A Novel Fundamental Voltage Synchronization Control Strategy for Shunt Single-Phase and Three-Phase Active Power Filters

M. I. Milanés Montero*, E. Romero Cadaval* and F. Barrero González*

Abstract—A novel control strategy to extract the reference currents for a shunt Active Power Filter is presented in this paper. The method is a modification of the Fundamental Voltage Synchronization (FVS) and can be applied to single-phase and three-phase three-wire or four-wire systems. Under unbalanced and distorted mains, the load plus the conditioner will demand a balanced and sinusoidal current, with unity displacement power factor. The control stage uses an Autoadjustable Synchronous Reference Frame (ASRF) for the synchronization to the positive-sequence fundamental component of the voltage in three-phase utilities or to the fundamental component in single-phase utilities.

Experimental results testing the performance of the control strategy in a laboratory prototype in three-phase and single-phase systems are included.

I. INTRODUCTION

The widely use of power electronic converters has caused a proliferation of non-linear loads producing harmonic distortion and imbalance in the voltage at the point of common coupling (PCC) and reactive power consumption. To improve the PCC voltage power quality, the most widely used solution is the installation of shunt Active Power Filters (APF). Most of the APFs use Load Current detecting Strategies (LCS), which need the knowledge of the power demanded by the load [1] –[6]. Less common are APFs using Source Current detecting Strategies (SCS), such as Voltage Synchronization (VS) [7]–[9] and Fundamental Voltage Synchronization (FVS) [10]. These strategies have the advantages of reducing the measurements for the control and being applicable to single-phase as well as three-phase systems. On the other hand, the dynamic of the system is slower because they are based on the control of the dc bus voltage of the inverter.

In this paper a novel FVS strategy is presented which exhibits the advantages of SCS methods but maintaining the dynamic behaviour of LCS methods. The strategy gets the source current to be balanced, with unity displacement power factor and accomplishing the harmonic limits proposed by the Standard IEEE-519, under harmonic and unbalanced utility conditions. Experimental results with a three-phase 1.5 kVA laboratory prototype are conducted.

II. NOVEL FUNDAMENTAL VOLTAGE SYNCHRONIZATION CONTROL STRATEGY

The FVS control strategy has the objective that the constant power demanded by the load will be delivered by the source as positive-sequence fundamental active power, eliminating harmonics and unbalance components in the source current. The reference source current vector for the system shown in Fig. 1 is:

\[ i_{sref} = K \cdot u_{PCC}^* \]

where \( K \) is the equivalent conductance of the load+APF, which behaves as a resistor for the positive-sequence fundamental component while as an open-circuit for the rest of components and \( u_{PCC}^* \) is the positive-sequence fundamental PCC voltage vector.

In the classical FVS strategy \( K \) is determined from the error between the measured dc bus voltage, \( U_{dc,meas} \) and a reference value \( U_{dc,ref} \), using a proportional-integral (PI) controller with transfer function \( k_c(s) \) [10], resulting finally the reference source current

\[ i_{sref} = (U_{dc,ref} - U_{dc,meas}) \cdot k_c(s) \cdot u_{PCC}^* \]

A phase-locked-loop (PLL) system with proper operation under unbalanced and distorted systems is needed for extracting the positive-sequence fundamental component of the PCC voltages.

The drawback of this strategy is that the control of the system is based on the dc bus voltage of the inverter, which has a slow behaviour, causing a poor dynamic when the APF is connected or in case of load or utility variations. In order to solve this shortcoming in this paper a novel FVS strategy has been developed with a principle of operation similar to PHC strategy [5], [6] with the difference that PHC is based on the measurement of the load current for calculating the demanded power, while FVS gets this energetic objective without its measurement, so the number of meters is reduced. In the proposed FVS strategy the reference source current in \( a-b-c \) coordinates is calculated as:
The first term in the numerator of (3), \(P_{S1}\), is the term with higher value, due to constant active power demanded by the load plus the positive-sequence fundamental constant active power absorbed from the utility to reach the minimum dc bus voltage so that the APF can operate. As this term depends mainly on the load, it has a fast behaviour. The second term, \(U_{dcP2}'\), is the small constant positive-sequence fundamental active power absorbed from the utility for controlling the dc bus voltage, so that it will not be over its design limits. It is obtained from the output of a PI controller whose input is the error between the reference dc bus voltage and its measurement (see Fig. 2). Although the dynamic of this term is slower, its influence on the control is very small.

The positive-sequence fundamental PCC voltage is obtained by an Autoadjustable Synchronous Reference Frame (ASRF). The block diagram of this modified PLL for three phase systems is shown in Fig. 3(a), while its particularization for being applied to single-phase systems is shown in Fig. 3(b). The principle of operation of the ASRF as well as its behaviour in transient and steady states are explained and tested in [11]. The inclusion of this block does not imply a loss of simplicity in the control algorithm and, due to its capability of operating in three or single-phase cases, it allows the use of this strategy in single-phase systems, where the reference current will be:

\[
i_{s ref} = K \cdot U_{PCC} \left[ \frac{P_{S1} + \Delta P_{S1}(t)}{U_{PCC}} \right] U_{PCC},
\]

being \(U_{PCC}\) the RMS value of the fundamental PCC voltage.

This novel strategy needs to measure the source current, the PCC voltage and the dc bus voltage, what implies three measurements in single-phase systems, five measurements in three-phase three-wire systems and seven measurements in case of three-phase four-wire systems.

### III. Operation or Tracking Technique

The tracking technique should secure that the reference compensating current is tracked by the active filter current with the minimum error. In a switching period, \(T_s\), it is satisfied (Fig. 1):

\[
\Delta i_f + \Delta i_{af} = \Delta i_s.
\]

As the switching frequency of the APF is high (about 10 or 20 kHz), the load current can be considered approximately constant in \(T_s\). Imposing this condition to (5), it is obtained

\[
\Delta i_f = i_{af ref} - i_{af meas} \approx -\Delta i_s = -(i_{s ref} - i_{s meas}).
\]

So the tracking error in the APF current can be obtained from the reference source current calculated by the control strategy and its measured value, what implies that the measurement of the source current is enough for the operation technique (see Fig. 2). Finally using a current controller, such as dead beat or hysteresis controllers, the switching signals for the inverter are obtained.

![Figure 1. Electric system supplying a non-linear load and shunt APF](image1)

![Figure 2. Block diagram of the control strategy and tracking technique of the APF with the novel FVS strategy](image2)
IV. EXPERIMENTAL RESULTS

The experimental system is shown in Fig. 4. The shunt APF is formed by a neutral-pointed-clamped voltage source inverter. The non-linear load is a controlled rectifier with resistive load. For testing the operation of the APF in case of zero-sequence load current components a resistive load has been connected between the phase A and the neutral conductor, commanded by the switch $S_1$. In case of single phase systems only one branch of the inverter is connected to the phase A conductor while the middle point of the dc bus is connected to the neutral conductor, and the rectifier is disconnected while the switch $S_1$ is ON.

The values of the parameters are summarized in Table I. A hysteresis current controller with a maximum switching frequency of 10 kHz is used in the tracking stage (Fig. 2).

The programmable disturbance source HP 6834B, 4.5 kVA, which allows the generation of variable single-phase or three-phase voltages has been used for obtaining the disturbed source voltages in the experiments. DS1104 (dSPACE) has been employed as the real time control platform.

In the following sections the results obtained in the experimental tests are shown. From top to bottom, the oscilloscope images show the waveform for phase A of the PCC voltage $u_{pcc}$, load current, $i_L$, source current, $i_S$, and APF current, $i_{APF}$. In case of unbalanced source voltages or load currents, experimental results are displayed using the Control Desk software of dSPACE, instead of oscilloscope images, since more variables can be shown at the same time.

A. Three-phase system: Sinusoidal and balanced source voltages, distorted and balanced load currents.

The experimental results in case of sinusoidal and balanced source voltages when the firing angle of the rectifier, $\alpha$, is null are shown in Fig. 5(a) and when fundamental reactive power is demanded by the load ($\alpha \neq 0$) are shown in Fig 5(b). In both cases sinusoidal and balanced source currents are obtained with unity displacement power factor.

B. Three-phase system: Sinusoidal and unbalanced source voltages, distorted and unbalanced load currents.

In Fig. 6, results under sinusoidal and unbalanced due to negative and zero-sequence components in the PCC voltage are displayed. In this test the load current is distorted and unbalanced due to negative-sequence components only, since a three-wire non-linear load is connected. It can be noticed that the source currents are sinusoidal and balanced.

![Figure 4. Experimental system.](image-url)
### TABLE I.
PARAMETERS OF THE EXPERIMENTAL SYSTEM

<table>
<thead>
<tr>
<th>$L_{ar}$ (mH)</th>
<th>$C_1 = C_2$ (mF)</th>
<th>$U_{PCC}$, $V$</th>
<th>$U_{dc,ref}$ (V)</th>
<th>$R_L$ (Ω)</th>
<th>$R_I$ (Ω)</th>
<th>$f_s$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.5</td>
<td>3</td>
<td>100</td>
<td>400</td>
<td>48</td>
<td>50</td>
<td>10</td>
</tr>
</tbody>
</table>

C. *Three-phase system: Sinusoidal and balanced source voltages, distorted and unbalanced load currents.*

Fig. 7 shows the results in case of sinusoidal and balanced PCC voltages, but load current with zero-sequence component formed by the three-phase rectifier and the resistive load connected between phase $A$ and the neutral conductor ($S_1 = ON$).

D. *Three-phase system: Distorted and balanced source voltages, distorted and balanced load currents.*

The results in case of balanced but distorted PCC voltages once the APF is ON are shown in Fig. 8. One can notice that sinusoidal source currents with unity displacement power factor are obtained.

E. *Single-phase system: Distorted source voltage, distorted load currents.*

Finally to test the proper performance of the strategy in case of single-phase systems, the rectifier has been disconnected and $S_1 = ON$. Results when the PCC voltage is distorted are shown in Fig. 9.
Figure 7. Experimental results under sinusoidal and balanced source voltage; unbalanced load current with zero-sequence component: (a) $u_{PCC,a,b,c}$; (b) $i_{Sa,b,c}$ when the active filter is off; (c) $i_{Sa,b,c}$ after the active filter is on.

Figure 8. Experimental results under harmonic source voltage: $u_{PCC}(150$ V/div), $i_{La}$, $i_{Sa}$, $i_{AFa}(5$ A/div).

Figure 9. Experimental results for a single-phase system ($S_1$ = on, controlled rectifier off) with harmonic source voltage: $u_{PCC}$ (150 V/div), $i_s$, $i_{AF}(5$ A/div).

V. CONCLUSIONS

A novel FVS strategy for shunt single-phase and three-phase active power filters is presented in this paper. The main advantages of the proposed control method are:

a) the control strategy and tracking technique are carried out without measuring the load current, so a reduction in the number of meters is attained,

b) it can be applied to single-phase and three-phase three-wire or four-wire systems without changing the control algorithm,

c) the control stage is simple, comparing with other control strategies, what allows the use of a high sample frequency in the control algorithm,

d) it adds the advantages of both Load Current detecting Strategies (LCS) and Source Current detecting Strategies (SCS): minimum measurements and simple control but with improved dynamic behaviour.

Experimental results in three-phase four-wire systems and single-phase systems are conducted. The tests confirm the proper operation of the proposed strategy.

ACKNOWLEDGMENT

The authors thanks to Víctor Manuel Miñambres Marcos his collaboration in the experimental part of this paper.

REFERENCES


