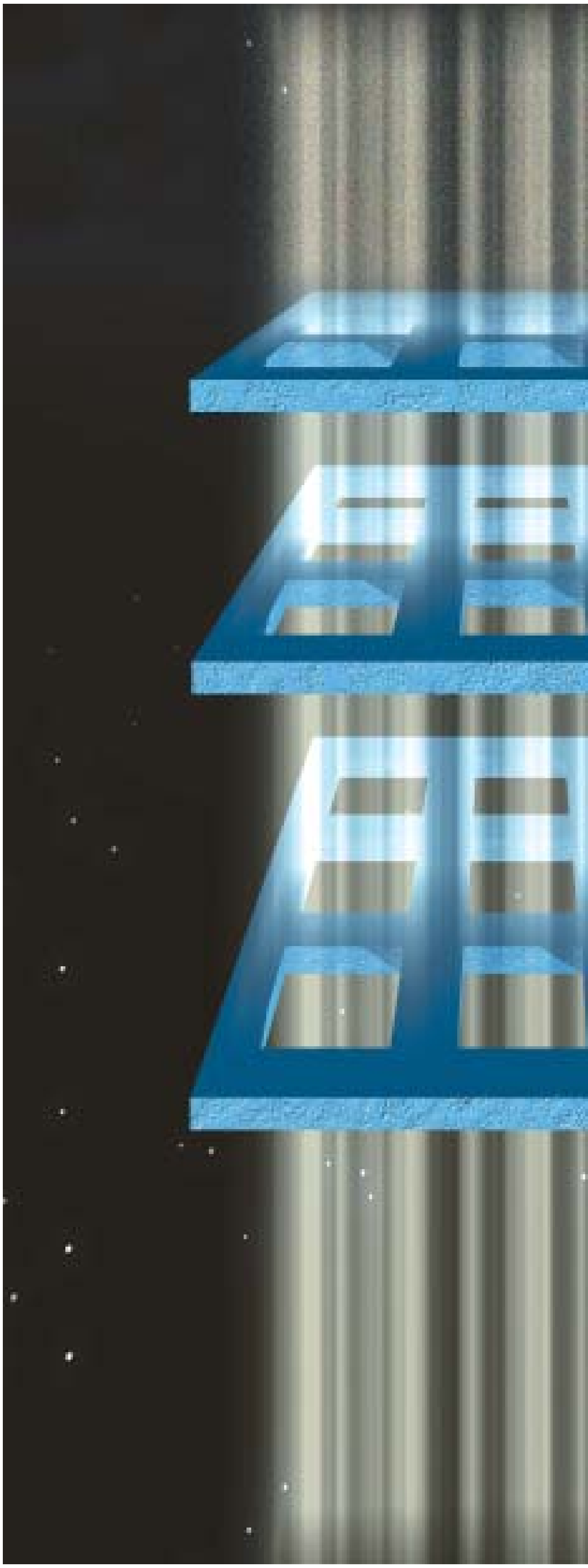
# Delivering Clean and Pure Power

**By Hugh Rudnick, Juan Dixon and Luis Morán**

## Active power filters as a solution to power quality problems in distribution networks



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POWER ELECTRONICS IN FACTS (FLEXIBLE AC TRANSMISSION systems) have not lived up to their expectations as the panacea to overcome transmission system limitations. However, power electronics are alive and well in useful applications to overcome distribution system problems. Power electronics has three faces in power distribution: one that introduces valuable industrial and domestic equipment; a second one that creates problems; and, finally, a third one that helps to solve those problems.

On one hand, power electronics and microelectronics have become two technologies that have considerably improved the quality of modern life, allowing the introduction of sophisticated energy-efficient controllable equipment to industry and home. On another hand, those same sensitive technologies are conflicting with each other and increasingly challenging the maintenance of quality of service in electric energy delivery, while at the same time costing billions of dollars in lost customer productivity.

Modern semiconductor switching devices are being utilized more and more in a wide range of applications in distribution networks, particularly in domestic and industrial loads. Examples of such applications widely used are adjustable-speed motor drives, diode and thyristor rectifiers, uninterruptible power supplies (UPSs), computers and their peripherals, consumer electronics appliances (TV sets for example), among others. Those power electronics devices offer economical and reliable solutions to better manage and control the use of electric energy. However, given the characteristics of most power electronics circuits, those semiconductor devices present nonlinear operational characteristics, which introduce contamination to voltage and current waveforms at the point of common coupling of industrial loads. These devices, aggregated in thousands, have become the main polluters, the main distorters, of the modern power systems.

At the same time, microelectronics processors have found their way into many applications: from automated industrial assembly lines, to hospital diagnostics and measurement schemes, to home appliances such as video and DVD units. These applications are sensitive and vulnerable to power quality problems such as either electrical disturbances or power system harmonics. But microelectronics-based applications are not the only ones facing the dangers of poor power quality. Those same semiconductor-based loads, which are the major contributors to power system pollution, are also very sensitive to that pollution.

## The Impact of Pollution

Unexplained computer network failures, premature motor burnouts, humming in telecommunication lines, and transformer overheating are only a few of the damages that quality problems may bring into home and industrial installations. What may seem like minor quality problems may bring whole factories to a standstill.

Studies by the Canadian Electrical Association indicate that power quality problems, including voltage sags and surges, transients, and harmonics, are estimated to cost Canada about $1.2 billion annually in loss production. Most of the cost of harmonics is not incurred in the power system itself but rather within the customer's facility. While system solutions are being searched and even power quality markets are being formulated in the present deregulated environments, the solution starts at the individual industrial and commercial facilities.

With the risks and costs of pollution in mind, researchers and equipment manufacturers are looking for alternatives for protection, while industry and

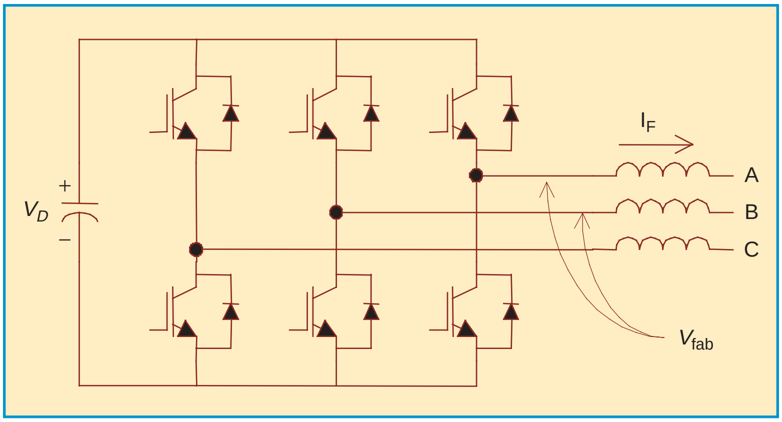

figure 1. Voltage source topology for active filters.

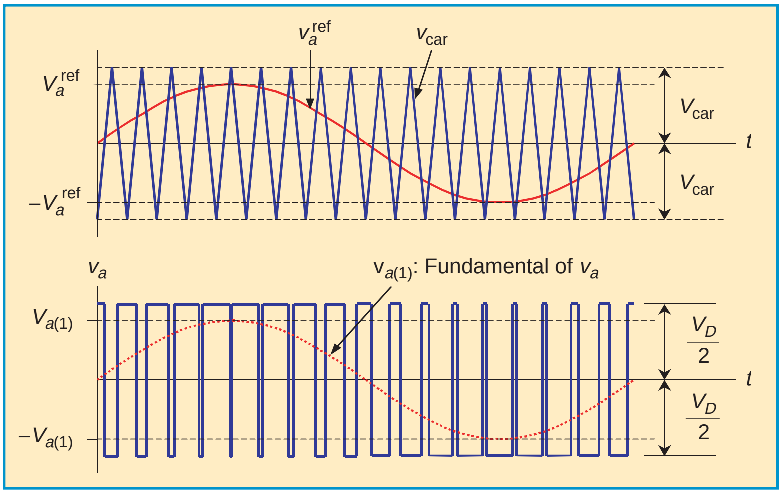

figure 2. The PWM carrier technique (triangular carrier).

table 1. Active filters applications depending on power quality problems.

| | Source of Problem | |
|---|---|---|
| **Active Filter Connection** | **Load Effect on AC Supply** | **AC Supply Effect on Load** |
| Shunt | -Current harmonic filtering<br>-Reactive current compensation<br>-Current unbalance<br>-Voltage flicker | |
| Series | -Current harmonic filtering<br>-Reactive current compensation<br>-Current unbalance<br>-Voltage flicker<br>-Voltage unbalance | -Voltage sag/swell<br>-Voltage unbalance<br>-Voltage distortion<br>-Voltage interruption<br>-Voltage flicker<br>-Voltage notching |
| Series-Shunt | -Current harmonic filtering<br>-Reactive current compensation<br>-Current unbalance<br>-Voltage flicker<br>-Voltage unbalance | -Voltage sag/swell<br>-Voltage unbalance<br>-Voltage distortion<br>-Voltage interruptions<br>-Voltage flicker and notching |

businesses are increasingly investing in sophisticated and innovative devices to improve power quality.

## Solutions to Power Quality Problems

There are two approaches to the mitigation of power quality problems. The first approach is called load conditioning, which ensures that the equipment is made less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line-conditioning systems that suppress or counteract the power system disturbances.

Passive filters have been most commonly used to limit the flow of harmonic currents in distribution systems. They are usually custom designed for the application. However, their performance is limited to a few harmonics, and they can introduce resonance in the power system.

Among the different new technical options available to improve power quality, active power filters have proved to be an important and flexible alternative to compensate for current and voltage disturbances in power distribution systems. The idea of active filters is relatively old, but their practical development was made possible with the new improvements in power electronics and microcomputer control strategies as well as with cost reduction in electronic components. Active power filters are becoming a viable alternative to passive filters and are gaining market share speedily as their cost becomes competitive with the passive variety.

Through power electronics, the active filter introduces current or voltage components, which cancel the harmonic components of the nonlinear loads or supply lines, respectively. Different active power filters topologies have been introduced, and many of them are already available in the market.

## Power Filter Topologies

The simplest method of harmonic filtering is with passive filters. They use reactive storage components, namely capacitors and inductors. Among the more commonly used passive filters are the shunt-tuned LC filters and the shunt low-pass LC filters. They have some advantages such as simplicity, reliability, efficiency, and cost. Among the main disadvantages are the resonances introduced into the ac supply; the filter effectiveness, which is a function of the overall system configuration; and the tuning and possible detuning issues. These drawbacks are overcome with the use of active power filters.

Most of the active power filter topologies use voltage source converters, which have a voltage source at the dc bus, usually a capacitor, as an energy storage device. This topology, shown in Figure 1, converts a dc voltage into an ac voltage by appropriately gating the power semiconductor switches. Although a single pulse for each half cycle can be applied to synthesize an ac voltage, for most applications requiring dynamic performance, pulse width modulation (PWM) is the most commonly used today.

PWM techniques applied to a voltage source inverter consist of chopping the dc bus voltage to produce an ac voltage of an arbitrary waveform. There are a large number of PWM techniques available to synthesize sinusoidal patterns or any arbitrary pattern. With PWM techniques, the ac output of the filter can be controlled as a current or voltage source device. Figure 2 shows the way PWM works by means of one of the simplest and most common techniques: the triangular carrier technique. It forces the output voltage $v_a$ over a switching cycle, defined by the carrier period of $v_{\text{car}}$, to be equal to the average amplitude of the modulating wave $v_a^{\text{ref}}$. The resulting voltages for a sinusoidal modulation wave contain a sinusoidal fundamental component $v_{a(1)}$ and harmonics of unwanted components. These unwanted components can be minimized using a frequency carrier as high as possible, but this depends on the maximum switching frequency of the semiconductors (IGBTs, GTOs, or IGCTs).

The modulation strategy shown in Figure 2 uses a triangular carrier, which is one of many strategies applied today to control power inverters. Depending on the application (machine drives, PWM rectifiers, or active power filters), some modulation strategies are more suitable than others. The modulation techniques not only allow controlling the inverters as voltage sources but also as current sources. Figure 3 shows the compensating current generated for a shunt active power filter using three different modulation techniques for current-source inverters. These three techniques are periodical sampling (PS), hysteresis band (HB), and triangular carrier (TC). The PS method switches the power transistors of the active filter during the transitions of a square wave clock of fixed frequency: the sampling frequency. The HB

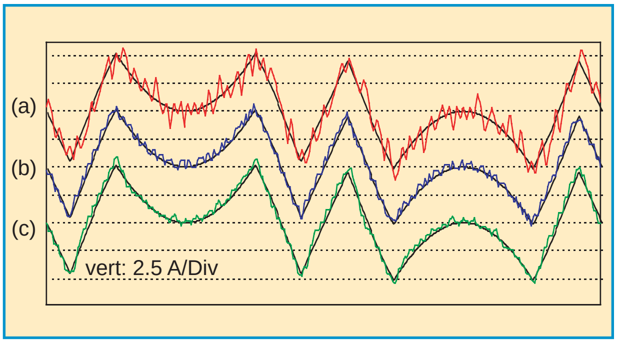

figure 3. Current waveforms obtained using different modulation techniques for an active power filter: (a) PS method, (b) HB method, (c) TC method.

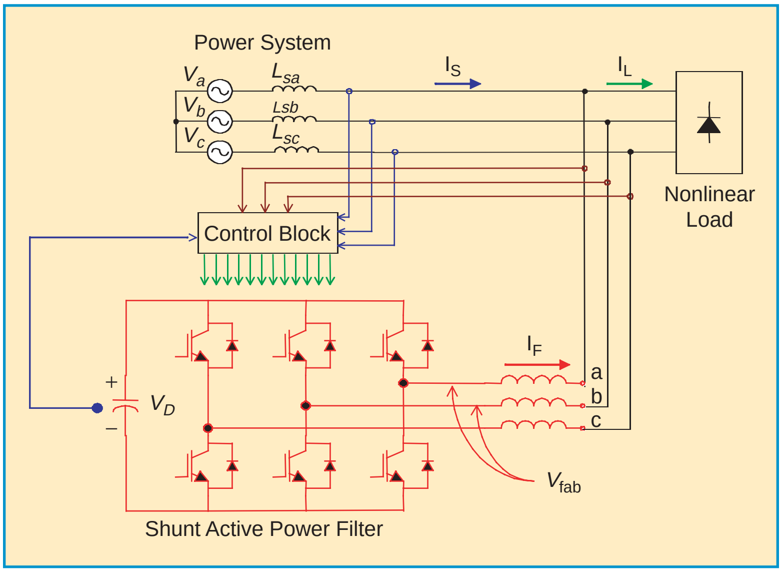

figure 4. Shunt active power filter topology.

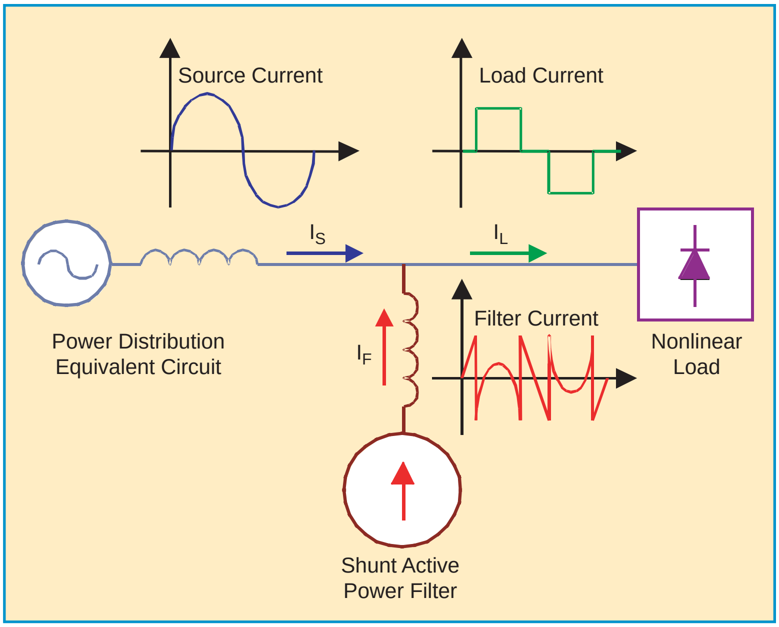

figure 5. Filter current IF generated to compensate load-current harmonics.

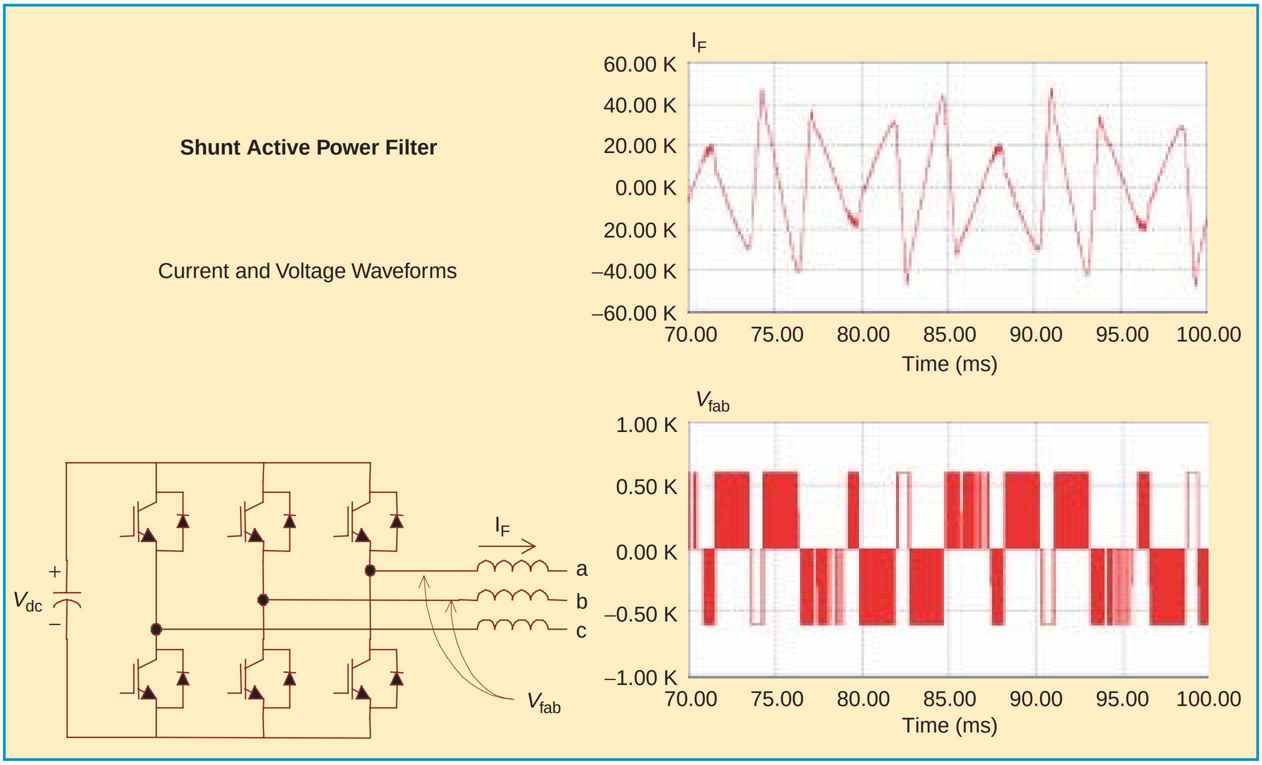

figure 6. Current waveforms and PWM voltage patterns to compensate load harmonics.

method switches the transistors when the error exceeds a fixed magnitude: the hysteresis band. The TC method compares the output current error with a fixed amplitude and fixed triangular wave: the triangular carrier. Figure 3 shows that the HB method is the best for this particular waveform and application because it follows more accurately the current reference of the filter. When sinusoidal waves are required, the TC method has been demonstrated to be better.

Depending on the particular application or electrical problem to be solved, active power filters can be implemented as shunt type, series type, or a combination of shunt and series active filters (shunt-series type). These filters can also be combined with passive filters to create hybrid power filters.

### Shunt Active Filters

The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase-shifted by 180°. Figure 4 shows the connection of a shunt active power filter and Figure 5 shows how the active filter works to compensate the load harmonic currents.

To be able to produce a filter current waveform $I_F$, as shown in Figure 5, the control block of Figure 3 needs to produce a PWM pattern $V_{fab}$ as shown in Figure 6.

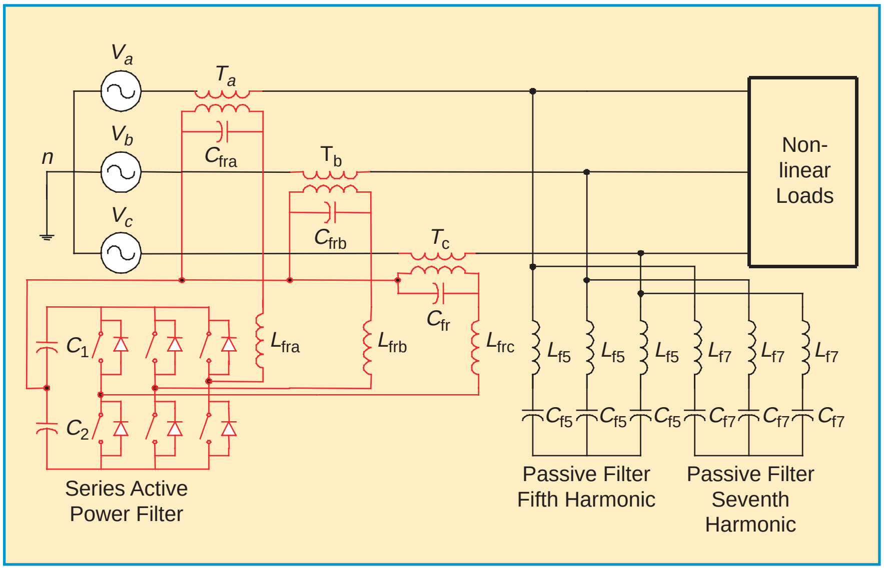

figure 7. Series active power filter topology with shunt passive filters

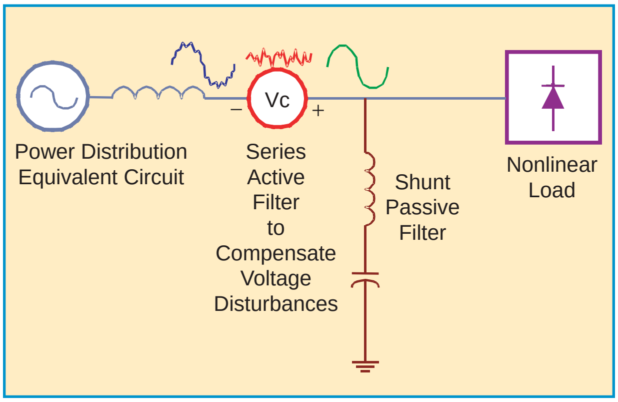

figure 8. Filter voltage generation (in red) to compensate voltage disturbances.

### Series Active Filters

Series active power filters were introduced by the end of the 1980s and operate mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series-connected filter protects the consumer from an inadequate supply-voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply and for low-power applications and represents an economically attractive alternative to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side. In many cases, series active filters work as hybrid topologies with passive LC filters. If passive LC filters are connected in parallel to the load, the series active power filter operates as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than the power distribution system. The main advantage of this scheme is that the rated power of the series active filter is a small fraction of the load kVA rating, typically 5%. However, the apparent power rating of the series active power filter may increase in case of voltage compensation. Figure 7 shows the connection of a series active power filter, and Figure 8 shows how the series filter works to compensate the voltage harmonics on the load side.

Series filters can also be useful for fundamental voltage disturbances. Figure 9 shows the series filter operation during an occasional supply voltage drop. The load voltage remains almost constant, and only small instabilities and oscillations are observed during initial and final edges of disturbance.

### Series-Shunt Active Filters

As the name suggests, the series-shunt active filter is a combination of the series active filter and the shunt active filter. An interesting combination topology is shown in Figure 10. The shunt active filter is located at the load side and can be used to compensate for the load harmonics. On the other hand, the series portion is at the source side and can act as a harmonic blocking filter. This topology has been called the Unified

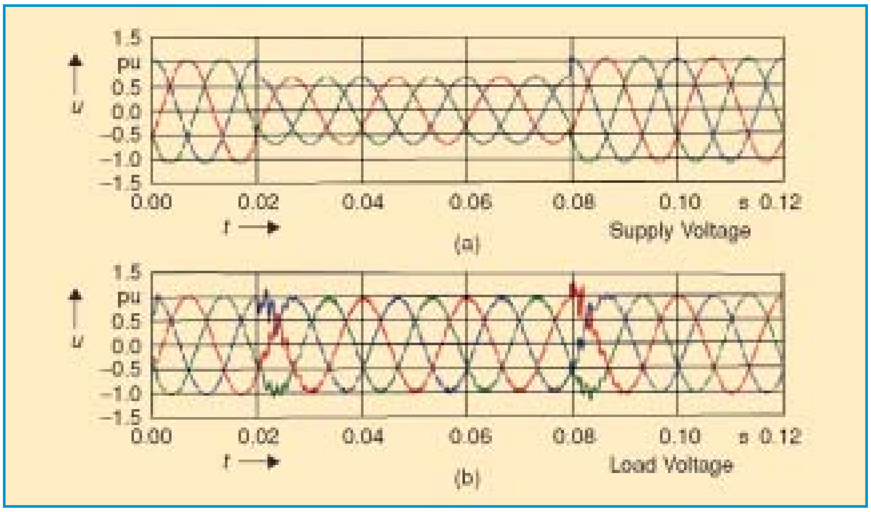

figure 9. Series active filter operation under supply voltage disturbances.

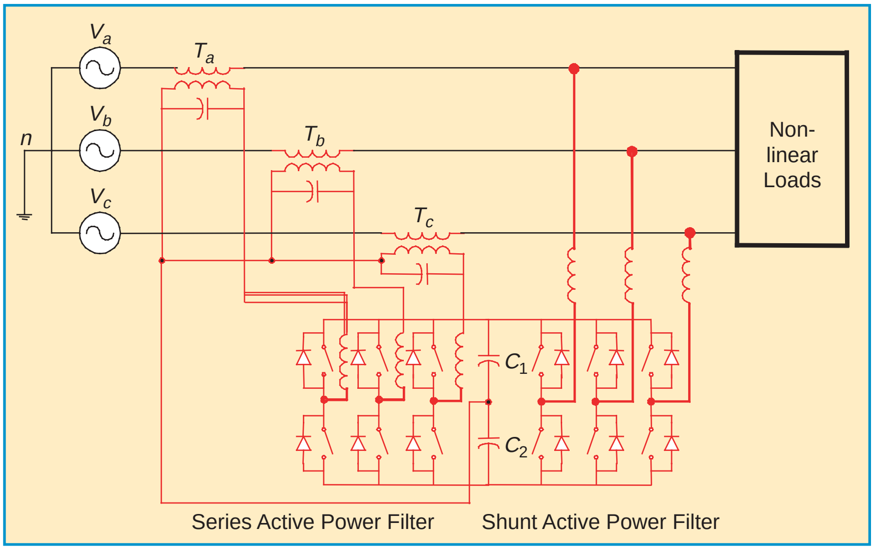

figure 10. Unified power quality conditioner.

Power Quality conditioner. The series portion compensates for supply voltage harmonics and voltage unbalances, acts as a harmonic blocking filter, and damps power system oscillations. The shunt portion compensates load current harmonics, reactive power, and load current unbalances. In addition, it regulates the dc link capacitor voltage. The power supplied or absorbed by the shunt portion is the power required by the series compensator and the power required to cover losses.

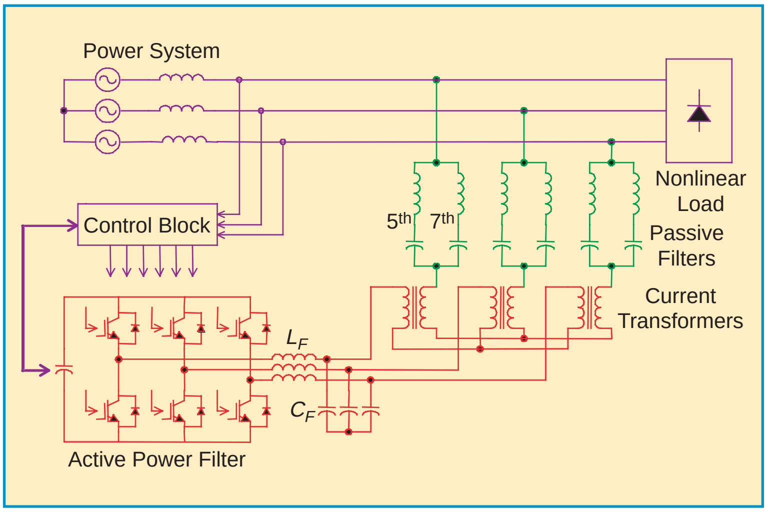

figure 11. Shunt hybrid power filter topology.

### *Hybrid Active Filters*

Hybrid power filters are a combination of active and passive filters. The series active power filter shown in Figure 7 is in fact a series hybrid filter because it has passive filters connected at the load side. A cost-effective solution for shunt hybrid power filters being investigated is the one shown in Figure 11. This topology allows the passive filters to have dynamic low impedance for current harmonics at the load side, increasing their bandwidth operation and improving their performance. This behavior is reached with only a small power rating PWM inverter, which acts as an active filter in series with the passive filter.

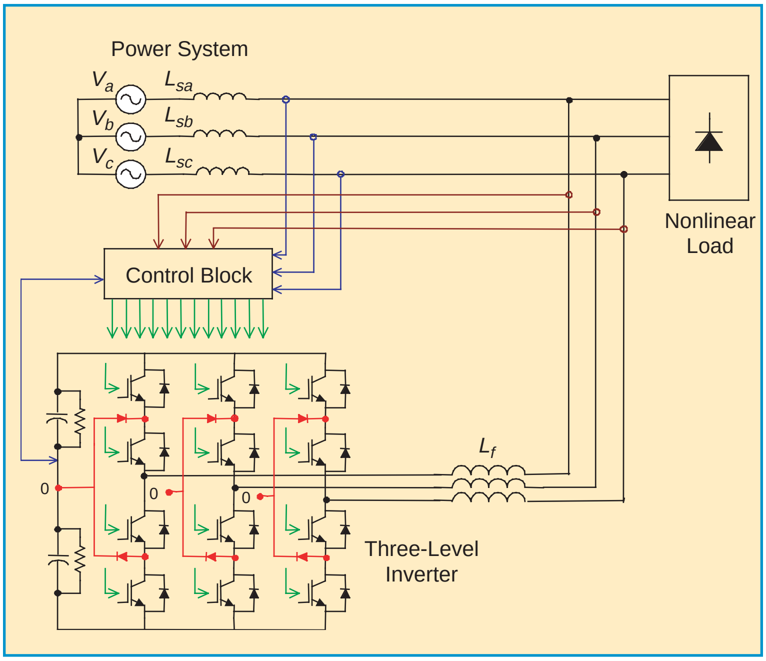

figure 12. Shunt active power filter using a three-level inverter.

## New Topologies Using Multilevel Inverters

Multilevel inverters are being investigated and recently used for active filter topologies. Figure 12 shows a shunt active power filter implemented with a three-level inverter. Three-level inverters are becoming very popular today for most inverter applications, such as machine drives and power factor compensators. The advantage of multilevel converters is that they can reduce the harmonic content generated by the active filter because they can produce more levels of voltage than conventional converters (more than two levels). This feature helps to reduce the harmonics generated by the filter itself. Another advantage is that they can reduce the voltage or current ratings of the semiconductors and the switching frequency requirements.

The more levels the multilevel inverter has, the better the quality of voltage generated because more steps of voltage can be created. A very new way to generate many steps of voltage is based on multistage connection of “H” converters with their dc voltage supplies scaled in the power of three. Using this strategy, a few converters in series are required to get very good voltage waveforms, which can be modulated in pulse width and amplitude simultaneously. In the example shown in Figure 13, amplitude modulation with 81 levels of voltage can be produced with only four “H” converters per phase (four-stage inverter). In this way, active power filters with “harmonic-free” characteristics can be implemented. Figure 14 shows a laboratory experimental implementation of the “four-stage, 81-level” shunt active power filter of Figure 13, and Figure 15 shows a comparison between current generated by a conventional PWM shunt active filter and a four-stage, 81-level, shunt active power filter.

## Applications

Active power filters are typically based on GTOs or IGBTs, voltage source PWM converters, connected to medium- and low-voltage distribution systems in shunt, series, or both topologies at the same time. In comparison to conventional passive LC filters, active power filters offer very fast control response and more flexibility in defining the required control tasks for particular applications.

The selection of equipment for improvement of power quality depends on the source of the problem (Table 1). If the objective is to reduce the network perturbations due to distorted load currents, the shunt connection is more appropriate. However, if the problem is to protect the consumer from supply-voltage disturbances, the series-connected power conditioner is most preferable. The combination of the two topologies gives a solution for both problems simultaneously.

## Current Success and Future Potential

Active power filters are offering unprecedented ability to clean the network from harmonics. They eliminate harmonics in a controlled way and can compensate load unbalances and power factor at the same time. Present devices can eliminate up to the 50th harmonic, with a programmable filtering strategy and free choice of harmonics.

With the new semiconductor devices and topologies coming in the near future, active power filters will increase their ability to keep the power distribution systems clean and free of dangerous perturbations. However, at the same time, electronic equipment will become more and more sensitive to power quality disturbances. For these two reasons, active power filters have a growing challenge in keeping the system completely free of unwanted harmonics. Research and development will have to continue for this purpose.

## Acknowledgments

The authors acknowledge the financial support from Fondecyt Project 1020460.

## For Further Reading

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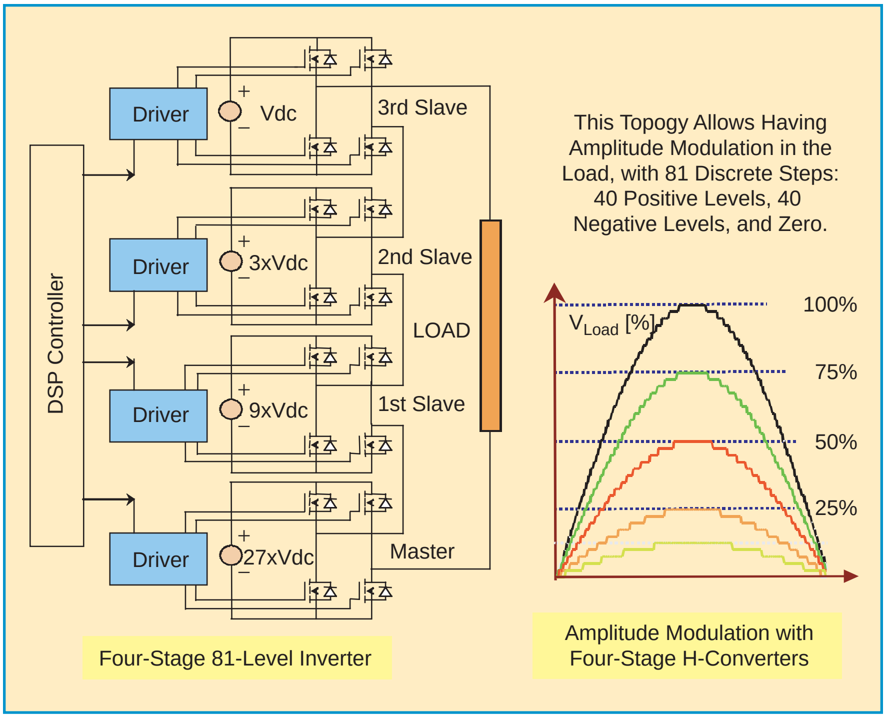

figure 13. “Four-stage, 81-level” inverter (one phase), which allows amplitude modulation.

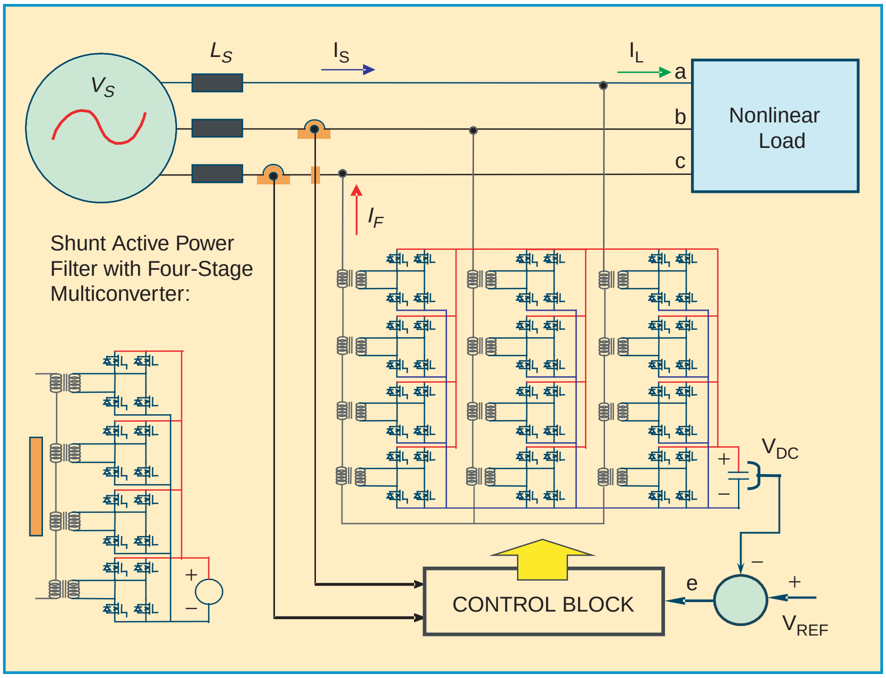

figure 14. Shunt active filter implemented with a “four-stage, 81-level” inverter.

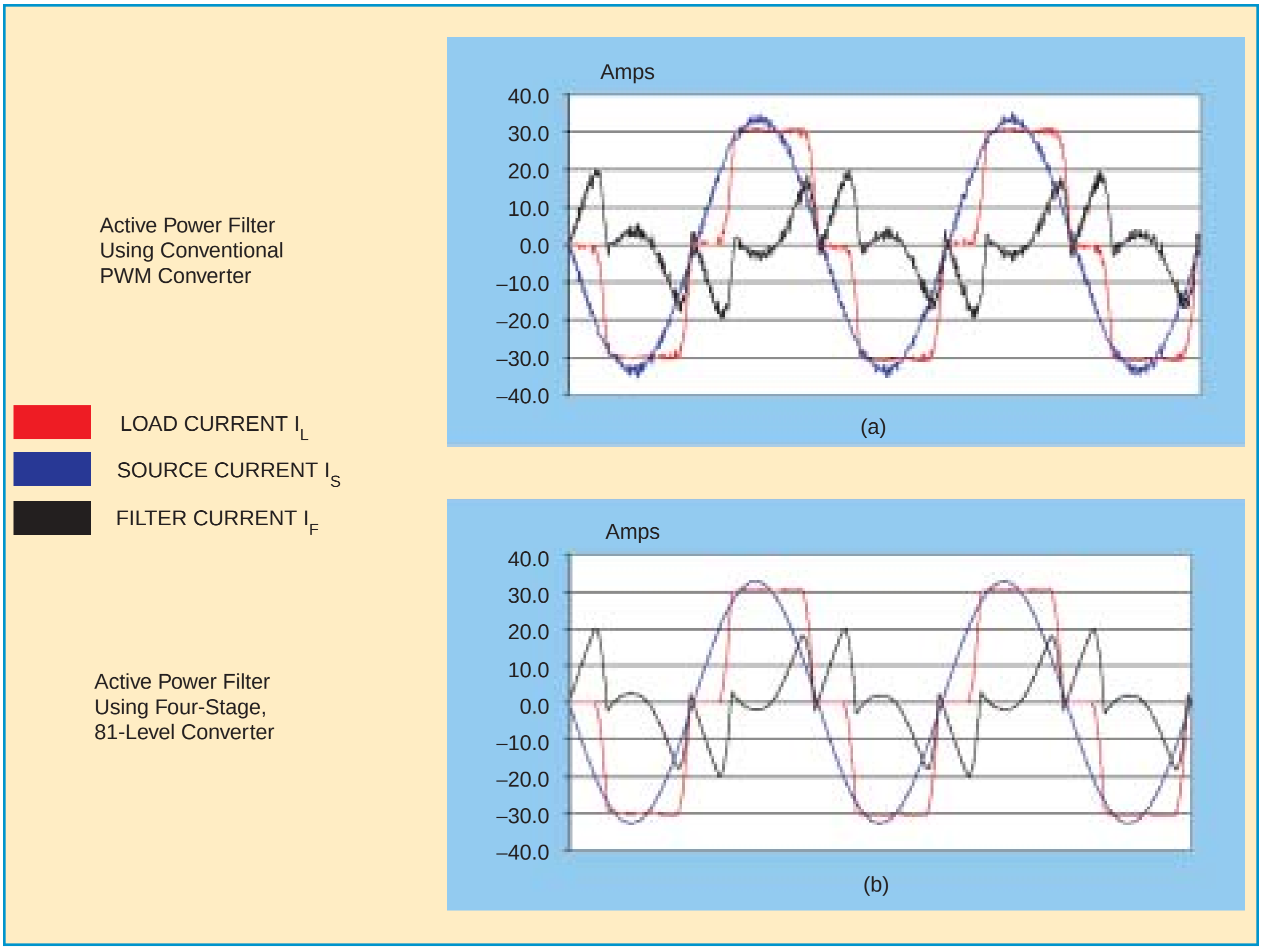

figure 15. A comparison between current generated by (a) a conventional PWM shunt active filter and (b) a four-stage, 81-level, shunt active power filter.

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## Biographies

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