### Abstract

A new Hybrid Power Line Conditioner is proposed in this paper. It is formed by an active conditioner in parallel with a hybrid conditioner composed by an active filter in series to one or more passive filters. This topology allows the reduction of the inverters rating, constituting an effective solution in high power levels where classical power filters cannot be used. The novel topology operates adequately in three-phase four-wire systems reducing the harmonic distortion and/or unbalance and attaining unity displacement power factor. Experimental results are included for testing the topology and its control.

### Index Terms

Active filter, hybrid filter, multiconverter topology, power line conditioner.

## I. INTRODUCTION

The use of non-linear loads injecting harmonic and reactive current components in the electrical power system has suffered a proliferation in the last years. The reduction or elimination of these components can be achieved by using compensation equipments installed at the point of common coupling (PCC). Conventional topologies such as passive filters, active or hybrid conditioners or universal conditioners have been used for this purpose [1]-[3]. However, these solutions can not be used in high power applications (above 500 kVA [4]) due to the inverter rating.

An idea for solving this drawback is the separation of the compensation among two or more equipments, resulting a multiconverter conditioner. An active multiconverter topology was first presented in [5] and recently similar topologies with different control strategies have been developed [6]. In this paper a new hybrid multiconverter topology, which we call pApH (parallel Active with parallel Hybrid conditioner) formed by two inverters connected in parallel sharing the dc bus is presented. One of the converters, called “slow” because it operates with low switching frequency, is in charge of the fundamental and dominant harmonic components in the load current. This equipment is helped by the “fast” conditioner, which operates with a higher frequency, compensating the higher harmonic components.

The advantages of this topology are on the one hand, the separation of the correction, which attains a reduction in the inverters ratings making viable this equipment in high power levels and, on the other hand, the reduction in the volume, losses and price of the conditioner due to the possibility of using ferromagnetic core filter inductors for the slow converter [5].

The sharing strategy between both conditioners and each principle of operation are explained in the following sections. Experimental results for a 1.2 kVA laboratory prototype are presented.

## II. SHARING STRATEGY AND PRINCIPLE OF OPERATION

The hybrid filter topology chosen for the multiconverter pApH conditioner is AsP (Active filter in series to Passive filter) because for loads above 10 MW it constitutes the most economic solution due to the reduction attained in the inverter power [4], [7]. If this hybrid filter is designed and controlled for behaving as a DHF (Dominant Harmonic Filter) [8] it will be formed by an active filter (AF) in series to one or more parallel passive filters (PF) tuned at the dominant harmonic frequencies in the load current, that usually have low orders. These components would be mainly filtered in a passive manner while the AF, which will have a small rating, will collaborate for solving the drawbacks of passive filters working alone. Besides, the hybrid filter could compensate dynamically the displacement power factor. As the harmonics in the reference current for this filter are low, a low commutation frequency could be used for the inverter of this equipment, which is called the slow conditioner.

The other parallel active (pA) conditioner will be then in charge of the higher harmonic orders, which usually have lower amplitude, so the inverter rating will be smaller. The tuned harmonic components left not compensated by the slow equipment for avoiding passive filters overload and the commutation harmonics of the hybrid conditioner could be also task for this equipment. As high harmonic components will be ordered to this conditioner, a higher commutation frequency would be needed for it, acting as the fast equipment.

If both filters operate as current-controlled sources, the single-phase equivalent circuit of the multiconverter topology is the one shown in Fig. 1, where $i_{AFs}$ and $i_{AFf}$ are the currents injected by the inverters of the slow and fast conditioners, respectively.

The reference current for the hybrid filter, $i_{HF, ref}$, behaving as a DHF is:

$$i_{HF, ref} = i_{AFs, ref} = (i_{1h} - i_{1fs}) + i_{1hm}, \quad (1)$$

![Fig.1. Correction using a hybrid multiconverter pApH conditioner.](image-url)
where \( i_{Ld} \) is the active positive-sequence fundamental component and \( i_{Ld,lim} \) is the limited tuned current allowed by the conditioner for avoiding passive filters overload, calculated as:

\[
i_{Ld,lim} = \frac{i_{Ld}}{I_{PPhy}} \cdot \frac{L_{h} \Delta P_{PF} \Delta I_{Ld}}{\Delta Q_{PF}} \text{ if } I_{Ld} \leq I_{PPhy} \text{ and } h \neq 1 \text{ and } h \neq 1,
\]

being \( I_{PPhy} \) the RMS value of a tuned harmonic component in the load current and \( I_{Ld,lim} \) the maximum RMS value of each tuned harmonic current in the passive filter/s.

The reference current for the fast conditioner will be the one necessary so that, collaborating with the slow equipment, attains the desired source current, \( i_{s,ref} \), which depends on the compensation objectives. This current will be calculated as:

\[
i_{diff,ref} = i_L - i_{s,ref} - i_{diff,mean},
\]

where \( i_{diff,mean} \) is the measured hybrid filter current.

With these references, the active element of the slow conditioner secures the fundamental reactive power compensation, unbalance elimination caused in the fundamental and tuned components, the active tuning of passive filters in case of mistuning, passive filters overload alleviation and elimination of series and parallel resonance among the passive filters and the source impedance.

On the other hand, if a PHC (Perfect Harmonic Cancellation) global control strategy [9] is selected for the multiconverter equipment, trying that the source current will be in phase with the positive-sequence fundamental component of the voltage at the PCC, the active equipment of the fast conditioner will be in charge of the non-tuning harmonics elimination, the unbalance in those components, the rest of the tuned harmonics not compensated by the hybrid equipment and the harmonics due to the operation of the slow conditioner.

It should be taken into account that under normal conditions, that means sinusoidal and balanced voltage and balanced currents with nominal fundamental reactive power demand (the value used as reference for the passive filters design), the active filter of the slow conditioner has not to operate and the active filter of the fast conditioner has not to be in charge of the tuned harmonics. These facts are summarized in Table I. Under normal operation conditions the power rating of the active filters are very small, however if they are wanted to operate also under the abnormal conditions described in Table I, the rating will increase.

### III. SELECTED TOPOLOGY AND CONTROL STAGE

#### A. Description of the topology

The experimental prototype tested in laboratory (Fig. 2) is used for describing the hybrid multiconverter topology. The hybrid filter is formed by one active branch and one passive branch per phase, what constitute a particular case of the proposed topology which allows the reduction of passive elements.

<table>
<thead>
<tr>
<th>Normal operation conditions</th>
<th>( AsP ) (slow conditioner)</th>
<th>( pA ) (fast conditioner)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO FUNCTION</td>
<td>- Filtering of harmonics ( h \neq h_{ref} )</td>
<td>- Changes in ( Q_{PF} )</td>
</tr>
<tr>
<td>Abnormal operation conditions</td>
<td>· Changes in ( Q_{PF} )</td>
<td>. Unbalance in the fundamental and tuned harmonics</td>
</tr>
<tr>
<td>· ( \Delta I_{PCC} )</td>
<td>· ( \Delta I_{Ld} )</td>
<td>· Mistuning ( P_F )</td>
</tr>
<tr>
<td>· ( \Delta Q_{PF} )</td>
<td>· Series resonance</td>
<td>· Parallel resonance</td>
</tr>
<tr>
<td>· ( \Delta I_{PPhy} )</td>
<td>. Commutation harmonics of the slow conditioner</td>
<td></td>
</tr>
</tbody>
</table>

The active part of the hybrid multiconverter conditioner is formed by a neutral-pointed-clamped voltage-source inverter with six branches. The three fast conditioner branches are connected to each phase of the utility by a filter inductor, while the slow conditioner branches are connected in series to the passive filters impedances. The inductor of the passive filter will be designed so that it can operate as a filter inductor in the active equipment, attaining another reduction in the elements of the conditioner.

A controlled rectifier has been selected as non-linear load, so the dominant harmonics are the 5th and 7th orders. As a 1 passive branch has been selected for the hybrid conditioner, it is possible to tune the passive filter to the lower, higher or an intermediate order. After studying these options, finally the tuning to the lower harmonic (5th order) has been selected because:

- the filter impedance at the higher dominant harmonic will be inductive, eliminating the possibilities of resonance near this frequency,
- as the amplitude of the harmonics in the load current decrease as the harmonic order increase, the voltage that the active filter has to generate to make the 7th order harmonic component to circulate across the hybrid filter will be reduced,
- besides, the passive filter will offer a higher impedance at higher and non-dominant harmonic orders \( h > 7 \), reducing the voltage provided by the active filter to avoid the derivation of these harmonics through the hybrid branch.

#### B. Control Stage

The conditioner has to be able to operate adequately for every firing angle of the rectifier between \( a = 0^\circ - 60^\circ \) (continuous operating range independently of the load) and for every type of resistive load with power lower than the basis power of the system. In a more precise way, the global compensation objectives are:

- displacement power factor correction for every firing angle in the controlled rectifier,
- harmonic reduction in the source current fulfilling the limits established by the standard IEEE 519 [10], and
- unbalance elimination in the source current.
Control Strategies

If control strategies based on the load current detection are employed, as it was previously proposed in section II, in three-phase four wire systems three load currents \( i_{L_a}, i_{L_b}, \) and \( i_{L_c} \), six compensating currents \( i_{HF_a}, i_{HF_b}, i_{HF_c}, i_{AF_a}, i_{AF_b} \) and \( i_{AF_c} \), three phase-to-neutral PCC voltages \( u_{PCCa}, u_{PCCb}, \) and \( u_{PCCc} \), and the dc bus voltage, \( U_{dc} \), need to be sensed, what implies thirteen measurements for controlling the multiconverter conditioner. An improvement is proposed so that the control strategy and tracking technique will be based on the source current detection in order to minimize the number of sensors.

The calculus of the reference currents for the hybrid filter proposed in (1) has to be changed because the load currents are not measured. An adaptive control which estimates these variables from the measure of the source currents will be used, resulting the reference current for the slow converter:

\[
i_{AF_s ref} = (i_{L_1} - i_{L_{a*}}) + i_{AF_s}^{lim} + i_{AF_s}^{lim}
\]

where the supper index "*" means that his variable is not measured, but estimated.

If the dominant harmonic load currents \( i_{L_h} \) are desired to be absorbed by the hybrid filter, it means that those components have to be null in the source current. Using PI controllers as it is shown in Fig. 3 it is possible to obtain an estimation of the load current components. Two synchronous reference frames, one positive-sequence and one negative-sequence and one 1-phase ASRF [11] for extracting the zero-sequence component are used for estimating the \( h \)-th dominant harmonic component in the load current. In Fig 3 the block diagram of a \( h \)th Harmonic Load Current Extractor (hLCE) is displayed.

Besides, for avoiding the 5th passive filter overload, equation (2) is particularized as:

\[
i_{L_h}^{lim} = \begin{cases} i_{L_h}^{*} & \text{if } i_{L_h}^{*} \leq I_{PF5}^{lim} \\ \frac{i_{L_h}^{*}}{I_{PF5}} I_{PF5}^{lim} & \text{if } i_{L_h}^{*} > I_{PF5}^{lim} \end{cases}
\]

being \( I_{L_h}^{*} \) the RMS value of the tuned harmonic component in the estimated load current, calculated from

\[
i_{L_h}^{lim} = \sqrt{\frac{(i_{L_{ha}}^{*})^2 + (i_{L_{hb}}^{*})^2 + (i_{L_{hc}}^{*})^2}{3}}
\]

and \( I_{PF5}^{lim} \) the maximum RMS value of each tuned harmonic current in the 5th passive filter. Finally, two blocks like the one in Fig. 4, one for the 5th harmonic and another for the 7th order will be needed.

Fig.2. Three-phase four-wire source with nonlinear load and shunt hybrid multiconverter conditioner.

Fig.3. \( h \)th Harmonic Load Current Extractor (hLCE) using control strategies based on the measure of the source current.

Fig.4. Harmonic load current extraction limited to the maximum 5th passive filter.
For the fundamental harmonic it is necessary to add an additional block for the dc bus voltage control. For getting this voltage to be constant and near its reference, the hybrid filter has to absorb fundamental positive-sequence active power from the utility. So in the reference source current a new term, \( \Delta i_{ref(1LCE)} \) has to be included, resulting finally:

\[
i_{i1(1LCE)} = (i_{ref} - i_{meas})^* + \Delta i_{ref(1LCE)}.
\]

This term is obtained from the output of a PI controller whose input is the error between the reference dc bus voltage and its measure. The PI controller has been designed with an enable signal for choosing if the slow conditioner is in charge of the dc bus control or this function is left to the fast conditioner. The control block for the fundamental component is shown in Fig. 5.

The reference source current using a Sinusoidal Source Current strategy operating as PHC, but based on the measurement of the source current in 0-d-q coordinates can be calculated as:

\[
\begin{bmatrix}
i_{dref} \\
i_{qref} \\
i_{sref}
\end{bmatrix}
= K
\begin{bmatrix}
0 & u_{PCCId}^* & 0 \\
0 & u_{PCCIq}^* & u_{PCCId}^* \\
0 & u_{PCCIq}^* & u_{PCCId}^*
\end{bmatrix}
\begin{bmatrix}
\Delta u_{AF(1LCE)}^+ \\
\Delta u_{AF(1LCE)}^- \\
\Delta u_{AF(1LCE)}^0
\end{bmatrix},
\]

where the term \( \Delta u_{AF(1LCE)} \) is the positive-sequence fundamental active power absorbed from the utility for controlling the dc bus voltage. This term is obtained from the output of a PI controller whose input is the error between the reference dc bus voltage and its measure.

Finally, the control block diagram of the hybrid multiconverter conditioner is shown in Fig. 6. One can notice that seven measurements are only needed for the control strategies (three source currents, the dc bus voltage and three PCC voltages). For obtaining the angle of the positive-sequence fundamental component of the PCC voltages, an Autoadjustable Synchronous Reference Frame (ASRF) [11] has been used.

**Tracking Technique**

The tracking technique determines the duty cycle for the conditioner trying to eliminate the error between the reference and the source current \( e \) in a commutation or sampling period \( T_s \). In a general manner the duty cycle for each branch applying a dead-beat technique [12] is calculated from

\[
D = 0.5 - e \frac{L_{af}}{T_c} - u_{af},
\]

where \( u_{af} \) is the voltage in the ac side of the active filter.

In the slow conditioner the hybrid filter current is measured so \( e \) will be determined from the difference between the reference and the measured current. The voltage \( u_{af} \) can be calculated as:

\[
u_{af} = u_{PCC} + i_{hFmeas} \cdot Z_{CPF5},
\]

where \( Z_{CPF5} \) is the impedance of the passive filter without inductance.

In Fig. 7 it is shown the block diagram of the dead-beat technique for the slow conditioner, in which \( T_{ps} \) is the commutation period.

As the fast conditioner current is not measured a strategy which allows the estimation of the error between the reference and the measured currents is needed. If the hybrid filter is turned on, from the fast converter point of view the set formed by the load plus the slow conditioner behaves as a new load without 1\(^{\text{st}}\), 5\(^{\text{th}}\) and 7\(^{\text{th}}\) orders components to correct. In a sampling period \( T_s \) it can be considered that the new load current is approximately constant, so:

\[
\Delta i_e + \Delta i_{af} = 0 \rightarrow \Delta i_i = -\Delta i_{af},
\]

what means that the error can be calculated as the difference between the reference and the measured source currents changing the sign. In Fig. 8 the dead-beat technique for the fast conditioner is displayed.

The tracking technique precise the measurement of three additional signals, the hybrid filter currents, resulting finally ten variables necessary for the control stage of the novel topology.

**IV. EXPERIMENTAL RESULTS**

The novel topology and control are tested on a 1.2 kVA laboratory prototype. In Fig. 2 the electric scheme of the experimental system is shown. A three-phase four-wire system has been proposed (with the aim of studying unbalance due to zero-sequence components), 50 Hz, and nominal basis parameters \( U_B^{L-L} = 100\sqrt{3} \) V and \( P_B^{L} = 1200 \) VA, from which the basis values of current, \( I_B = 4 \) A, and impedance, \( Z_B = 25 \) \( \Omega \), can be obtained.

The non-linear load is formed by a three-phase controlled rectifier with resistive load, \( R_L = 48.23 \) \( \Omega \), selected so that the maximum power demanded (\( S_{L_{max}} = 1170 \) VA) is lower than the basis power of the system.

The values of the passive filter parameters are indicated in Table II. As the inductor of the passive filter has to operate as a filter inductor in the active equipment, the value of \( L_{PF5} \) has to be between the design limits of \( L_{af(1LCE)} \), taking into account the double criterion: ripple and control. In Table III the parameters used in the experimental conditioner are indicated. The values of the capacitances \( C_1 \) and \( C_2 \) are calculated assigning a maximum ripple in the voltage of 3\%. 

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**Fig. 5. Fundamental compensating load current extraction (1LCE) using control strategies based in the measure of the source current, with the addition of a dc bus control loop.**

**Fig. 7.** Dead-beat technique for the slow conditioner.
The control algorithms are implemented using a real time control system DS1104 (dSPACE), with PCI target composed by a processor Power PC603e/250MHz and the Texas Instruments DSP TMS320F240. This platform has 4 multiplexed inputs A/D 16 bits (2 \( \mu \text{s} \) sampling time) and 4 inputs A/D 12 bits (8 ns sampling time).

Many tests have been conducted by simulation, confirming the proper performance of the topology and its control in three-phase four-wire systems with harmonic distortion and unbalance in the PCC voltages and four-wire loads. However, due to the hardware limitation in the number of inputs, experimental tests have been simplified using a three-wire load (see Fig. 2), so zero-sequence components currents are not demanded. As the control platform has only 8 inputs they have been used for measuring the three source currents \((i_{a}, i_{b}, \text{ and } i_{c})\), two of the three hybrid currents \((i_{HFa} \text{ and } i_{HFb})\), obtaining the other one by subtraction, supposing these currents to form a three-phase system without zero-sequence components, two of the three line-to-line PCC voltages \((PCC_{ab} \text{ and } PCC_{cb})\) from which the three phase-to-neutral voltages are calculated, and the dc bus voltage, \(U_{dc}\).

The control strategies and tracking technique employed
are the detailed in the previous section. For the switching signals generation of the multiconverter inverter two symmetric PWM has been employed. These are generated by the slave DSP of the DS1104 platform from the duty cycles calculated in the tracking techniques.

The commutation frequency of the slow and fast conditioners has been fixed to 4kHz and 20 kHz, respectively.

The experimental results when the fast conditioner is turned on firstly, so it is in charge of the dc bus control, are shown in Fig. 9 for different firing angle values. In Fig. 9(a) there is not fundamental reactive power so the fundamental hybrid current component is null appearing only the 5th and 7th compensating currents which fully eliminate these components in the load current. The active conditioner demands fundamental current for the dc bus control and reduces the high orders components in the load current. However in Fig. 9(b) the firing angle of the rectifier is not zero, so fundamental reactive power is demanded by the load. This term of power is delivered by the slow conditioner, so the hybrid filter current contains fundamental component in this situation.

In Fig. 10 similar experiments have been conducted but turning on the slow conditioner first, so the dc bus control is task of this equipment. This is the reason why fundamental component appear in the hybrid conditioner although no fundamental reactive power is demanded by the load (see Fig. 10(a)).

For testing the operation of the conditioner under unbalanced PCC voltage conditions, the phase c conductor is connected to the neutral conductor of the utility, causing inverse-sequence and zero-sequence components \( \frac{U_{PCC}^-}{U_{PCC}^+} = \frac{U_{PCC}^0}{U_{PCC}^+} = 50\% \). As the zero-sequence component of the PCC voltage does not take part in the control algorithms and zero-sequence power is not demanded by the load because it has only three wires, the existence of this component does not affect to the control stage and the experiment can be conducted in spite of the limited number of inputs of the experimental platform. The load currents for each phase are shown in Fig. 11(a) while the three source currents are presented using the same axis in Fig. 11(b) so that balanced and sinusoidal source currents can be appreciated.

It has been calculated by simulation, using the load proposed in the experimental tests, the ratio maximum apparent power of the inverter in the least favourable firing angle situation related to the load power. For a conventional active conditioner this ratio is over 90%. With a hybrid multiconverter topology the fast conditioner inverter ratio is below 16% and approximately 20% for the slow conditioner inverter. These results validate the usefulness of the topology for high power levels where classical power filters can not be used due to the inverter rating.

The reduction in volume, losses and price attained with this topology due to the use of ferromagnetic core inductors in the slow converter are demonstrated in [5].
Fig. 10. Operation of the multiconverter conditioner under unbalanced PCC voltages. From up to down: Waveforms of the currents for phases \( a \), \( b \) and \( c \) and frequency spectra of these currents in the same order. (a) \( i_L \); (b) \( i_S \).

V. CONCLUSIONS

A novel hybrid multiconverter topology composed by a hybrid conditioner in parallel with an active one is proposed in this paper. There is a slow converter working with low switching frequency, which is in charge of the fundamental and dominant harmonic components in the load current. The fast conditioner, operating with a higher frequency, compensates the higher harmonic components. The inverter of the conditioner is a neutral-pointed-clamped VSI with six branches. The hybrid filter is formed by one active branch and one passive branch per phase tuned to the 5th order. The inductance of the passive filter acts simultaneously as the filter inductance of the active part, reducing the number of passive elements in the conditioner. This topology results especially proper for high power loads with a spectrum content with many harmonic components over the limits of total and individual harmonic distortion allowed by the standard IEEE 519. The main advantages of the topology are the decrease attained in the rating of the inverters and the reduction in volume, losses and price due to the use of ferromagnetic core inductors in the slow converter. Control strategies and tracking techniques for the global conditioner without the measurement of the load current have been developed, needing only ten measurements for the control of the two converters. The operation of the equipment in three-phase four-wire systems with harmonic distortion and unbalance has been tested in simulation. Some experimental results with a 1.2 kVA laboratory prototype are presented under different load conditions and under unbalanced voltages.

REFERENCES


