Abstract—An industrial controller, specifically designed for two- and three-level converters, was adapted to work on an asymmetrical nine-level active power filter (APF). The controller is now able to make all required tasks for the correct operation of the APF, such as current-harmonic elimination and removal of high-frequency noise. The low switching-frequency operation of the nine-level converter was an important advantage in the application of the industrial controller. In addition, with the nine-level filter, switching losses were significantly reduced. The filter was designed to work as voltage source and operates as harmonic isolator, improving the filtering characteristics of the passive filter. The control strategy for detecting current harmonics is based on the “p-q theory” and the phase-tracking system in a synchronous reference frame phase-locked loop. The dc-link voltage control is analyzed together with the effect of controller gain and delay time in the system's stability. Simulations for this application are displayed and experiments in a 1-kVA prototype, using the aforementioned industrial controller, were tested, validating the effectiveness of this new application.

Index Terms—Active filters, harmonic distortion, multilevel systems, power quality.

I. INTRODUCTION

THE constant increase in power electronic devices, used by industrial and commercial consumers, has deteriorated seriously electric power systems. More transmission losses, power-transformer and neutral-conductor overheating, power-factor correction-capacitor overloading, and induced noise in control systems are only a few of the problems that harmonic distortion may bring into home and industrial installations [1], generating considerable economic losses to distribution companies and end users [2].

During many years, the solution used to minimize harmonic pollution has been tuned passive filters. However, they have quite a few disadvantages, like fixed compensating characteristic (given only by the tuned frequencies), parallel and series resonance with source-voltage harmonics, and filtering characteristics strongly affected by source impedance. They are also bulky, and they lost their effectiveness with the passage of time [3], [4].

Several topologies of active power filters (APFs) have been proposed [5]–[7] as a solution to passive-filter problems. Most of the APFs that have been implemented until now are of shunt type [8]–[11], but they are comparatively more expensive due to its large rating of about 30%–60% of the load [12]. Even more, they cannot compensate correctly for harmonic voltage produced by power rectifiers with large dc-link capacitor [13].

Numerous series APF have been proposed [3], [4], [12], [14], [15], most of them operating as hybrid, in conjunction with shunt passive filters. The advantages of hybrid topologies are quite significant since the series active filter can be very low rated, between 3% and 10% [12], and the disadvantages of the passive filters are mitigated. Another advantage of this hybrid topology is that harmonic voltage and current-producing loads can be effectively compensated. However, series active filters proposed until now had been implemented in two-level PWM based inverters, with the known disadvantages that they present, such as high-order harmonic noise and additional switching losses due to high-frequency commutation [16].

Multilevel inverters have become very popular in the last few years, due to their capability to generate cleaner voltage waves and lower switching losses [17], [18]. If the cascaded H-bridge topology scaled in powers of three is utilized, the number of sources and semiconductors is minimized [19]–[24]. With this topology, each H bridge operates at a lower frequency, decreasing switching losses and permitting the use of slower semiconductors. This paper shows that lower frequency operation of the asymmetrical converter has permitted the adaptation of industrial controllers for filtering purposes.

II. SYSTEM DESCRIPTION

A. System Configuration

The circuit of Fig. 1 shows the basic topology of the system, which is composed by three 9-level inverters connected in series between the source and the load and a shunt passive filter tuned at fifth and seventh harmonics. The passive filter presents a low-impedance path to load-current harmonics and also helps to partially correct the power factor.

B. Multilevel Inverter

Each phase of the nine-level series APF comprises two H bridges connected at the same dc-link capacitor. The two bridges are connected to the ac line using independent
improve noticeably the filtering characteristics.

than nine levels increases hardware complexity and does not
transformers scaled in power of three, as shown in Fig. 2. More
than nine levels increases hardware complexity and does not
improve noticeably the filtering characteristics.

The H-bridge converter is able to produce three levels of
voltage at the ac side: +v_{dc}, −v_{dc}, and zero. The outputs
of the modules are connected through transformers whose voltage
ratios are scaled in power of three, allowing 3^n levels of voltage
[23]. Then, with only two converters per phase (n = 2), nine
different levels of voltage are obtained: four levels of positive
values, four levels of negative values, and zero.

The transformer located at the bottom of the figure has the
highest voltage ratio and, with its corresponding H bridge,
is called main converter. The other transformer defines the
auxiliary converter (Aux). The main converter manages most of
the power but works at the lowest switching frequency, which
is an additional advantage of this topology.

Amplitude modulation is used to determine the output level
of the inverter, rounding the reference signal to the nearest
integer between the nine possible levels.

C. Operation Principle

In order to eliminate line-current harmonics, the APF is
controlled to present very high impedance to these currents.
This is achieved by generating a voltage proportional to the
harmonic current i_{s,h}. To keep the dc-link voltage constant, it is
necessary to add to the reference signal a compensating signal
of fundamental frequency, being the reference voltage to each
phase as shown in

\[ v^*_{AF,h} = v^*_{AF,f} = K \cdot i_{s,h} \]  

Fig. 3 shows an equivalent circuit for the harmonics, where
the APF is represented as a resistor of value K since v_{AF,h} is
equal to the harmonic voltage appearing across the resistor. The
load is represented as a harmonic voltage source.

Equation (2) can be directly derived from Fig. 3 and (1)

\[ i_{s,h} = \frac{v_{s,h} - v_{L,h}}{Z_s + K}. \]  

If K is large enough (several times Z_s), the harmonic current
i_{s,h} becomes zero, and an almost purely sinusoidal current is
drawn from the utility. The voltage at the point of common
coupling v_{PCC} is also improved with the action of the filter,
depending only on the utility-voltage distortion instead of the
harmonic voltage of the load.

D. Harmonic-Current Detection

To detect the harmonic content of the line current, the so-
called p−q theory [25] was used. According to this theory,
when three symmetrical and sinusoidal source voltages and
three asymmetrical or distorted line currents are present in a
three-phase power system, the dc components i_{p,dc} and i_{q,dc}
of the instantaneous active and reactive currents i_p and i_q
correspond to the fundamental active and reactive components
of the line current, whereas the corresponding ac components of
i_p and i_q, i_{p,ac} and i_{q,ac}, are related to the asymmetric and
harmonic components.

The complete control scheme of the APF is shown in Fig. 4.
In the diagram, it can be seen that the instantaneous active and
reactive currents i_p and i_q are obtained by transforming the
instantaneous source currents i_s, i_b, and i_c (which is obtained
by subtracting both i_a and i_b) by means of Clark and Park
transformations as shown in

\[ \begin{bmatrix} i_p \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin \omega t & -\cos \omega t \\ \cos \omega t & \sin \omega t \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \]  

A low-pass filter (LFP) then extracts the dc components of
i_p and i_q, resulting in i_{p,dc} and i_{q,dc}. A compensating dc-link
voltage is subtracted from the fundamental active current i_p,
and the resulting signal, together with i_{q,dc} are transformed
back to a three-phase system by the inverse Park and Clark
transformations as shown in (4). The cutoff frequency of the
LFP used in this paper was 10 Hz

\[ \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} \sqrt{3} & 0 \\ -\frac{1}{2} \sqrt{3} & 1 & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} \sin \omega t & \cos \omega t \\ -\cos \omega t & \sin \omega t \end{bmatrix} \begin{bmatrix} i_p \\ i_q \end{bmatrix}. \]  

\[ \begin{bmatrix} v_{AF}^* \end{bmatrix} = K \cdot i_{s,h} + v_{AF,f}. \]
where $I_s$ is the effective value of line current. Doing a linearization of (5) at the operation point $v_{dc}(t) = v_{dc,0}$ and $i_e(t) = i_{e,0}$, where $v_{dc,0}$ is the reference voltage from the capacitor, the transfer function $G(s)$ can be obtained as follows:

$$G(s) = \frac{\Delta v_{dc}}{\Delta i_e} = \frac{\sqrt{3} \cdot K \cdot I_s \cdot \cos(\phi)}{s \cdot C \cdot v_{dc,0}}.$$  

(6)

Since the controller is a proportional plus integral one, its transfer function is

$$C(s) = K_P \cdot \left(1 + \frac{1}{T_I \cdot s}\right).$$  

(7)

Then, the closed-loop transfer function of the dc-link control system is as shown in

$$\frac{\Delta v_{dc}}{\Delta v_{ref}} = \frac{\sqrt{3} \cdot K_P \cdot K_I \cdot C_{v_{dc,0}} \cdot \cos(\phi)}{s^2 + \frac{\sqrt{3} \cdot K_P \cdot K_I \cdot C_{v_{dc,0}} \cdot \cos(\phi)}{T_I}}.$$

(8)

Equation (8) corresponds to a second-order system, where the damping factor $\zeta$ and natural angular velocity $\omega_n$ can be calculated from (9) and (10). Since the poles of the system are always at the left side of the s-plane, the system is always stable

$$\zeta = \frac{1}{2} \sqrt{\frac{\sqrt{3} \cdot K_P \cdot T_I \cdot K \cdot I_s \cdot \cos(\phi)}{C \cdot v_{dc,0}}}.$$  

(9)

$$\omega_n = \frac{\sqrt{3} \cdot K_P \cdot K \cdot I_s \cdot \cos(\phi)}{T_I \cdot C \cdot v_{dc,0}}.$$  

(10)

For simulations and experiments, $\zeta = 1$ and $\omega_n = 2\pi \cdot 100$ rad/s were used. In this way, a critically damped response, where minimal voltage oscillation happens, is obtained.

F. Stability Analysis for Harmonic Currents

The delay times introduced by the controller, large gain $K$, and high system stiffness seriously affect the active-filter stability [27].

Assuming purely inductive source impedance, (11) can be directly derived from Fig. 3

$$i_{s,h} = \frac{v_{s,h} - v_{L,h} - v_{AF,h}}{s \cdot L_s}. $$

(11)
If a delay time $\tau$ is introduced by the controller, the harmonic voltage generated by the filter in Laplace domain is

$$v_{AF,h} = K \cdot i_{s,h} \cdot e^{-s\tau}.$$  

(12)

Hence, the closed-loop block diagram of the harmonic control system can be represented as shown in Fig. 6.

From the Nyquist stability criterion, the selected gain $K$ of the filter must satisfy (13) so that the system will be stable

$$K < \frac{\pi}{2} \cdot \tau \cdot L_s.$$  

(13)

For a typical line inductance $L_s = 0.02$ per unit (p.u.) in a 50-Hz system and a gain $K = 2$, the delay time should be less than 50 $\mu$s, which will ensure system stability.

III. SIMULATIONS AND EXPERIMENTAL RESULTS

The proposed hybrid-series APF was simulated in MATLAB/Simulink, using a source impedance of 2% p.u. For the experiments, a 1-kVA/110-V 50-Hz system using an IGBT-based multilevel inverter was implemented. All the control tasks in the experiments were performed by the aforementioned industrial controller, which combines a 600-MHz CPU and a large field-programmable gate array (FPGA). The controller and the complete experimental system are shown in Fig. 7.

The high-speed control tasks are programmed into the industrial controller using the MATLAB/Simulink. This allows implementing the same model used in simulations for real-world operation, ensuring an error-free and fast implementation. The complete control loop is executed by the controller every 50 $\mu$s.

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>$C$ [\mu F]</th>
<th>$L$ [mH]</th>
<th>$Q$</th>
<th>Tuned freq./desired freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>88</td>
<td>5.1</td>
<td>4</td>
<td>0.95</td>
</tr>
<tr>
<td>7th</td>
<td>20</td>
<td>11</td>
<td>6</td>
<td>0.97</td>
</tr>
</tbody>
</table>

TABLE I

PASSIVE FILTERS USED

A gain $K = 24$, equivalent to 2 p.u. was used in both simulation and experiments. The turn ratios of the output transformers were 220:18 and 220:54 for the auxiliary and main transformers, respectively. The dc-link capacitor was selected to be $C = 4700 \ \mu$F. The load connected to the six-pulse diode rectifier was $R_L = 22 \ \Omega$, and $C_L = 4700 \ \mu$F.

The values of the shunt passive filters can be seen in Table I. The quality factor $Q$ of the passive filters is very low in comparison with industrial passive filters that operate without an active section. This can be an advantage considering that the cost of passive filters with a lower $Q$ factor is lower. The passive filters were also slightly off tuned, decreasing its performance even more.

In the simulations shown in Fig. 8, the active filter starts to operate at $t = 0.08$ s. It can be seen that the source voltage $v_s$ and line current $i_s$ are improved with a negligible delay, changing to an almost purely sine wave. As the load current $i_L$ does not change with APF operation, the rectifier operation is not being affected. It is quite important to mention that the maximum switching frequency of the main converter (which manages 70% of the kilovolt-ampere) is only 500 Hz. This small switching frequency allows using the APF in the high-power range, using the relatively slow gate-turn-off thyristor. On the other hand, the Aux, which only manages 30% of the power,
switches at a maximum frequency of only 2 kHz. For a very high power application using two-level converters and PWM to compensate, the switching frequency must be at least 10 kHz to get a similar result. Following the analysis given in Fig. 8, a considerable fundamental voltage appears at the terminals of the active filter, which is due to resistive losses at the ac side of the filter transformers. This problem can be improved using better quality transformers. The capacitor voltage $v_{dc}$ follows its reference, and minimal fluctuations appear when the filters start their operation.

The harmonic content and total harmonic distortion (THD) of line current and source voltage without filters, only with passive filters and with both passive and active sections, are shown in Fig. 9. It can be seen that the line-current THD dramatically improves with the APF, passing from 20% to 2.4%, and hence, all harmonics goes to almost zero. The THD of the line current without passive filters was 34%. The source-voltage THD improves from 2.3% to 0.65% when the APF starts its operation. The improvement in this case depends on utility stiffness; if the system is very strong, the source voltage is not too affected by harmonic currents flowing to the load, and the action of the APF cannot be seen clearly. In the other case, if the system is weak, line current affects the source voltage noticeably, and the effect of the APF is more evident.

In Fig. 10, the response of the active filter under a load change can be seen. The load of the rectifier changes from $RL = 22 \Omega$ to $RL = 44 \Omega$, without affecting neither the source-current clearness nor dc voltage stability.

Experimental results corroborate the successful operation of the active filter shown in the simulations. Fig. 11 shows the transient response when APF starts to operate. The line current immediately becomes sinusoidal and the capacitor-voltage behavior is as expected.

The reduction in harmonic content, as seen on Fig. 12, is also similar to the simulated one, but in the experiments, the effect of passive filters is greater, the line-current THD, with only the passive filters connected, being 15%. This is due to bigger line inductance introduced by the autotransformer used to connect the system to the grid.
capacitor voltage returns to its reference in two cycles, with minimum variation when the load changes. In the experimental results, the load was increased from \( R_L = 44 \Omega \) to \( R_L = 22 \Omega \).

### IV. Conclusion

A hybrid-series AFP based on a low-rated multilevel inverter, acting as a high-harmonic impedance, and a shunt passive filter acting as a harmonic-current path, were developed and tested. All the control tasks were programmed in an industrial controller, which was adapted for this particular application. With the proposed control algorithm and taking advantage of the multilevel topology of the active filter, almost purely sinusoidal currents and voltages were achieved, without the usual high-frequency content present in PWM inverters.

The proposed filter, which compensates harmonic-voltage source generated by contaminating loads, was simulated and tested using MATLAB/Simulink. It has been demonstrated that the filter responds very fast under connections and sudden changes in the load conditions, reaching its steady state in about two cycles of the fundamental.

### References


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**Fig. 13.** Line current and active-filter voltage close-up. Up: Only with passive filter. Bottom: With both active and passive filters operating.

**Fig. 14.** Experimental transient response under load change. From top to bottom: Active filter voltage \( v_{AF} \), line current \( i_s \), and capacitor voltage \( v_{dc} \).


Alexander Varschavsky was born in Santiago, Chile. He received the B.S. degree in electrical engineering and the M.Sc. degree from the Pontificia Universidad Católica de Chile, Santiago, in 2008. From 2007 to 2008, he was a Student Researcher with the “Núcleo de Electrónica Industrial y Mecatrónica,” Santiago, where he was involved with the design and application of power electronics devices. Currently, he is an Engineer with CGE Distribución, Santiago, a Chilean utility company. His research interests are active power filters, electrical machines, power electronics, and power systems.

Juan Dixon (M’90–SM’95) was born in Santiago, Chile. He received the B.S. degree in electrical engineering from the Universidad de Chile, Santiago, Chile, in 1977 and the M.S.Eng. and Ph.D. degrees from McGill University, Montreal, QC, Canada, in 1986 and 1988, respectively.

In 1976, he was with the State Transportation Company in charge of trolleybuses operation. In 1977 and 1978, he was with the Chilean Railways Company. Since 1979, he has been with the Electrical Engineering Department, Pontificia Universidad Católica de Chile, Santiago, where he is currently a Professor. He has presented more than 70 works in international conferences and has published more than 30 papers related with power electronics in IEEE Transactions and IEE proceedings. His main areas of interest are in electric traction, power converters, PWM rectifiers, active power filters, power-factor compensators, multilevel, and multistage converters. He has consulting work related with trolleybuses, traction substations, machine drives, hybrid electric vehicles, and electric railways. He has created an electric vehicle laboratory where he has built state-of-the-art vehicles using brushless dc machines with ultracapacitors and high specific-energy batteries.

Mauricio Rotella received the Electrical Engineer Professional and Master of Science degrees from Pontificia Universidad Católica de Chile, Santiago, Chile, in 1999 and 2006, respectively.

Since 1998, he has been working with ABB in various positions, including product manager for large drives in ABB Chile and Regional Sales Manager for Latin America MV Drives in ABB Switzerland. Currently, he is with Automation Products Local Division in ABB Chile.

Luis Morán (F’05) was born in Concepción, Chile. He received the Ph.D. degree from Concordia University, Montreal, QC, Canada, in 1990.

Since 1990, he has been with the Electrical Engineering Department, University of Concepción, Concepción, where he is a Professor. He has written and published more than 30 papers in active power filters and static Var compensators in IEEE Transactions. His main areas of interest are in ac drives, power quality, active power filters, FACTS, and power protection systems.

Dr. Morán is the principal author of the paper that got the IEEE Outstanding Paper Award from the Industrial Electronics Society for the best paper published in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS during 1995, and the coauthor of the paper that was awarded in 2002 by the IAS Static Power Converter Committee.