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Selective Current Compensators Based on the Conservative Power Theory

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***Abstract*--This paper presents possible selective current compensation strategies based on the Conservative Power Theory (CPT). This recently proposed theory, introduces the concept of complex power conservation under non-sinusoidal conditions. Moreover, the related current decompositions results in several current terms, which are associated with a specific physical phenomena (power absorption P, energy storage Q, voltage and current distortion D). Such current components are used in this work for the definition of different current compensators, which can be selective in terms of minimizing particular disturbing effects. The choice of one or other current component for compensation directly affects the sizing and cost of active and/or passive devices and it will be demonstrated that it can be done to attend predefined limits for harmonic distortion, unbalances and/or power factor. Single-phase compensation strategies will be discussed by means of the CPT and simulation results will demonstrate their performance.**

I. INTRODUCTION

CONSIDERING possible solutions for minimizing the impacts caused by non-linearities and asymmetries of a multiphase power system, it can be pointed out the application of active and hybrid power filters, especially during the last two decades [1]. Most of them directed to the active power filters (APF) topologies [1,5], their compensation strategies [6-10] and the corresponding voltage and current controllers [11,12,13].

Concerning with the compensation strategies, many authors have been working on the issue of proposing new methodologies in order to improve the active filter compensation results or even to simplify its implementation. The most focused methods are based on the *pq-Theory* or any of its adaptations [2,3,5,6], but it is very important to point out that there are many other alternatives, which can be, theoretically, even more flexible than the previous one and can make easier the understanding of physical phenomena and the potential of selective power quality conditioning [10].

Therefore, this paper proposes using the Conservative Power Theory (CPT), recently proposed and described in [14,15] (summarized in next section), as an alternative to the design and implementation of passive, active and hybrid power filters. The CPT current decompositions can be applied either to the definition of active filter control references, as well as for designing the filter components (switches, inductors, capacitors, etc.). Besides, the compensation strategies can be very flexible, since the decompositions enable selective identification (and elimination) of different disturbing causes (harmonics, unbalances, reactive power, etc).

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II. THE CPT FRAMEWORK

The Conservative Power Theory (CPT) was recently proposed by Tenti *et al.* [14] and it is based on the definition of instantaneous complex power under non-sinusoidal conditions and it represents an extension of the usual complex power, defined for sinusoidal conditions. Even though detailed discussion has been directed to single-phase systems, this theory is also easily extended to multiphase systems [14-17].

The authors had introduced the so-called homo-variables (integral and derivate) which can be defined under periodic conditions and are homogeneous to the current, voltage and power terms. Since homo-voltages and homo-currents satisfy the Kirchhoff's Laws, the corresponding homo-powers are conservative in any electric network, what allows introducing the concept of conservation of the complex power under non-sinusoidal conditions. In addition, a current decomposition was proposed, on which every term is related to a specific physical phenomenon (power absorption P, energy storage Q, voltage and current distortion D). Moreover, it has been discussed its application to harmonic and reactive compensation, for local or distributed devices [15,18].

Assuming multidimensional systems, the following definitions make use of bold variables to vector representation and the index "μ" for each m-phase variable. Thus, the homo-integrals of the voltages and currents are defined as:

$$\hat{v}_\mu(t) = \omega(v_{\mu\int}(t) - \bar{v}_{\mu\int}) \\ \hat{\imath}_\mu(t) = \omega(i_{\mu\int}(t) - \bar{\imath}_{\mu\int}) \tag{1}$$

where: $v_{\mu\int}(t) = \int_0^T v_\mu(\tau)\,d\tau$, $i_{\mu\int}(t) = \int_0^T i_\mu(\tau)\,d\tau$, are time integral of voltages v_μ and currents i_μ, and $\bar{v}_{\mu\int}$, $\bar{\imath}_{\mu\int}$ are the average value of each $v_{\mu\int}$ and $i_{\mu\int}$, over period T.

Note that $\hat{v}_\mu$ and $\hat{\imath}_\mu$ are dimensionally homogeneous to voltage and current respectively. This means that the operation of integration will not influence the amplitude of the resultant signals, since they are multiplied by the angular frequency.

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Considering periodical quantities, with period T and fundamental angular frequency $\omega = 2\pi/T$, the authors made use of well-known definitions, such as the internal product of voltage and current vectors:

$$\langle \boldsymbol{v}, \boldsymbol{i} \rangle = \langle \boldsymbol{i}, \boldsymbol{v} \rangle = \frac{1}{T}\int_0^T \boldsymbol{v}(t).\boldsymbol{i}(t)dt. \quad (2)$$

and in the same way, the voltage and current norms of each vector:

$$\|\boldsymbol{v}\| = \sqrt{\langle \boldsymbol{v}, \boldsymbol{v} \rangle}\,, \qquad \|\boldsymbol{i}\| = \sqrt{\langle \boldsymbol{i}, \boldsymbol{i} \rangle} \quad . \quad (3)$$

Under the assumption of periodic behavior, the following quantities have been defined (among others), which are valid for sinusoidal or distorted, balanced or unbalanced conditions:

Active power: that represents the conveyed average power. This definition is identical to the one of the conventional active power (Steinmetz, Budeanu, Fryze, Buchholz).

$$P = \langle \boldsymbol{v}, \boldsymbol{i} \rangle = \frac{1}{T}\int_0^T \boldsymbol{v}(t).\boldsymbol{i}(t)dt\,. \quad (4)$$

Reactive power: that represents the average energy stored in the network and was defined as:

$$Q = \langle \hat{\boldsymbol{v}}, \boldsymbol{i} \rangle = \frac{1}{T}\int_0^T \hat{\boldsymbol{v}}(t).\boldsymbol{i}(t)dt\,. \quad (5)$$

Following, the original currents are split into some parcels, regarding to their association to the power terms. The **active current** is the minimum current (i.e., with minimum norm) conveying active power P to the load and it is defined as:

$$i_{a\mu} = \frac{P}{\|\boldsymbol{v}\|^2}.v_\mu = G_e.v_\mu\,. \quad (6)$$

The **reactive current** is the minimum current transferring reactive power Q, and it is related to the average energy being exchanged through the circuit:

$$i_{r\mu} = \frac{Q}{\|\hat{\boldsymbol{v}}\|^2}\hat{v}_\mu = B_e\hat{v}_\mu\,. \quad (7)$$

Both the active and reactive currents have an explicit physical meaning. They are associated with the presence of the active and reactive powers, P and Q, and are related to the *load average equivalent* conductance G_e, and susceptance, B_e.

The **void current** is the remaining current (residual term), since it does not convey active P nor reactive Q power:

$$i_{v\mu} = i_\mu - i_{a\mu} - i_{r\mu}. \quad (8)$$

According to the authors, the void currents may exist only in presence of current distortion, however it has been demonstrated that it is also influenced by current unbalances in case of polyphase circuits [16,17]. Further details of each current component and its physical meaning can be found in [14,15,18].

By definition, all current terms are orthogonal:

$$\|\boldsymbol{i}\|^2 = \|\boldsymbol{i_a}\|^2 + \|\boldsymbol{i_r}\|^2 + \|\boldsymbol{i_v}\|^2\,. \quad (9)$$

Therefore the **apparent power** has been defined as:

$$A^2 = \|\boldsymbol{i}\|^2\|\boldsymbol{v}\|^2 = S^2 + D^2, \quad (10)$$

where S is the absolute value of the **complex power** and D is the **distortion power**:

$$S^2 = P^2 + Q^2; \quad D^2 = D_v^2 + D_i^2, \quad (11)$$

Further details of the complex power can be found in [18]. The distortion power is composed by two terms; the first term is called **voltage distortion power** and it is given by:

$$D_v = Q\sqrt{\frac{\|\boldsymbol{v}\|^2 - \|\hat{\boldsymbol{v}}\|^2}{\|\hat{\boldsymbol{v}}\|^2}}\,. \quad (12)$$

Such power exists only in the presence of reactive power (Q) absorption and voltage distortion and the second term is called **current distortion power** and is given by:

$$D_i = \|\boldsymbol{v}\|\|\boldsymbol{i_v}\|\,. \quad (13)$$

D_i exists only in presence of void current absorption. Contrary to active and reactive power, distortion power is a non-conservative quantity.

Finally the power factor is defined as:

$$\lambda = \frac{P}{A}. \quad (14)$$

According the authors, under the assumption of limited voltage and current distortion we can assume $\lambda \approx \frac{P}{S} = PF$.

As discussed in [16,17], when considering multi-phase systems, the void currents (i_v) represent not only harmonic distortion, but also the effects of load unbalances. Thus, such unbalances can influence the distortion power component D. Consequently, in order to approximate λ and PF it is necessary to limit not only the waveform distortions, but also the unbalances.

III. Selective current compensators

Considering possible reactive and harmonic compensators, two important definitions should be done: the compensator topology [4] and the compensation strategy [6-10]. Regarding to the topology definition, either passive, active or hybrid compensators can be considered. In this paper, in order to elucidate the application of the CPT, the following structures were applied (Fig. 1-4).

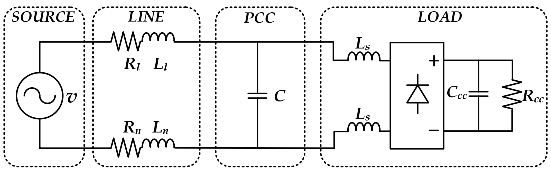

Figure 1: Point of Common Coupling (PCC) with capacitor compensator.

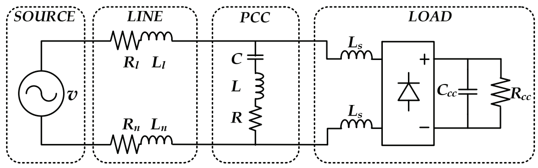

Figure 2: PCC with tuned LC compensator.

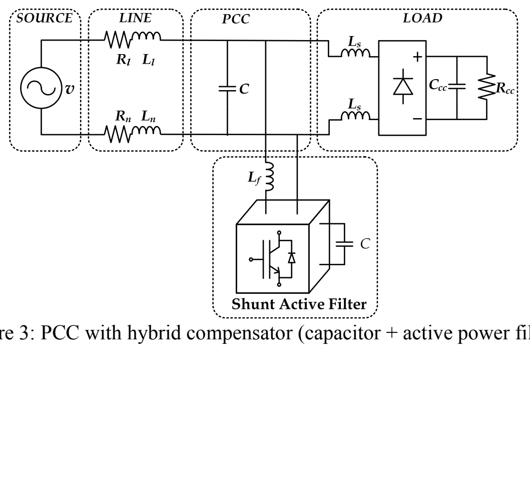

Figure 3: PCC with hybrid compensator (capacitor + active power filter).

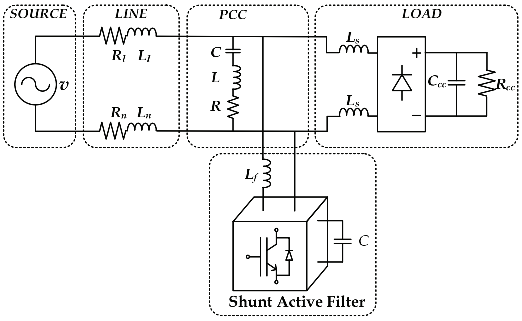

Figure 4: PCC with hybrid compensator (LC filter + active power filter).

Concerning to the compensation strategies, several different possibilities can be defined by means of the CPT current and power decompositions. Some proposals of the authors of this paper are discussed following.

If one is interested in compensating just the reactive current components, a possible formulation should be:

$$\|i_{r(comp)}\| = \|i_{r(load)}\| - \|i_{a(load)}\|\sqrt{\frac{1}{PF(lim)} - 1} \quad , \qquad (15)$$

where $i_{r(comp)}$ is the parcel of the reactive current that should be compensated in order to ensure a resulting power factor approximately equal to $PF(lim)$. This could be done by means of a permanent passive compensator (capacitor).

The average energy in the capacitor is:

$$W_C = \frac{1}{T}\int_0^T \frac{1}{2} C v^2(t)dt = \frac{1}{2} C\|v\|^2 \qquad (16)$$

and the reactive power is giving by:

$$Q_C = -2\omega W_C = -\omega C\|v\|^2 = -\|v\|\|i_{r(comp)}\| \quad , \qquad (17)$$

therefore, the capacitor value is:

$$C = \frac{1}{\omega}\frac{\|i_{r(comp)}\|}{\|v\|} \quad . \qquad (18)$$

Of course, if an active power filter is available, the overall reactive current or $i_{r(comp)}$ could be minimized by means of on line compensation. In addition, if one is interested in minimizing the reactive power and also some specific harmonic frequency (ω_h), a passive LC filter could be designed using the same capacitor (18) and $L = \frac{1}{\omega_h^2 \cdot C}$, .

Considering single-phase systems, the harmonic content could be minimized using the void current i_v. First of all, let's define a current distortion factor as:

$$DF_i = \frac{\|i_v\|}{\|i\|} \approx THD_i \quad . \qquad (19)$$

If one is interested in limiting the current distortion in order to ensure that the compensated system results with $DF_{i(lim)}$, the compensator should be able to eliminate part of the void current $i_{v(comp)}$:

$$DF_{i(load)} - DF_{i(comp)} = DF_{i(lim)}$$

$$\frac{\|i_v\|}{\|i\|} - \frac{\|i_{v(comp)}\|}{\|i\|} = DF_{i(lim)}$$

$$\|i_{v(comp)}\| = \|i_v\| - \|i\|DF_{i(lim)} \quad . \qquad (20)$$

Such current component could be compensated based on active power filter or either based on associations of particular LC filters. Of course, if it were necessary the compensation of the total void current, it is also possible, however it will clearly results in more expensive solutions.

It is also possible the definition of hybrid compensators, as those in Fig. 3-4. In such cases, the reactive and void current compensation are split in terms of the passive and active filters. It can be done designing the active filter in order to complete the compensation provided for the passive compensators.

Considering three-phase systems, as discussed in [16,17], the influences of current unbalances are included in the void current components, which means that their compensation should result in minimizing either the current harmonics and the unbalances. If one is interested in identifying just the fundamental unbalancing current components, it could be done isolating the fundamental component of the void current:

$$\boldsymbol{i}_v^1 = \boldsymbol{i}_v - \boldsymbol{i}_v^h .$$

IV. Simulation Results and Discussion

Considering a single-phase system, Fig. 5 shows the simulated system, while Table 1 presents the values of the grid voltage, line impedance and load parameter.

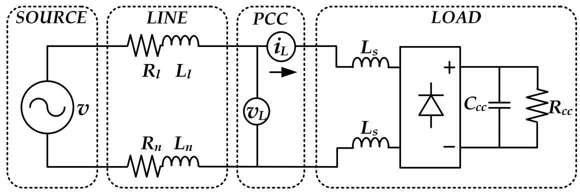

Figure 5: Power circuit – non linear load (harmonic voltage source type).

Figure 6 shows the measured PCC voltage and current before the compensation. Note they are not in-phase and the current is very much distorted.

Figure 7 shows the current decomposition (waveforms and respective spectra) in active, reactive and void current components (CPT). The goal is to demonstrate the possibility of compensating each phenomenon separately, for example: only the reactive current, only the void current or even both. This can be done by means of using the resulting current components as active filter reference signals (i_{Lr}^* , i_{Lv}^* or $i_{Lr}^* + i_{Lv}^* = i_{Lna}^*$) or during the design of passive compensators.

Table 1 – Voltages and impedances for the simulated power system.

Source	Line	Load
$V = 127\angle 0^O$ Vrms	$R_{Lf} = 10m\Omega$ $L_{Lf} = 0.1mH$	$L_S = 1mH$
		$C_{DC} = 8mF$
	$R_{Lr} = 10m\Omega$ $L_{Lr} = 0.1mH$	$R_{DC} = 4\Omega$

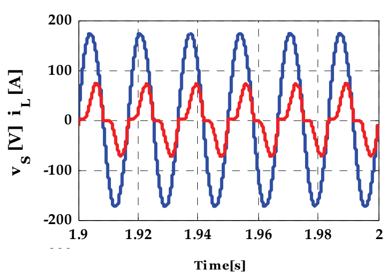

Figure 6: Load voltage and current before the compensation.

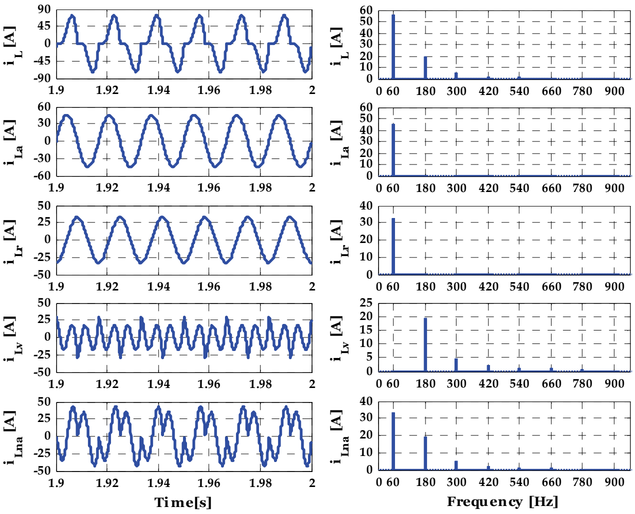

Figure 7: Current decomposition: Load current (i_L), active current (i_{La}), reactive current (i_{Lr}), void current (i_{Lv}) and non-active current (i_{Lna}).

Table 2 indicates the RMS and peak values of the different load current components. Such values could be very useful for estimating the costs of a specific compensator, depending on which current component should be minimized. For example, if one is interested in compensating just the void current, the compensator should be able to deal with currents about 15A. However, if the compensator were designed to manage the total non-active current, it should deal with almost 30A. This certainly affects the costs of power electronics, sensors, temperature regulators, etc.

Table 2 – Load current values.

Parameter	Load	
	Norm (RMS value)	Peak value
i_L	42,1744	72,7838
i_{La}	32,2146	44,8548
i_{Lr}	23,2150	33,2102
i_{Lv}	14,2114	30,2962
i_{Lna}	27,2194	42,5577
v_s	124,917	173,935

Considering the topologies from Fig. 1-4, Table 3 indicates the main parameters of each compensator. The capacitor was chosen so that the corrected power factor results to 0,92 (15-18). The passive LC filter was set to the third harmonic (quality factor equal to 30).

Table 3 – Compensators parameters.

Capacitor	Passive filter	Active power Filter
C=201,55uF	*R_3 = 0,1462 Ω*	*R =0,013Ω*
	L_3=3,9mH	*L = 0,35mH*
	c_3=201,55uF	*C = 3500uF*

In order to discuss the application of the CPT in different compensation schemes, four cases have been analysed. The results were summarized in Table 4 and indicated in figures from 8-19.

A. Case 1 – Capacitor compensator

Figures 8-10 show the compensation results of the reactive current, by means of a capacitor bank, designed according to (18). Note that after compensation, the voltage and compensated current not are totally in-phase (Fig. 8). It happens because the power factor was set to 0,92. However, the source current keeps distorted, since just the reactive current was compensated. Note from Table 4 that the RMS reactive current reduces from 23,21 A to 13,82 A, while the void current remains practically the same. Consequently, the power factor changes from 0,81 to 0,92.

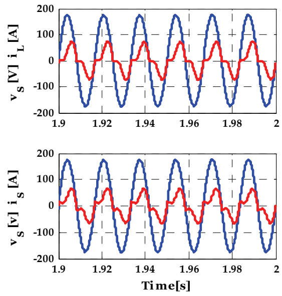

Figure 8: Source voltage and current after the compensation - Case 1.

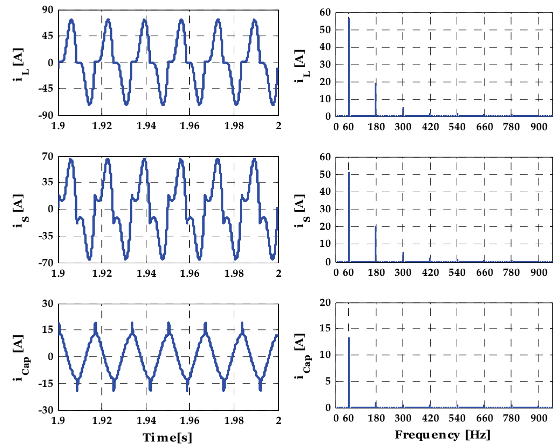

Figure 9: Load current (i_L), source current (i_S) and capacitor current (i_{Cap}) (waveforms and spectra) - Case 1.

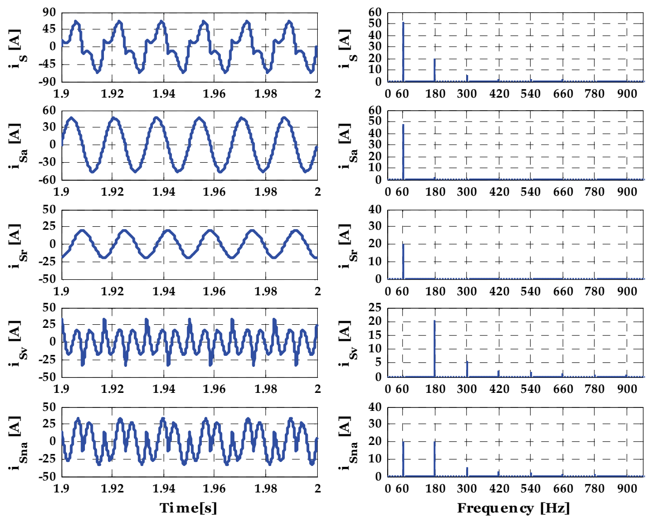

Figure 10: Decomposition after compensation: source current (i_S), active current (i_{Sa}), reactive current (i_{Sr}), void current (i_{Sv}) and non-active current (i_{Lna}).

B. *Case 2 – LC Passive filter*

Figures 11-13 show the compensation results considering a passive LC filter, designed using the same capacitor as in Case 1 and an inductor corresponding to the third harmonic frequency. Note that the current distortion reduces approximately 40%, what could be improved by means of series filter topologies. The power factor results 0,93.

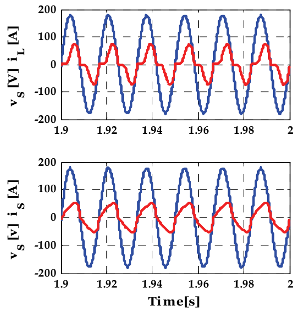

Figure 11: Source voltage and current after the compensation - Case 2.

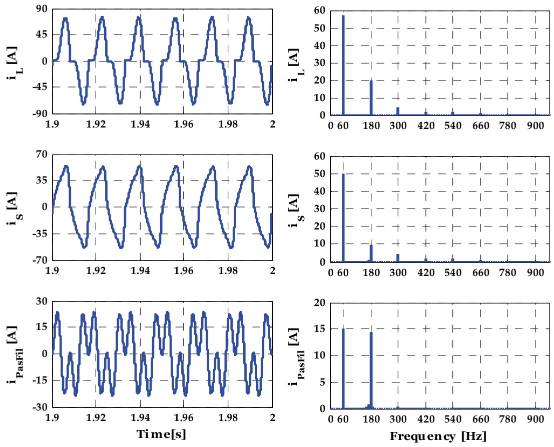

Figure 12: Load current (i_L), source current (i_S) and compensator current (i_{Cap}) (waveforms and spectra) - Case 2.

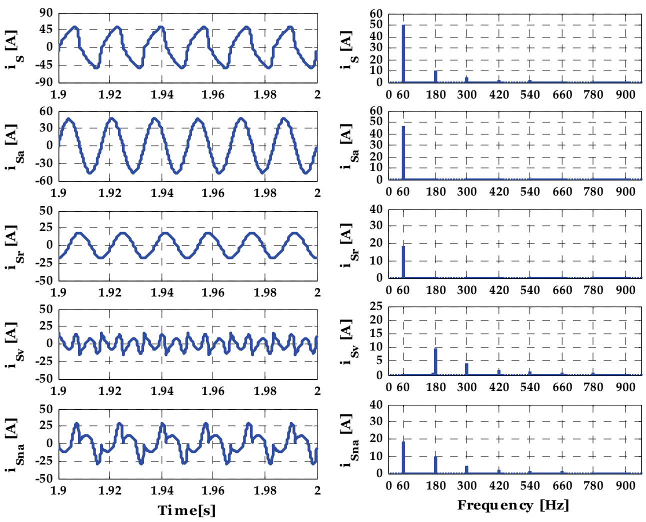

Figure 13: Decomposition after compensation: source current (i_S), active current (i_{Sa}), reactive current (i_{Sr}), void current (i_{Sv}) and non-active current (i_{Lna}).

C. *Case 3 – Hybrid compensator (capacitor + active filter)*

In this case, the arrangement of the capacitor bank and the active filter yields in a better compensation results (see Fig. 14-16). The capacitor bank was set as in Case 1 and the active filter was set to minimize the void current. The current distortion of the source current was reduced from 34% to 10% (see Table 4). In this case, the power factor results 0,98, since the active filter complete the reactive current compensation.

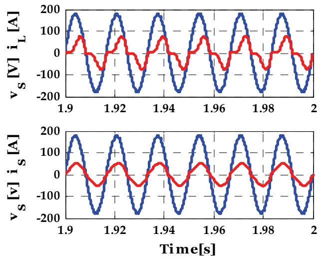

Figure 14: Source voltage and current after the compensation - Case 3.

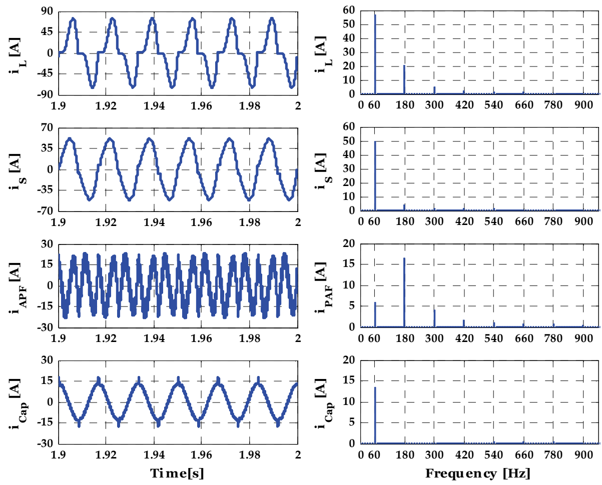

Figure 15: Load current (i_L), source current (i_S), active filter current (i_{APF}) and capacitor current (i_{Cap}) (waveforms and spectra) - Case 3.

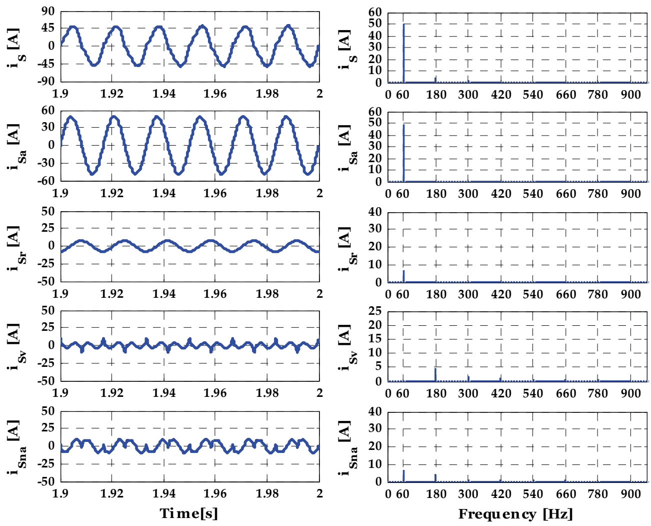

Figure 16: Decomposition after compensation: source current (i_S), active current (i_{Sa}), reactive current (i_{Sr}), void current (i_{Sv}) and non-active current (i_{Lna}).

D. Case 4 – Hybrid compensator (LC filter + active filter)

Figures 17-19 show the compensation results of both reactive current and void current. In this case the compensation was split between the two compensators. As discussed in Case 2, the passive filter compensates about 40% of the current distortion. Thus, the active filter was set to compensate 50% of the third harmonic (in the void current - $i_{ref}^{*} = i_v - 0.5(i_{v3h})$. Note that in this case the resulting THDi is slightly superior than in Case 3 (Table 4), since in that case

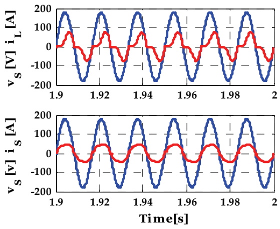

Figure 17: Source voltage and current after the compensation - Case 4.

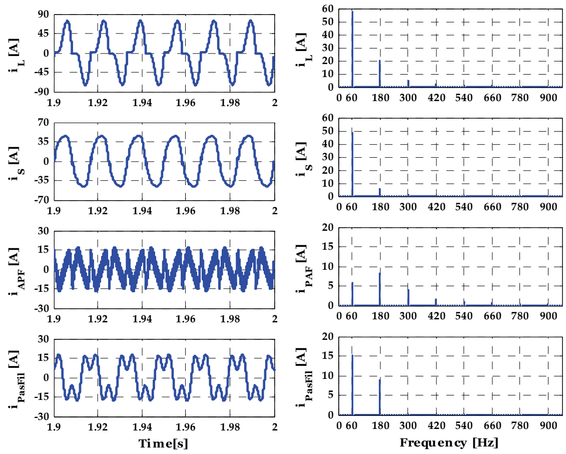

Figure 18: Load current (i_L), source current (i_S), active filter current (i_{APF}) and passive filter current (i_{PasFil}) - Case 4.

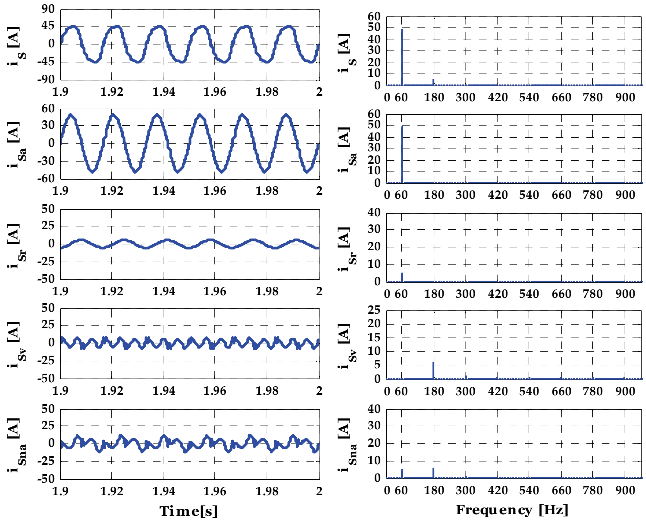

Figure 19: Decomposition after compensation: source current (i_S), active current (i_{Sa}), reactive current (i_{Sr}), void current (i_{Sv}) and non-active current (i_{Lna}).

the active power filter was set to minimized the total void current.

Table 4 presents all the information regarding to the compensation using each of the simulated topologies. Table 5 indicates the RMS and peak values of the expected currents through the discussed compensators. Note that such information could help during the designing of the compensator's parameters. Besides, the compensation results and the design of the compensators could be very influenced changing the limits of (15) and (20) or also changing the percentage of reactive and void current compensated by the active filter.

Table 4 – PCC power and current components before and after compensation.

Parameter	Load	Passive Compensator		Hybrid Compensator	
		Capacitor	RLC	Passive Filter C (i_r) Active Filter (i_v)	Passive Filter RLC ($i_r + 0.37(i_{v3h})$) Active Filter ($i_v - 0.5(i_{v3h})$)
A [VA]	5268,29	4911,04	4543,62	4457,21	4395,69
S [VA]	4960,18	4534,03	4434,20	4434,16	4358,97
P [W]	4024,14	4188,43	4136,55	4382,63	4335,89
Q [Var]	2899,94	1736,25	1597,22	673,502	446,022
D [VA]	3400,04	2564,21	1879,68	811,482	721,172
D_i [VA]	1775,24	1887,04	991,144	451,684	566,092
D_v [VA]	2899,80	1736,16	1597,14	674,155	446,798
$FP = (P/S)$	0,81129	0,92377	0,93287	0,98839	0.99475
$\lambda = (P/A)$	0,76384	0,85285	0,91041	0,98328	0,98644
$\|\|i_a\|\|$	32,2146	33,3473	32,9171	34,6801	34,2699
$\|\|i_r\|\|$	23,2150	13,8236	12,7100	5,32947	3,52527
$\|\|i_v\|\|$	14,2114	15,0242	7,88758	3,57421	4,47428
$\|\|i_{na}\|\|$	27,2194	20,4161	14,9585	6,42162	5,70125
$\|\|i\|\|$	42,1744	39,1006	36,1564	43,0621	34,7426
$\|\|v\|\|$	124,917	125,600	125,6666	126,373	126,522
THD_i[%]	34,74	40,5019	21,8739	10,0279	12,738
THD_v[%]	2,936	3,10291	1.91854	0,95158	1,4922

Table 5 – Current values for the compensator's design.

Compensator	RMS value	Peak value
Capacitor	9,62495	20,0376
Passive filter (RLC)	15,1180	23,6945
Hybrid filter Cap (i_r) + PAF ((i_v))	9,58715(CAP) 13,1238(APF)	17,7209 (CAP) 22,7051(APF)
Hybrid filter LC (($i_r + 0.37(i_{v3h})$) + APF ($i_v - 0.5(i_{v3h})$)	12,5157(LC) 8,4770(APF)	17,9225(LC) 16,2892(APF)

V. Conclusions

This paper has demonstrated some of the possible compensation strategies based on the Conservative Power Theory. As verified, different passive, active or hybrid compensators could be designed or controlled by means of such proposal. It is important to notice the flexibility of the methodology, which able the designer to chose among one or more disturbing effects to be minimized (reactive or void current) or also the percentage of the compensation among them (based for example, on specific standard limits) or among the compensator's topologies.

The interest of these authors in such time domain power theory is mainly based on the fact that it matches the traditional concepts of active and reactive power and power factor under the assumption of sinusoidal and balanced conditions and proposes new concepts for the nonsinusoidal situations. The definitions are not based on any variable frame transformations (d-q, αβ, etc.) and they seem to be very useful for other applications them power conditioning, such as power metering and power quality monitoring, what is quite difficult using many other power theories proposals.

Next studies and papers will deal with the application of the CPT for three-phase compensation, especially trying to split the influences of harmonics and unbalances in the void current definition.

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VII. Biographies

Helmo Kelis Morales Paredes, was born in Puno-Perú. He received his B.S. degree (2002) in Electrical Engineering from Arequipa National University (UNSA), Perú. In 2006 he received his Master degrees from University of Campinas (UNICAMP), Brazil. Currently, he is a PhD student at UNICAMP. His current interests are mainly concerned with power quality evaluation and power definitions under multiphase nonlinear systems.

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Luiz C. P. da Silva was born in Brazil in 1972. He graduated in electrical engineering from the Federal University of Goiás, Brazil in 1995, and obtained MSc and PhD degrees in power systems engineering from the University of Campinas, Brazil, in 1997 and 2001 respectively.

He worked as a visiting researcher at the University of Alberta, Canada, in 1999-2000, and as a guest professor at the Technical University of Denmark, in 2008. Since 2002 he is with the University of Campinas, Brazil, where he is an Associate Professor. His main areas of interest are power system stability and control and distributed generation.