control the shunt active power filter SAPF. This theory, known as p-q Theory, consists of a Clarke transformation of three-phase voltages and load currents from the a-b-c coordinates to the α-β-0 coordinates:

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

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{3}$$

One advantage of applying the α-β-0 transformation is the separation of zero-sequence components into the zero sequence axis. Naturally, the α and β axis do not have any contribution from zero-sequence components. If the three phase system has not neutral conductor, no zero sequence current components are present and can be eliminated in the above equations [14], simplifying them. In this situation the p-q instantaneous power components are calculated by using load currents and source voltages as:

$$\begin{bmatrix} \mathrm{P} \\ \mathrm{q} \end{bmatrix} = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \\ -V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{4}$$

Instantaneous real and imaginary powers include AC and DC components. Normally only the average value of the instantaneous power is desirable and the other power components can be compensated using a shunt active filter.

Hence, the load currents components can be obtained from direct and alternative powers as follow:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \frac{1}{{V_{s\alpha}}^2 + {V_{s\beta}}^2} \begin{bmatrix} V_{s\alpha} & -V_{s\beta} \\ V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} P \\ q \end{bmatrix} \tag{5}$$

In general, when the load is nonlinear the real and imaginary powers can be divided in average components $\overline{P}$ and $\overline{q}$ and oscillating components $\widetilde{P}$ and $\tilde{q}$, as shown below.

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \underbrace{\frac{1}{\Delta} \begin{bmatrix} V_{s\alpha} & -V_{s\beta} \\ V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} \overline{P} \\ 0 \end{bmatrix}}_{\text{active current}} + \underbrace{\frac{1}{\Delta} \begin{bmatrix} V_{s\alpha} & -V_{s\beta} \\ V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} 0 \\ \overline{q} \end{bmatrix}}_{\text{reactive current}} + \underbrace{\frac{1}{\Delta} \begin{bmatrix} V_{s\alpha} & -V_{s\beta} \\ V_{s\beta} & V_{s\alpha} \end{bmatrix} \begin{bmatrix} \widetilde{P} \\ \tilde{q} \end{bmatrix}}_{\text{harmonic current}} \tag{6}$$

In order to calculate the reference currents that the active filter should inject, it is necessary to separate the desired average power components $\overline{P}$ and $\overline{q}$ from the undesired oscillating harmonic power components $\widetilde{P}$ and $\tilde{q}$. This is obtained by a low pass filter applied to P and q as shown in the Fig.9. Harmonic components of $i_{L\alpha}$ and $i_{L\beta}$ are the reference currents of shunt active power filter. And then they are transformed to three-phase system by:

$$\begin{bmatrix} i_{fa} * \\ i_{fb} * \\ i_{fc} * \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{f\alpha} * \\ i_{f\beta} * \end{bmatrix} \tag{7}$$

The inputs of the shunt active filter controller are the network voltages, load currents and real filter currents as shown in the Fig.8. The switching signals used in shunt active power filter control algorithm are generated by comparing filter reference currents and actual filter currents and using hysteresis band current control algorithm. The hysteresis band current control technique has proven to be most suitable for applications of current controlled voltage source inverters. The hysteresis band current control is characterized by unconditioned stability, very fast response, and good accuracy [15]. The hysteresis band current control scheme is composed of a hysteresis around the reference filter current. The hysteresis band current controller decides the switching pattern of active power filter. The switching logic of transistors is given as follows:

$$\begin{aligned} i_{fa} &< i_{fa}^{*} - \Delta i_{f} \;\rightarrow \text{Ta on and Ta}'\text{off} \\ i_{fa} &> i_{fa}^{*} + \Delta i_{f} \;\rightarrow \text{Ta off and Ta}'\text{on} \end{aligned} \tag{8}$$

The switching functions of transistors T_B, T_B', T_C and T_C' for phases B and C are determined similarly.

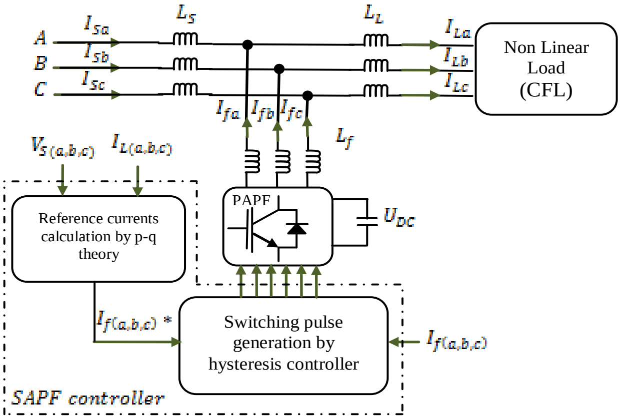

Fig.8. Shunt active power filter structure

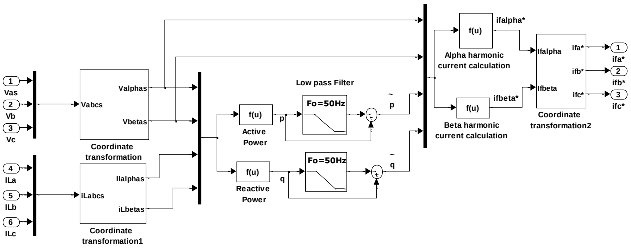

Fig.9. SIMULINK blocks of the P-Q theory applied to calculate SAPF reference currents

5. Simulation results of SAPF

The performances of the shunt active power filter are simulated using MATLAB software. Simulink and SimPower Systems block sets are used for implementing the global system (CFL and SAPF). The performances are studied for different operating conditions for both the balanced and unbalanced load conditions.

At first, Simulation results are given here for one CFL per phase as a nonlinear load. Figures 10 to 13 (left curves) show the source current i_S, the load current i_L and the filter current i_f before and after active filter connection (at t=0.1s the SAPF is connected). It may be noted that, before filter connection, the source current waveform is non-sinusoidal because of which its THD is as 147% and its fundamental value is 0.075 A, Harmonic distortion of the source current drawn by the grid is observed. It can be seen that the THD in this cases is higher; The SAPF works correctly even in low values of current and high THD. After connecting SAPF, The THD is significantly reduced to 4%. The fundamental value remains approximately the same when the filter is connected which prove that the filter injects only the harmonic currents and the grid injects the fundamental component of the load current.

Same results can be obtained for a group of CFLs, as shown in Figures 10 to 13 (right curves). From the results obtained, it was found that the waveform is significantly improved. The THD changes from a value of 148% up to 1% after the incorporation of active power filter.

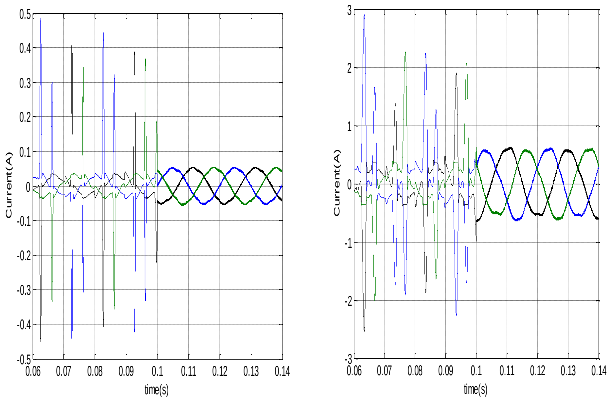

Fig.10. Source current before and after Shunt active filter connection (left: One CFL per phase, right: 10 CFLs per phase)

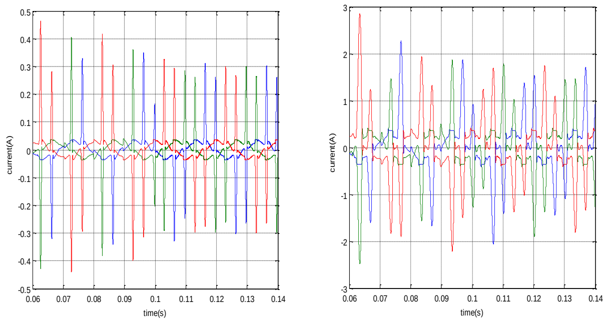

Fig.11. Load currents before and after Shunt active filter connection (left : One CFL per phase, right: 10 CFLs per phase)

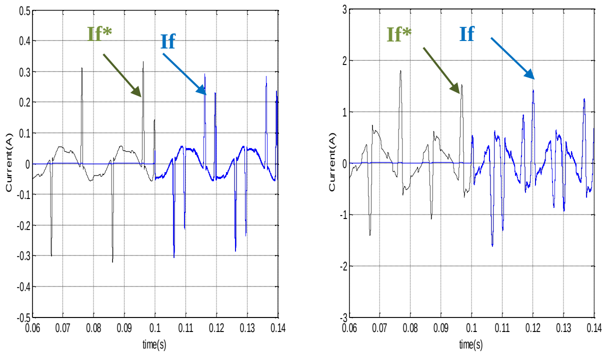

Fig.12. Real and reference filter currents before and after Shunt active filter connection (left: One CFL per phase, right: 10 CFLs per phase) (Blue: reference filter current, Green: real filter current)

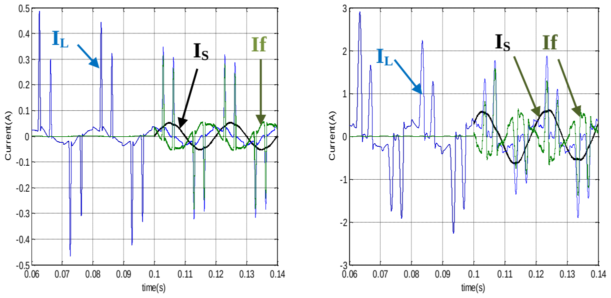

Fig.13. Source current, load current and filter current before and after Shunt active filter connection (left: One CFL per phase, right: 10 CFLs per phase) (green: source current, red: filter current, blue: load current)

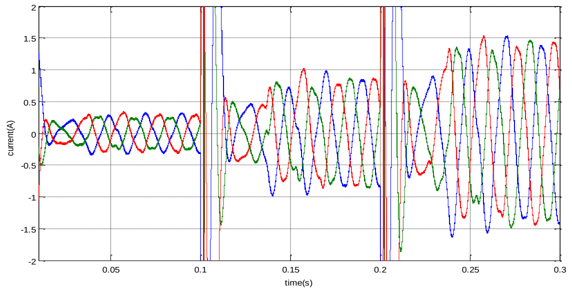

Fig.14. Response of SAPF for variable CFLs load: 15 CFLs, 45 CFLs and 75 CFLs.

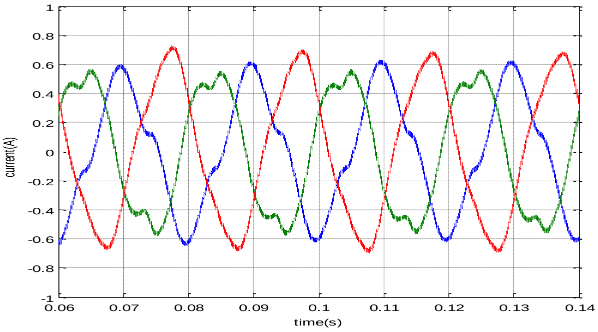

Fig.15. Response of SAPF for unbalanced CFLs load: 15 CFLs in phase A, 10 CFLs in phase B, 5 CFLs in phase C.

Figure 14 shows the currents waveform imposed by increase and decrease in load. It can be observed that the SAPF adapts its self to load variation and the currents drawn from the grid remain sinusoidal while the load changes. The THD of the source current is reduced from 115.45% to 4.02% for 15 CFLs, from 103.26% to 3% for 45 CFLs and from 92.91% to 3.68% for 75 CFLs. The fundamental values of the sources currents are respectively 0.29A, 0.86A and 1.42A.

Figure 15 shows the response of the SAPF for unbalanced load. It is clearly shown that even when the CFLs load is unbalanced the source currents i_{sabc} are unbalanced and they are not purely sinusoidal. However, their THD is reduced from 102.85% to 11.7% for phase A, from 135.75% to 14% for phase B and from 112.55% to 8.7% for phase C. The fundamental values of the three phase currents are respectively 0.83A, 0.557A and 0.39A.

7. Conclusion

In this paper we presented the solution to reduce the non-sinusoidal current created by a CFLs lamps, this solution is the active filtering. First, we carried out the diagnosis of lamps FCLs and second we use a shunt active filter to improve the current delivered by the power supply and therefore reduce the total harmonic distortion of current

The shunt active power filter is based on the instantaneous power theory proposed by Akagi and on current hysteresis band control technique of the static power converter. The active filter controller is able to determine the fundamental component of the load current even under very high distortion conditions. The results show that the THD is improved from an extremely high value to a much more convenient value.

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Samir Moulahoum received the Engineer degree in Electrical Machines in 1995 and the Magister degree in Electrical Engineering in 1998 and the Doctorate degree in Power Elctronics and Drives in 2006 from University of Sciences and Technology of Algiers USTHB. He is actually an associate professor in Department of Electrrical Engineering at the University of Médéa. His research interests are Power Electronics, Electrical Drives, Power Generation and Power Quality.

Hamza Houassine received the Engineer degree in Electrical Engineering in 2001 from Mouloud Mammeri University of Tizi-Ouzou, the Magister degree in electrotechnical systems in 2004 from polytechnic Military School of Algiers. The Doctorate degree in Electrical Engineering in 2010 from Mouloud Mammeri University of Tizi-Ouzou. He is currently an associate professor in Electrical Engineering Department at The University of Médéa. His research interests include Electric Machines, field analysis and Power systems.

Nadir Kabache received the Engineer, Magister and Doctorate degrees in Electrical Engineering in 1997, 2001 and 2007 respectively from M'hamed Bouguerra University of Boumerdès. He is currently an associate professor in Electrical Engineering Department at The University of Médéa. His research interests include Electric Machines, Variable Speed Drives. He is also Director of Research Laboratory in University of Médéa since 2010.