CONTROL STRATEGIES FOR ACTIVE POWER LINE CONDITIONERS: A LITERATURE REVIEW

Eumir V. Salgado[1,2], Maurício Aredes[2], Luis F. C. Monteiro[2] *and* João A. M. Moor[2]
[1] IME – Instituto Militar de Engenharia – Departamento de Engenharia Elétrica
[2] UFRJ – Universidade Federal do Rio de Janeiro – COPPE – Programa de Engenharia Elétrica
eumir@ieee.org, aredes@ufrj.br, lfcm@coe.ufrj.br, moor@coe.ufrj.br

Abstract – **Active power line conditioner has been successfully applied in power systems. This paper will present a review in the common used active filters control strategies with emphasis in *p-q* theory, synchronous *d-q* reference, generalized Fryze Current, and *p-q-r* theory. Simulation results of some active filter configurations will be present to show their characteristics and performance.**

KEYWORDS

Active Filters, Active Power Line Conditioners, Instantaneous Active and Reactive Power, Instantaneous Power Theory, review control strategies.

I. INTRODUCTION

In the last decades, the use of power electronics devices introduced several nonlinear characteristics in the power system. Voltage and current harmonics are some examples of modern power quality problems. On the other hand, problems concerning voltage unbalances and voltage sags, which represent some kinds of disturbances at the fundamental frequency, have become also important issues in the modern power system, since it has causing losses in consumers with sensitive loads. Due these drawbacks, many efforts have been made in order to improve the power quality in distribution systems. Many power electronics circuits for power quality conditioning have been developed, including solid-state devices and control strategies. Active filters have been successfully used to compensate current and voltage harmonics, unbalances and reactive power, improving power quality at the point of installation.

Some specialists have the opinion that "the best control strategy" is that guarantees compensated currents drained from the network, that are proportional (they have the same waveforms) to the system voltages. Under balanced, undistorted system voltages, this strategy compensates load current to force the compensated current to become sinusoidal and in phase with the system voltage. However, if the voltage is itself already distorted, the compensated currents become the same waveform. Other specialists defend the idea that "the best control strategy" is that guarantees sinusoidal and balanced compensated currents, even in the presence of distorted/unbalanced voltages at the PCC. In same special cases, it might be imperative to have compensated currents that draw only a constant active instantaneous power from the network that corresponds to the average active power of the load being compensated.

In summary, under distorted and / or unbalanced system voltages, it is impossible to implement a shunt active filter that satisfies simultaneously:

i) Constant real power drained from the network;
ii) Sinusoidal compensated current;
iii) Proportionality between the system voltage and the compensated current.

In this paper, the focus will be on the control strategies applied in active power line conditioners based on time domain techniques, like the *pq* theory, synchronous *dq* reference, generalized Fryze current and *pqr* theory. The *pq Theory* proposed by Akagi *et al.,* in 1983 [1] is valid for generic voltages and currents waveforms, including transient periods [2]. It guarantees sinusoidal current and voltage or source constant power, since if the voltages are distorted and/or unbalanced it is impossible to satisfy simultaneously sinusoidal current and constant power conditions. It defines the power in terms of $\alpha\beta0$-reference frame, with possibility of compensating separately the power p, q, and p_0. In the synchronous *d-q* reference frame, voltage and current signals are transformed to a synchronously rotating frame, in which fundamental quantities become dc quantities, and all harmonics are transformed to non-dc quantities and undergo a frequency shift of 60Hz in the spectrum [3],[4].

In the beginning 30´s, *Fryze* proposed a set of active and reactive power definitions in the time domain. A control strategy, called *Generalized Fryze Currents* was developed and applied in power electronics in the 90´s [2],[5], based on minimization methods, where the non-active current of a three-phase system which does not produce any active power is determined to become the instantaneous reference value of the compensating current of a shunt active filter.

Finally, the focus will be in the instantaneous power compensation based on the Power Theory on the Rotating *pqr* Reference Frames [6]. In this theory, one instantaneous active power p, and two instantaneous reactive powers q_q, q_r are defined.

II. CONTROL STRATEGIES

A. Control strategy based on the p-q theory

This control strategy is based on the instantaneous power definitions in $\alpha\beta0$ reference frame and considers harmonics and unbalances due to fundamental negative- and zero-sequence components, in voltage and currents. Two control strategies were proposed, considering constant source instantaneous power and sinusoidal source current [2][7] for the shunt active filter. In the constant instantaneous power, the power $\tilde{p}$ is separated from p and $\bar{p}_0$ from p_o and to provide optimal power flow to the source $\tilde{p}$, p_o and q should be compensated.

The sinusoidal source current control strategy is substantiated on the original one proposed by *Akagi et al.* [1], but using a positive-sequence voltage detector. The control block diagram is shown in Fig. 1. It is able to compensate the current of a nonlinear load, even under unbalanced and/or distorted system voltage. For the source, the current is sinusoidal, balanced and free of harmonics. This control strategy is obtained by replacing the low-pass filters (LPF) of the voltage measurements by the signals from the fundamental positive-sequence detector in the control block for the constant instantaneous power. Also, the 50 Hz LPF should be removed because the signals v_a', v_b' and v_c' contain no zero sequence. In both cases the signal $\overline{p}_{loss}$ is produced by a dc voltage regulator to keep the dc capacitor charged at a desired value.

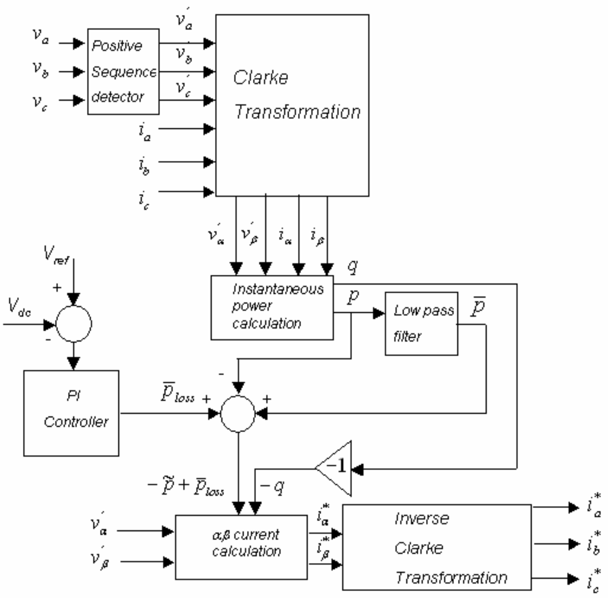

Fig. 1. Control block for the sinusoidal Source Current Control Strategy

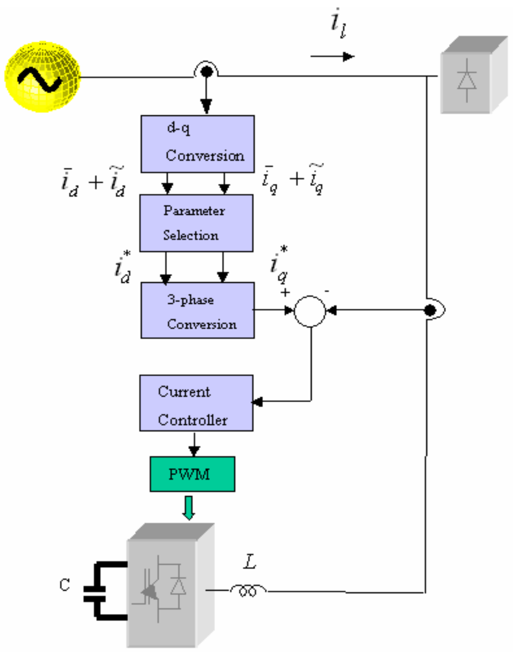

Fig. 2. Control block for the synchronous reference frame

B. Control strategy based on the synchronous d-q reference frame method

In this control strategy the AF is modeled with reference to a synchronously rotating *dq0* reference axes. This transformation extracts the negative and zero sequence and harmonics present in power supply. [8].

In Fig. 2 a shunt active filter is presented. Load currents are measured and converted into d-q coordinates as follow [9]:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\omega t & \sin(\omega t - \frac{2}{3}\pi) & \sin(\omega t - \frac{4}{3}\pi) \\ \cos\omega t & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t - \frac{4}{3}\pi) \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (1)$$

where ω is the power supply frequency from an PLL. The current components i_d and i_q are decomposed as:

$$i_d = \bar{i}_d + \tilde{i}_d \text{ and } i_q = \bar{i}_q + \tilde{i}_q$$

where $\bar{i}_d$ and $\bar{i}_q$ are the positive-sequence component and $\tilde{i}_d$ and $\tilde{i}_q$ correspond to the negative-sequence and harmonic components of load current. The reference currents will depend on what kind of application purpose the shunt active filter will be used. For example, if negative-sequence and current harmonics is to be compensated, $\tilde{i}_d$ and $\tilde{i}_q$ should be the compensating current reference. If just reactive power has to be compensated, the current references are built up from $i_d^* = 0$ and $i_q^* = \bar{i}_q$.

Other controllers for hybrid passive and active filters are developed based on d-q synchronous reference frame. An example is presented described in [3].

C. Sinusoidal Fryze Currents Control Strategy

Another control strategy for active filters, derived from *Generalized Fryze Currents* is called *Sinusoidal Fryze Currents Control Strategy* [5]. Instead of using the measured voltages, the fundamental positive-sequence voltage is used. Now, it is possible to obtain sinusoidal and balanced compensated currents, when applied in shunt active power filters, even under unbalanced or distorted system voltages. The dual method can be applied in series active filters.

Fig 3 shows the *Generalized Fryze Currents Control Strategy*. The instantaneous active currents (minimized) can be calculated from the instantaneous conductance. This conductance, defined as:

$$G_e = \frac{p_{3\phi}}{v_a^2 + v_b^2 + v_c^2} \quad (2)$$

establishes the relationship between the phase voltages v_a, v_b, v_c and the active currents which produces the same instantaneous active three-phase power, but generate no reactive power, hence, they have smaller rms values. Those currents are subtracted from the measured load currents and the compensation current is achieved.

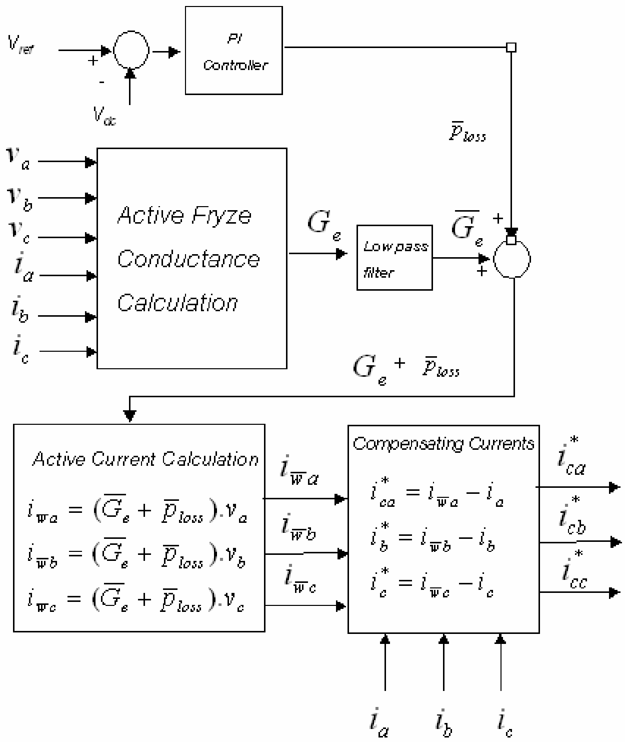

Fig 3. Control block for Generalized Fryze Currents Control Strategy

D. Control strategy based on the p-q-r theory

The instantaneous power theory on the rotating *p-q-r* was proposed by H. Kim and H. Akagi [6], where was defined one instantaneous active power p and two instantaneous reactive power q_q and q_r in three-phase four-wire system. The geometrical sum of all the instantaneous powers p, q_q, and q_r is the same when compared with the power s, which is the product of the current and voltage space vectors.

Again, the voltages and currents are transformed to the αβ0 coordinates. The *p-q-r* coordinates are rotating along with system voltage, as defined in [6]:

$$\begin{bmatrix} i_p \\ i_q \\ i_r \end{bmatrix} = \frac{1}{e_{0\alpha\beta}} \begin{bmatrix} e_0 & e_\alpha & e_\beta \\ 0 & -\frac{e_{0\alpha\beta}}{e_{\alpha\beta}} & \frac{e_{0\alpha\beta}}{e_{\alpha\beta}} \\ e_{\alpha\beta} & -\frac{e_0 e_\alpha}{e_{\alpha\beta}} & -\frac{e_\beta e_0}{e_{\alpha\beta}} \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \qquad (3)$$

where

$$e_{0\alpha\beta} = \sqrt{e_0^2 + e_\alpha^2 + e_\beta^2}, e_{\alpha\beta} = \sqrt{e_\alpha^2 + e_\beta^2}$$

Similarly, this transformation is valid for the voltages. The instantaneous real power p is defined as a scalar product of the voltage and current vectors,

$$p \equiv \vec{e}_{pqr} . \vec{i}_{pqr} = e_p i_p \qquad (2)$$

and the instantaneous imaginary power q as a vector product of the voltage and current vectors:

$$\vec{q} \equiv \vec{e}_{pqr} \times \vec{i}_{pqr} = \begin{bmatrix} 0 \\ -e_p i_r \\ e_p i_q \end{bmatrix} \qquad (3)$$

Thus, they can be expressed as:

$$\begin{bmatrix} p \\ q_q \\ q_r \end{bmatrix} = \begin{bmatrix} e_p i_p \\ -e_p i_r \\ e_p i_q \end{bmatrix} \qquad (4)$$

In three-phase systems, the voltages and currents in *p-q-r* coordinates can be described by Fourier´s series, containing two parts: a dc value representing balanced sinusoidal positive sequence, and an ac component. In consequence, the instantaneous power p and q_r also have the same two components. According to [10], the compensating currents can be calculated as

$$i_{pc} = i_{pac} \qquad (5)$$

$$i_{qc} = i_q \text{ or } i_{qdc} \text{ or } i_{qac} \qquad (6)$$

$$i_{rc} = i_r + \left(\frac{e_0}{e_{\alpha\beta}}\right).(i_p) \qquad (7)$$

The instantaneous imaginary power q_q is related to compensation of the neutral current (Eq. 7).

Fig 5 shows the control block diagram for the *p-q-r* control strategy.

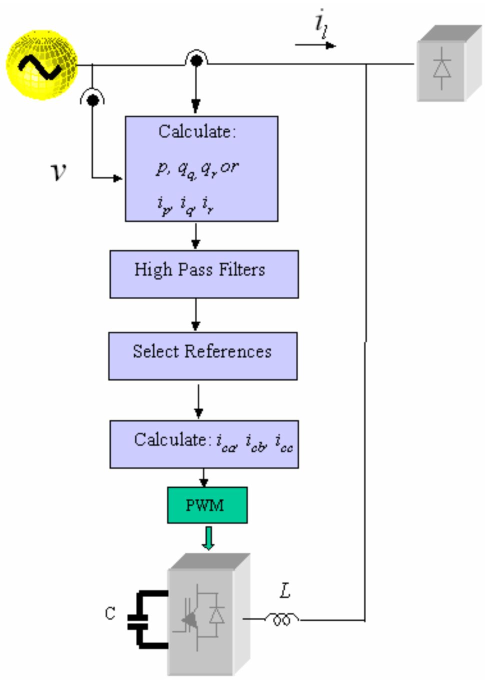

Fig 4 . Control block for instantaneous power compensation in the p-q-r theory.

E. Other control strategies

There are several control strategies in the literature. This paper is focused on the compensation in the time-domain, but there are control strategies based in the frequency domain. The Fourier analysis is used to extract compensating signal from the distorted voltage or current signals. The on-line application of Fourier transform has a significant computer effort, resulting in a large response time [4].

Wavelet transform has been used as a control algorithm for active filters, extracting the distortion features [11]. Artificial Neural Networks are also used for harmonic currents and voltages compensation [12]. A neural network control circuit was developed to generate reference signals to PWM inverters.

III. SIMULATION RESULTS

In this section, some simulation results will be presented to show the different control strategies performances for the shunt and series active filters. Both filters were implemented in PSCAD/EMTDC simulator. For the shunt filter a unbalanced (f_d = *4,8%*) and distorted three-phase, 220V voltage source was used, with 7,87% of 7^{th} harmonic. The system impedance was R = 0,107 Ω and Ls = 20mH. A three-phase diode rectifier was used as non-linear load, with R_{DC}=100Ω. In the active filter, a capacitor is used as storage element with 1200μF, and its voltage is set to 700V and the commutation inductance was 5mH.

Fig. 5 shows the unbalanced and distorted system voltages. The load's current effect also can be observed.The currents behavior for the pq theory, the synchronous d-q reference frame method and sinusoidal Fryze currents control strategy is shown in figures 6, 7 and 8.

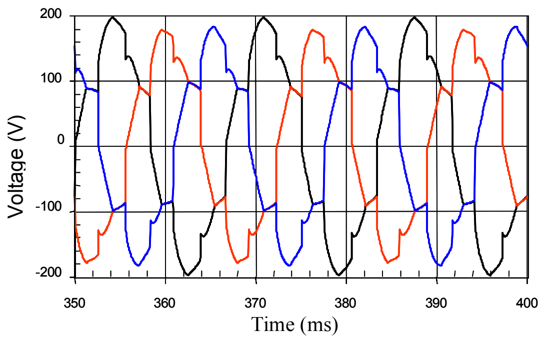

Fig 5. Source voltages

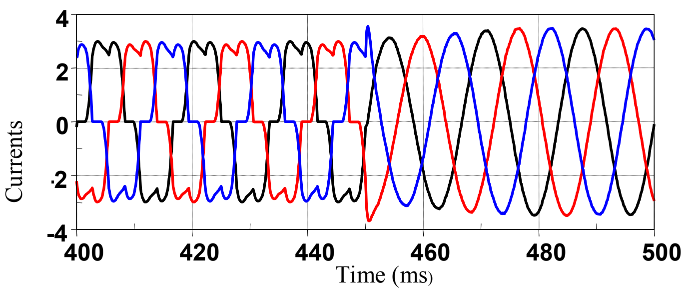

Fig 6. Source currents in pq theory.

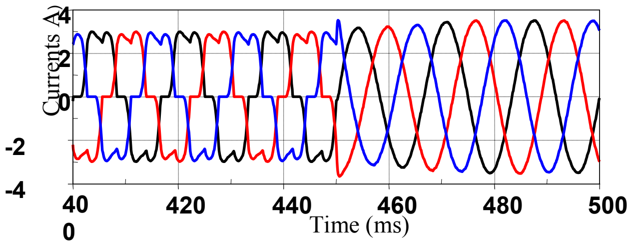

Fig 7. Source currents in the synchronous d-q reference frame method

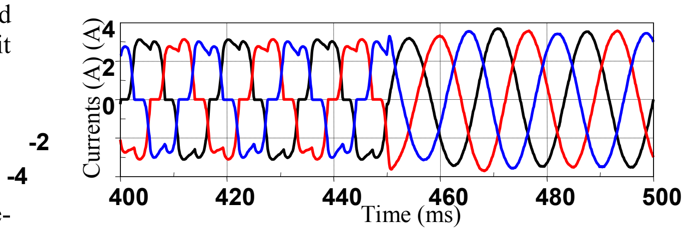

Fig 8. Source currents in the sinusoidal Fryze currents control strategy

The results for all control strategies were very similar, where the compensated currents become sinusoidal and balanced, considering the three-phase three-wire system.

For the series filter a unbalanced (f_d = *3%*) and distorted three-phase, 440V voltage source was used, with 5% of 5^{th} harmonic. The system impedance was R = 0,128 Ω and Ls = 3,5mH. A three-phase diode rectifier was used as non-linear load, with I_{DC}=18,2A. In the active filter, a capacitor is used as storage element with 1200μF, and its voltage is set to 600V and the commutation inductance was 1,5mH. Results for the pq theory and Fryze voltages control strategy are show in figures 9 and 10.

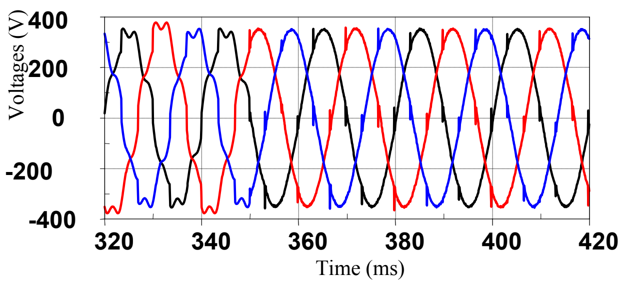

Fig 9. Load voltages in pq theory.

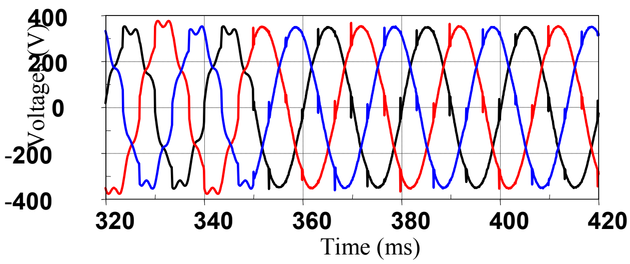

Fig 10. Load voltages in Fryze voltages control strategy

IV. CONCLUSION

In this paper, a literature review on the principal control strategies for active power line conditioners in the time domain was carried out. A selective compensation is possible with reduced time delay using time domain control obtaining satisfactory results.

All strategies can obtain balanced and sinusoidal currents even under distorted and unbalanced system voltages. In this case, no strategy will obtain simultaneously constant active power in the source and sinusoidal currents. An advantage of the *Sinusoidal Frize Currents Control Strategy* is the reduced computational efforts when compared with *pq theory*.

Simulations results are shown for the series and shunt active power filters, separately. But both filters can be combined, originating the UPQC – The Unified Power Quality Conditioner [13], adopting the control strategies discussed.

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