Control Strategies to Improve Power Quality

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Abstract **– This paper presents a comparison between different control strategies to control active filters in order to solve typical power quality problems. An alternative to evaluate control reference signals is also discussed. Instantaneous decompositions of the measured voltages and currents are used to identify the distorting and unbalancing components, and can be used to compensate non-active power, power oscillations, harmonics and unbalances in a different way as provided by the traditional *pq Theory*. Simulation results are presented to show the main differences between the control strategies facing non-linear, unsymmetrical and variable loads. These results show there are some shunt active filtering strategies capable of improving even the PCC voltages.**

I. INTRODUCTION

In the last twenty years several researches have been developed about active filtering. Most of them concerned with active filters topologies and their control strategies, particularly those based on the instantaneous power theory (*pq Theory*) presented in [1].

This work compares the use of instantaneous voltages and currents decompositions, which were developed in [8,9] and summarized in next section, as an alternative to control active filters and power conditioners. The compensation based on this methodology is quite flexible, since the decompositions enable the selective identification and elimination of several disturbing effects. As presented in [9], this methodology was originated from works like [1,2,3,4] and can be considered a combination of *Fortescue*'s and *Fryze*'s classic theories, along with the use of instantaneous vector algebra concepts [7]. It can also be used to formulate an instantaneous power theory under generic conditions and can be applied to power quality monitoring, such as discussed in [8,10]. In this work, the decompositions will be used for calculation of active filters control variables, independent of periodicity, distortions, unbalances, number of phases and the presence of neutral wire.

Since the correct choice of the control strategy for a compensation device is one of the most important requirements for power quality improvement in power systems, Section III presents various considerations about positive and negative aspects of some techniques to control active filters, particularly shunt filters, in order to compensate non-active power components, harmonics, unbalances, active power oscillations, power factor, etc.

II. DISTURBING VOLTAGES AND CURRENTS: IDENTIFICATION AND COMPENSATION FEATURES

Instantaneous signal decompositions can be used to determine the voltage and current parcels responsible for power disturbing effects and thus to identify the main power quality deterioration causes and to develop methods and techniques to improve the power quality demanded by sensitive costumers or in order to provide minimum losses.

For simplicity, the formulation presented in this work uses the three-phase power system, and the voltage and current variables are assigned as instantaneous multidimensional vectors ($\boldsymbol{v}$ e $\boldsymbol{i}$), and represented in this text by bold variables as follows:

$$\boldsymbol{v} = [v_a \ v_b \ v_c] \qquad \boldsymbol{i} = [i_a \ i_b \ i_c]\,. \tag{1}$$

Taking for example a system with non-sinusoidal and unbalanced voltages feeding a generic non-resistive load; the *first decomposition* breaks the measured signals ($\boldsymbol{v}$ and $\boldsymbol{i}$), into their fundamental components ($\boldsymbol{v}_1$ and $\boldsymbol{i}_1$) and residual signals ($\boldsymbol{v}_{res}$ and $\boldsymbol{i}_{res}$), which correspond to the voltages and currents waveform distortions. This decomposition can be implemented in different ways, for example using band-pass or band-stop filters [8,10]. However, the best solution for compensation proposes seems to be an algorithm based on a tuned DFT (*Discrete Fourier Transform*) to identify the fundamental waves of the measured signals [11]. The fast dynamic convergence justifies this choice.

Indeed, if the main focus of the application is the elimination of harmonic distortion from the voltages and currents, this objective can be achieved using the residual signals $\boldsymbol{v}_{res}$ and $\boldsymbol{i}_{res}$ as the error signals to be eliminated by the control of a series or a shunt compensation device, depending on the project requirements.

The *second decomposition* provides the identification and compensation of fundamental voltages and currents unbalances. Starting from the identified instantaneous fundamental vectors ($\boldsymbol{v}_1$ and $\boldsymbol{i}_1$), which can be unbalanced, the *second decomposition* realizes the calculation of the instantaneous *Fortescue* symmetrical components:

$$\boldsymbol{v}_1^+ = [v_{1a}^+ \ v_{1b}^+ \ v_{1c}^+] \qquad \boldsymbol{i}_1^+ = [i_{1a}^+ \ i_{1b}^+ \ i_{1c}^+]\,. \tag{2}$$

The difference between the voltages and currents from (1) and (2) correspond to the distortion and unbalance parcels of $\boldsymbol{v}$ and $\boldsymbol{i}$, and hence, this difference can be considered as a correction signal for active filters with the purpose of eliminating harmonics and unbalancing effects of the system. This will reduce losses and oscillating effects, besides increasing the installation power factor.

Therefore, the ideal compensation of voltages at the Point of Common Coupling (PCC) could utilize the instantaneous *distorting voltages* represented by:

$$\boldsymbol{v_d} = [(v_a - v_{1a}^+)\ (v_b - v_{1b}^+)\ (v_c - v_{1c}^+)]\,. \qquad (3)$$

If one needs to compensate only the fundamental unbalance, the difference between (2) and the fundamental waves after the first decomposition ($\boldsymbol{v_1}$ and $\boldsymbol{i_1}$) could be utilized as the error signals to be eliminated.

A *third decomposition* is necessary to identify the parcel of the instantaneous fundamental current, which is proportional to the balanced sinusoidal voltages, thus representing the current fed to a pure resistive load, supplied by the sinusoidal and balanced voltages $\boldsymbol{v_1^+}$. The method used in this decomposition is based on the *Lagrange Multiplier* or *Orthogonal Decomposition* presented in [2,3,8,9]. The ideal current parcel is defined as the *positive sequence fundamental active current* and is expressed by means of the instantaneous vector:

$$\boldsymbol{i_{1p}^+} = [i_{1ap}^+\ i_{1bp}^+\ i_{1cp}^+]\,. \qquad (4)$$

In the same way of definition (3), the difference between the instantaneous measured currents (1) and the evaluated ideal currents (4) defines the *disturbing currents* $\boldsymbol{i_d}$, which are responsible for waveform distortions, phase current unbalances and also for the non-active power, which does not contribute to the unidirectional power exchange between power supplies and loads, and thus it means that it does not realize useful work [1,2,8,9]. The disturbing current vector $\boldsymbol{i_d}$ can be represented by:

$$\boldsymbol{i_d} = [(i_a - i_{1ap}^+)\ (i_b - i_{1bp}^+)\ (i_c - i_{1cp}^+)]\,, \qquad (5)$$

and this current parcel compensation ensures that the remaining current will be sinusoidal, balanced and in-phase with the ideal PCC voltages $\boldsymbol{v_1^+}$. According to [8,9], this decomposition uses the voltages defined in (2) as reference waveforms.

If the PCC voltages were non-sinusoidal and/or unsymmetrical, the methodology presented can be used in different ways for active filtering, e.g. using $\boldsymbol{v_d}$ to compensate the voltages by means of a series active filter or just using $\boldsymbol{v_1^+}$ as reference in the calculation of the ideal current vector i_{1p}^+, similar to the *Modified SSC* method described in next section.

III. ACTIVE FILTERING STRATEGIES: ADVANTAGES AND DISADVANTAGES

1) CPS method - constant power supply synthesis [1,5,7,12]: This compensation strategy has been well explored and is a very efficient solution, especially if the PCC voltages were practically sinusoidal and symmetrical. Under these conditions, any shunt active filter based on this technique is able to compensate the instantaneous imaginary power, as well as load unbalances and harmonics, increasing the power factor, without energy storage elements.

Nevertheless, if the supply voltages do not present the ideal features respective to symmetry and waveform, the compensation based on this strategy suffers of some limitations. From the point of view of an installation where an active filter is located, this compensation strategy tries to eliminate the imaginary power, thus increasing the power factor. But for the purpose of dragging constant power at the PCC with distorted voltages, there is no guarantee that the current after compensation will be sinusoidal and balanced or even better than without compensation. From the power quality point of view, if the voltages present distortions, the filters will imposed distorted currents on the generation, transmission and distribution systems, which produce constant power, absorbed in frequencies different from the fundamental. The circulation of this compensated currents can propagate again the distorted effects to the voltages, increasing their deterioration or exciting eventual system's resonance.

For the implementation, the authors of the CPS method suggest to use the *pq Theory* and low-pass filters to calculate de current control references to provide constant power at the PCC. The use of such filters makes the dynamic response of this method relatively slow.

2) Modified SSC method - sinusoidal source current synthesis: Such technique is quite efficient for harmonic, unbalanced and non-active currents compensation, even when the PCC voltages are non-sinusoidal and/or unsymmetrical. After compensation, the currents demanded from the system assume sinusoidal waveform and balanced conditions, independently of the PCC voltages. Looking to the current distortion, this technique is clearly better than the previous one. For power system quality concerns, the utilization of this method may be controversial, since imposing sinusoidal and symmetrical currents with generic voltages may produce oscillatory power.

Furthermore, the sinusoidal currents imposed in the presence of disturbed voltages forces the system to "see" the load only at the fundamental frequency. At other frequencies the system senses an infinite impedance load, since no current will flow at these frequencies. If there are capacitors for power factor correction near the active filter installation, which is a quite common situation, there will be at least one resonant frequency related to it. The lack of damping of this resonance due to the sinusoidal current synthesis could lead the PCC voltages to a worse condition related with the resonance.

Using the instantaneous decompositions presented in [8,9] and summarized in Section II, in this work the references to the active filter are provided in a different way that was originally proposed in [5] and discussed in [12]. As described in [5], the authors suggested some adaptations of the *pq Theory*, which uses a PLL (Phase Locked Loop) algorithm to identify the correct voltage and current references. The present work shows that it is possible to evaluate the disturbing currents ($\boldsymbol{i_d}$) based on the three decompositions.

The first two decompositions are implemented using a *Modified Tuned DFT*, a digital algorithm calculates the balanced fundamental voltage and current waves, and a fast dynamic response (one fundamental cycle – worst case) is ensured even under transient conditions. Since the ideal voltages (v_I^+) are calculated and used as references for the third decomposition, thus the ideal currents (i_{Ip}^+) are evaluated, making possible to identify the disturbing currents.

3) RLS method - resistive load synthesis [6]: This technique imposes symmetrical currents proportional to the voltages in the PCC, similar to a balanced resistive load, even if the voltages present distortion and low levels of unbalances at the fundamental frequency. Such strategy uses some adaptations of the Orthogonal Theory presented by *Fryze* and generalized in [2,3,8], to calculate the active filter reference signals. Following the active filter based on this method, the power factor is increased to unity and the damping effect created by the synthesis of a resistive load contributes to reduce any resonance in the power system. From the point of view of a specific installation with this kind of filter, it increases the power factor and provides the necessary damping to decrease the voltage distortion in the network. However, if the standard limits to the current distortion (THD) were used as charging indicators by the utilities, this technique could lead to penalty charges if the voltage deterioration were significant. From the point of view of power quality, this control method also has a controversial feature, since it provides large damping effect and reduces non-active (reactive) currents, however demanding active power at other frequencies present in the PCC voltages (oscillatory power).

This strategy's implementation is based on the instantaneous voltage sensing and a slow varying current proportionality factor, which is originated from the active power balance at the active filter DC link [6].

4) VRLS method - variable resistive load synthesis: Considering the same idea of the previous strategy, this work also analyses the direct use of the third decomposition (Instantaneous Lagrange Multiplier) to emulate an instantaneous proportionality factor to the PCC voltages. The proportional current is calculated here using the ratio between the instantaneous three-phase power and the instantaneous voltage norm, as described in [8,9,10]. Given that this ratio can vary instantaneously, the proportional current is variable; which means that this control synthesizes a variable resistive load. Since this strategy is based on an instantaneous mathematical function, its dynamic response is quite faster than the previous one; besides, it can be applied to systems with any voltages and current deterioration. However, it is not able to provide alone the currents balance and because of its fast response, the current closed control loop adjustment is much more sensible than the previous. Some predictive control technique may be required to improve its performance.

Similar to the RLS method, this method is also able to provide beneficial damping effects to power system's resonance.

The previous comments show there are several ways to control active filters, specially shunt topologies and each one presents advantages and disadvantages. This fact indicates that it is quite important to understand the differences and to decide when to use one or another technique to solve a specific or a more general power quality problem, since it is clearly impossible to achieve the advantages of each strategy in a single shunt active filter. Moreover, it can be still interesting to exploit new possibilities to control power conditioners.

IV. SIMULATION RESULTS

Fig. 1 shows the simulated power system used to compare filtering methods, considering three different situations in a general PCC. In each case were used three of the mentioned strategies to improve the power quality, respectively the RLS, Modified SSC and VRLS methods.

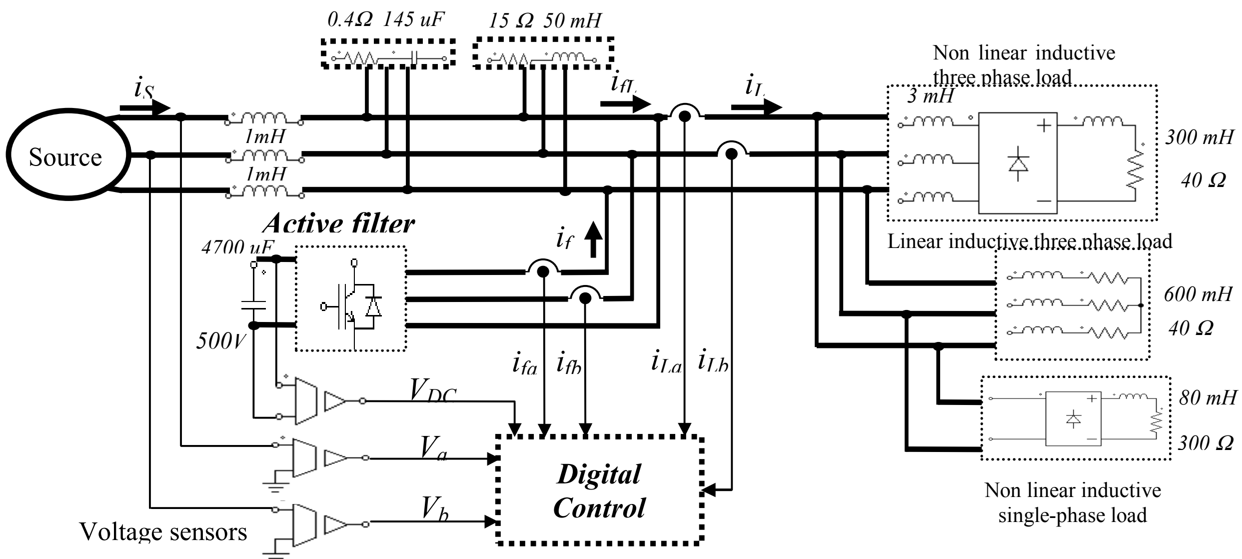

Fig. 1 – Simulated System (Power Grid, Load Side and Shunt Active Filter)

Due to space limitation and since the CPS is well documented in literature, it was not considered here.

The active filter was installed to compensate specially the non-linear inductive behavior of the load side, which was represented by a three-phase inductive linear load, along with a three-phase and a single-phase rectifier. Particularly in the first two simulation cases, an additional three-phase rectifier was connected to the power grid some time (*85ms)* after the simulation beginning for comparison of the active filters dynamic response.

The power grid voltages in the *first case* were assumed sinusoidal and balanced. Fig.2 shows that before the filter connection (*50ms*), the PCC current has the same waveform of the load side (rectifiers and linear inductive loads) and after this moment, an active filter using the *RLS method* starts the balanced resistive load emulation turning the PCC currents sinusoidal (proportional to the voltages) and symmetrical. Thus, it decreases the instantaneous active power oscillations, reduces to zero the instantaneous imaginary power, as defined in [8,9] and increases the power factor to unit. This figure also shows the slow dynamic response of this strategy when the second rectifier is connected (*85ms*).

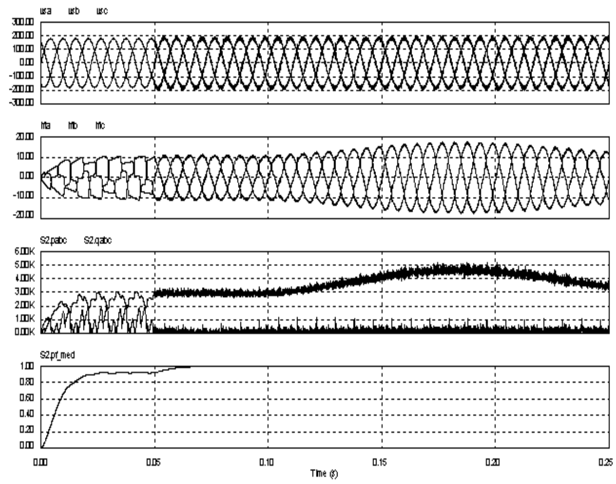

Fig. 2 – CASE 01: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *RLS Method*

Fig. 3 represents the compensation based on the *Modified SSC method*. However, as discussed in Sections II and III the methodology to calculate the filter references is based on the instantaneous decompositions in a different way that proposed by [5]. This alternative methodology can also improve the dynamic response of this strategy. After the filter initialization (*50ms*), the current becomes sinusoidal, balanced and in-phase with the voltages, the power factor is increased to unit, the instantaneous power oscillation is eliminated, as well as the instantaneous imaginary power. It is also possible to notice the fast dynamic response of this strategy using the proposed signal decompositions, when the second rectifier is connected.

Fig. 4 shows the compensation based on the *VRLS method*. The compensated currents are quite better than without compensation, but since the control strategy follows the instantaneous Lagrange Multiplier and the load is unbalanced, the currents remain unsymmetrical, thus retaining the active power oscillatory characteristics.

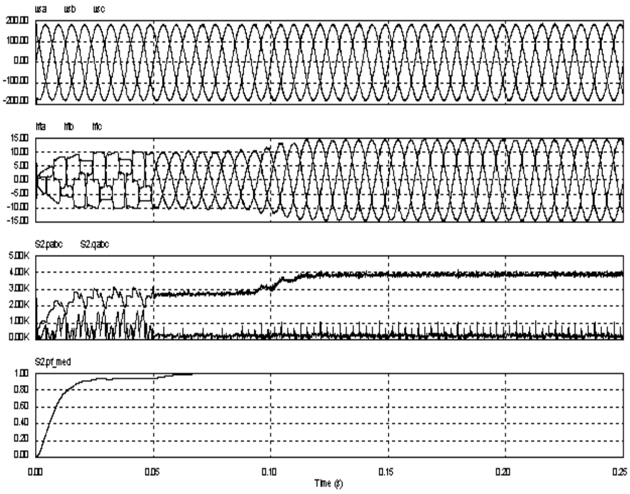

Fig. 3 – CASE 01: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *SSC Method*

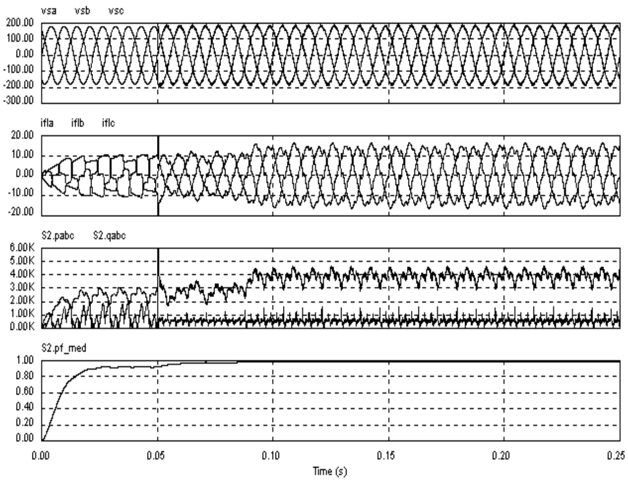

Fig. 4 – CASE 01: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *VRLS Method*

However, the power factor is increased to unit, since the imaginary power is eliminated and the dynamic response is practically instantaneous compared to the *RLS method*. This strategy was implemented using PI controllers in the current control loops; nevertheless, as mentioned before, some faster controllers could improve its performance.

In the *second case,* the power grid voltages present *5%* of 7^{th} harmonics and *4%* of unbalance in phases *b* and *c*, respective to phase *a*. For this case, Fig. 5 presents the compensation in the PCC using the *RLS method*. Since the source voltages are rather good shaped, the compensated currents are almost balanced and proportional to the distorted voltages (much better than the non-linear load currents) and the power factor is increased near to unity.

Fig. 6 represents the compensation of this second case using the *Modified SSC method.* As described before, this strategy uses the instantaneous decompositions to eliminate the disturbing currents ($\boldsymbol{i_d}$) in such way that the PCC currents are sinusoidal and balanced and the power factor is unitary after compensation. Nevertheless, since the voltages and currents have different frequency compositions, there is no damping effects related to any power system resonance.

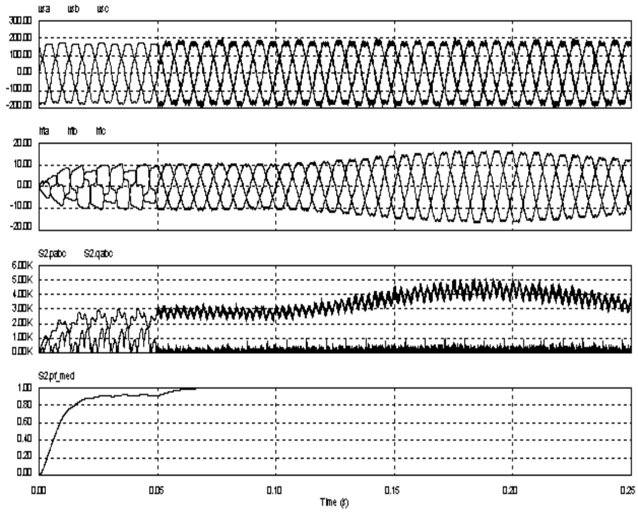

Fig. 5 – CASE 02: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *RLS Method*

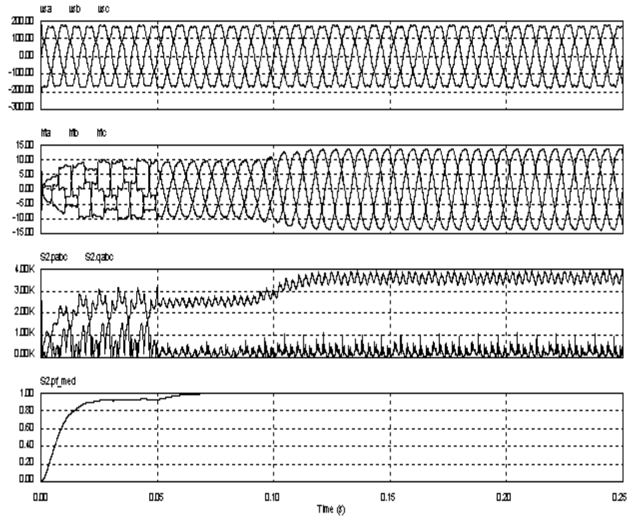

Fig. 6 – CASE 02: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *SSC Method*

Concerning the second case, Fig. 7 demonstrates the compensation using the *VRLS method*. The method forces the PCC currents to follow the voltages by a variable proportionality factor, that increases the power factor, reduces the current distortion and also provides damping effects to the power system. However, since it emulates a variable resistance, the resulting PCC currents are not symmetrical.

In the <u>*third case*</u>, the voltages distortion was reduced to *2%* and a three-phase linear inductive load and a power factor correction capacitor in parallel to it, were connected between the active filter PCC and the power source sides. This case represents a very common distribution system, especially in industrial utilities.

The capacitor values (*145uF*) were intentionally chosen to create a resonance frequency along with the line impedances (*1mH*) at the 7th harmonic, which was present in the source side voltages and also in the PCC load currents. This situation was simulated in order to demonstrate the different effects of each kind of active filtering strategies in such resonant condition.

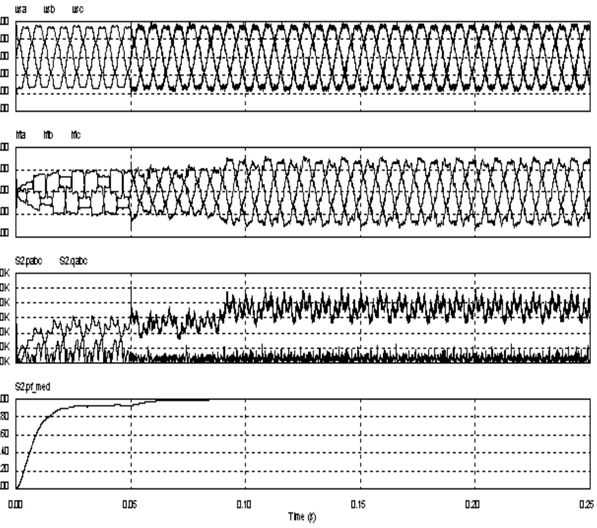

Fig. 7 – CASE 02: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *VRLS Method*

In order to show that the source voltages were distorted by the passive resonance even without the PCC's loads, these were connected just *20ms* after the simulation beginning. Notice in Fig. 8 (*RLS method)* that when the non-linear loads are connected, there is a small increase in the resonance values due to the rectifiers behavior. It is possible to observe when the active filter using the *RLS method* is inserted (*50ms*), the resistive load emulation is able to improve the current waveform and the power factor. Besides, the increased damping effect also provides a significant improvement in the power grid voltages, remaining only the imposed voltages source deterioration levels.

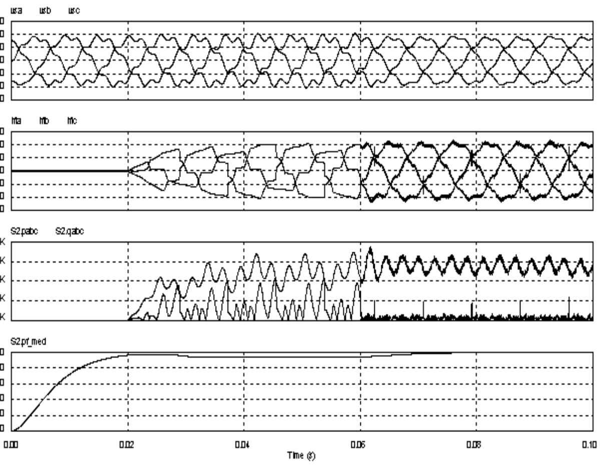

Fig. 8 – CASE 03: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *RLS Method*

Fig. 9 shows the compensation which results using the *Modified SSC method* for this case. Notice that after compensation, the current waveforms are sinusoidal and balanced and the power factor is improved near to unity. However, this strategy does not provide any damping effects to the voltage's resonance and in a broader sense, if the source voltages distortion were more significant (e.g. *4%*), this strategy could even amplify the resonance effects.

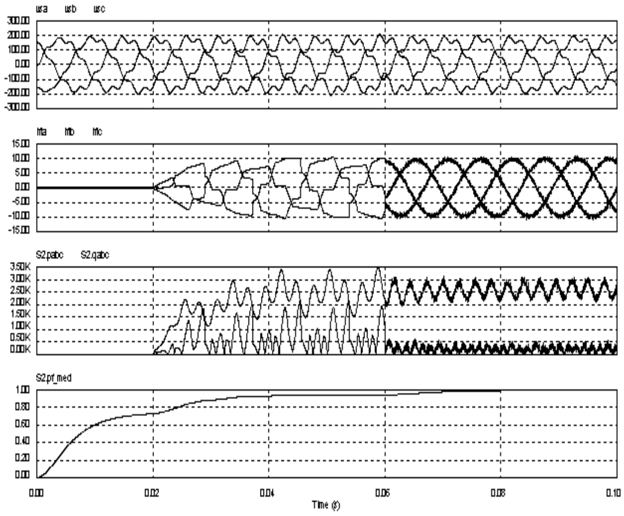

Fig. 9 – CASE 03: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *SSC Method*

Fig. 10 shows that the *VRLS method* is also able to provide damping over the system's voltages and improve the power factor almost to unit. However, in this case a more advanced current controller should be implemented to ensure the active filter to follow the correct control references.

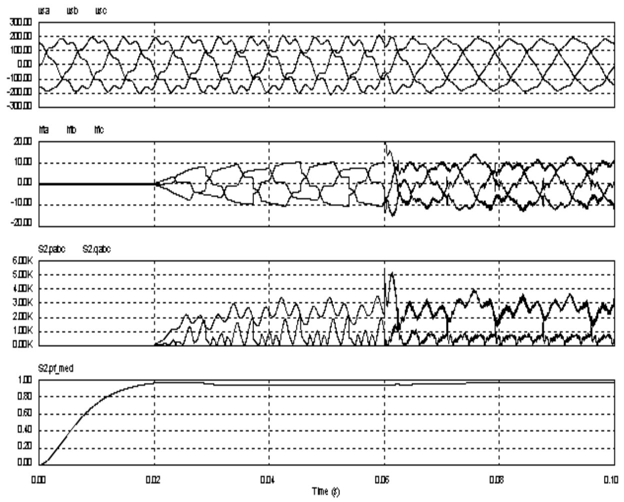

Fig. 10 – CASE 03: Instantaneous PCC voltages, currents, active and imaginary powers and power factor – *VRLS Method*

V. CONCLUSIONS

This work discussed advantages and disadvantages of some strategies to control shunt active filters in order to improve the power systems quality, showing the resulting problems if voltages were not sinusoidal and balanced.

An alternative methodology is also presented to generate the reference signals to control active filtering, which uses the instantaneous decompositions proposed in [8,9,10] and summarized in Section II. Such method allows to identity selectively the disturbing effects of voltages and currents signals, without the use of axis transformations (d,q or α,β), power calculations or low-pass filters to identify the compensation references. Moreover, the method is independent of periodicity, distortions, unbalances, number of phases and presence of the neutral wire in the system.

Three simulation cases were used to compare the results of applying the strategies, pointing out that the *Modified SSC* and *VRLS* methods were implemented based on the mentioned signal decompositions.

Such simulations show that in order to maximize the power system's quality in a general way or to ensure the ability of controlling different levels of custom power, sometimes it is necessary to improve not only the current but also the instantaneous voltages.

According to the procedure described from (1) to (5), which allows evaluating either the current compensation references as the voltage references, the utilization of these signals to control a unified (shunt and series) active filter seems to be a very interesting application. Nevertheless, it is important to notice that this *ideal compensation* has its real drawbacks, specially related to increasing technical complexity and economical costs.

Moreover, the presented simulations show that shunt active filters based on the *RLS* and *VRLS* methods are able to improve even the PCC voltages.

VI. ACKNOWLEDGEMENT

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