A Series Active Power Filter Based on a Sinusoidal Current-Controlled Voltage-Source Inverter

Juan W. Dixon, *Senior Member, IEEE,* Gustavo Venegas, and Luis A. Morán, *Senior Member, IEEE*

***Abstract*—A series active power filter working as a sinusoidal current source, in phase with the mains voltage, has been developed and tested. The amplitude of the fundamental current in the series filter is controlled through the error signal generated between the load voltage and a preestablished reference. The control allows an effective correction of power factor, harmonic distortion, and load voltage regulation. Compared with previous methods of control developed for series active filters, this method is simpler to implement, because it is only required to generate a sinusoidal current, in phase with the mains voltage, the amplitude of which is controlled through the error in the load voltage. The proposed system has been studied analytically and tested using computer simulations and experiments. In the experiments, it has been verified that the filter keeps the line current almost sinusoidal and in phase with the line voltage supply. It also responds very fast under sudden changes in the load conditions, reaching its steady state in about two cycles of the fundamental.**

***Index Terms*—Active filters, current control, power electronics, power filters, pulsewidth-modulated power converters.**

I. INTRODUCTION

HARMONIC contamination, due to the increment of nonlinear loads, such as large thyristor power converters, rectifiers, and arc furnaces, has become a serious problem in power systems. These problems are partially solved with the help of *LC* passive filters. However, this kind of filter cannot solve random variations in the load current waveform. They also can produce series and parallel resonance with source impedance. To solve these problems, shunt active power filters have been developed [1], [2], which are widely investigated today. These filters work as current sources, connected in parallel with the nonlinear load, generating the harmonic currents the load requires. In this form, the mains only need to supply the fundamental, avoiding contamination problems along the transmission lines. With an appropriated control strategy, it is also possible to correct power factor and unbalanced loads [3] .

However, the cost of shunt active filters is high, and they are difficult to implement in large scale. Additionally, they also present lower efficiency than shunt passive filters. For these reasons, different solutions are being proposed to improve the practical utilization of active filters. One of them is the use of a combined system of shunt passive filters and series active filters. This solution allows one to design the active filter for only a fraction of the total load power, reducing costs and increasing overall system efficiency [4].

Series active filters work as isolators, instead of generators of harmonics and, hence, they use different control strategies. Until now, series active filters working as controllable voltage sources have been proposed [5]. With this approach, the evaluation of the reference voltage for the series filter is required. This is normally quite complicated, because the reference voltage is basically composed by harmonics, and it then has to be evaluated through precise measurements of voltages and/or current waveforms. Another way to get the reference voltage for the series filter is through the "p–q theory" [6]. However, this solution has the drawback of requiring a very complicated control circuit (several analog multipliers, dividers, and operational amplifiers).

To simplify the control strategy for series active filters, a different approach is presented in this paper, i.e., the series filter is controlled as a *sinusoidal current source,* instead of a harmonic voltage source. This approach presents the following advantages.

1) The control system is simpler, because only a sinusoidal waveform has to be generated.
2) This sinusoidal waveform to control the current can be generated in phase with the main supply, allowing unity power-factor operation.
3) It controls the voltage at the load node, allowing excellent regulation characteristics.

II. GENERAL DESCRIPTION OF THE SYSTEM

The circuits of Fig. 1(a) and (b) show the block diagram and the main components, respectively, of the proposed system: the shunt passive filter, the series active filter, the current transformers (CT's), a low-power pulsewidth modulation (PWM) converter, and the control block to generate the *sinusoidal template* I_{ref} for the series active filter. The shunt passive filter, connected in parallel with the load, is tuned to eliminate the fifth and seventh harmonics and presents a low-impedance path for the other load current harmonics. It also helps to partially correct the power factor. The series active filter, working as a sinusoidal current source in phase with the line voltage supply V_L, keeps "unity power factor," and presents a very high impedance for current harmonics. The CT's allow

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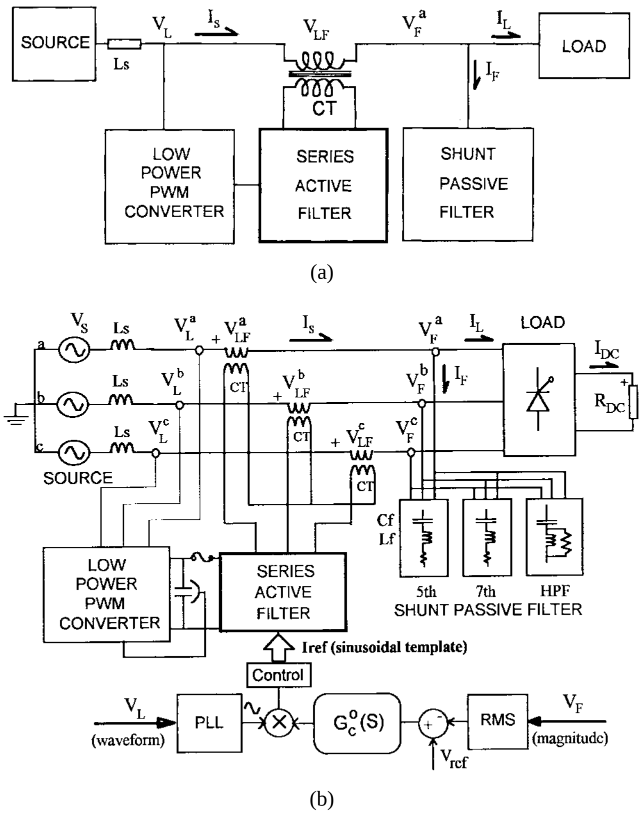


(a)

(b)

Fig. 1. Main components of the series active filter. (a) Block diagram. (b) Components diagram.

for the isolation of the series filter from the mains and the matching of the voltage and current rating of the filter with that of the power system. In Fig. 1, I_L represents the *load current,*, I_F the current passing through the *shunt passive filter,* and I_S the *source current*. The source current I_S is forced to be sinusoidal because of the PWM of the series active filter, which is controlled by I_{ref}. The *sinusoidal waveform* of I_{ref} comes from the line voltage V_L, which is filtered and kept in phase with the help of the PLL block [Fig. 1(b)].

By keeping the load voltage V_F constant, and with the same magnitude of the nominal line voltage V_L, a "zero-regulation" characteristic at the load node is obtained. This is accomplished by controlling the magnitude of I_{ref} through the error signal between the load voltage V_F and a reference voltage V_{ref}. This error signal goes through a PI controller, represented by the block $G_c^o(S)$. V_{ref} is adjusted to be equal to the nominal line voltage V_L.

The two aforementioned characteristics of operation ("unity power factor" and "zero regulation"), produce an automatic phase shift between V_F and V_L, without changing their magnitudes.

A. Power-Factor Compensation

To have an adequate power-factor compensation in the power system, the series active filter must be able to generate a voltage V_{LF} the magnitude of which is calculated through the circle diagram of Fig. 2 according to

$$V_{LF} = 2 \cdot V_L \cdot \sin\frac{\phi}{2}. \tag{1}$$

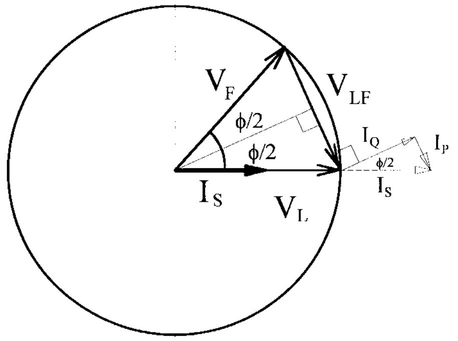


Fig. 2. Circle diagram of the series filter.

Assuming, for example, a series filter able to generate a voltage V_{LF}, the magnitude of which is 50% of the fundamental amplitude V_L, the maximum phase shift should be approximately $\phi = 29°$, which poses a limit in the ability to maintain unity power factor. The larger the value of V_{LF}, the larger the rating of the series active filter (kvar). From Fig. 2:

$$Q_{\text{FILTER}} = V_{LF} \cdot I_S \cdot \cos\left(\frac{\phi}{2}\right). \tag{2}$$

Replacing (1) into (2)

$$\begin{aligned} Q_{\text{FILTER}} &= 2\,V_F \cdot I_S \cdot \sin\left(\frac{\phi}{2}\right) \cdot \cos\left(\frac{\phi}{2}\right) \\ &= V_F \cdot I_S \cdot \sin\phi. \end{aligned} \tag{3}$$

Then, (2) corresponds to the total reactive power required by the load to keep unity-power-factor operation from the mains point of view.

It can be observed from the circle diagram of Fig. 2 that, in order to obtain unity power factor at the line terminals (V_L), a little amount of active power has to go through the series filter. However, most of this active power is returned to the system through the low-power PWM converter shown in Fig. 1. The amount of active power that has to go through the series active filter, according to Fig. 2, is given by

$$\begin{aligned} P_{\text{FILTER}} &= V_{LF} \cdot I_P \\ &= V_{LF} \cdot I_S \cdot \sin\left(\frac{\phi}{2}\right). \end{aligned} \tag{4}$$

P_{FILTER} can also be obtained through

$$\begin{aligned} P_{\text{FILTER}} &= P_{\text{LINE}} - P_{\text{LOAD}} \\ &= V_F \cdot I_S(1 - \cos\phi). \end{aligned} \tag{5}$$

Equations (4) and (5) are equivalent. They are related through (1) and the trigonometric identity $2 \cdot \sin^2(\phi/2) = 1 - \cos\phi$.

For cost considerations, it is important to keep P_{FILTER} as low as possible. Otherwise, the power ratings of both the series filter and the small PWM rectifier shown in Fig. 1 become large. This means that the capability to compensate power factor of the series filter has to be restricted. The theoretical kilovoltampere ratings of the series filter and the low-power

PWM converter can be related to the kilovoltampere rating of the load (S_{LOAD}). The kilovoltampere rating of the series filter, from Fig. 2 or from (2) and (4), is

$$\begin{aligned} S_{\mathrm{FILTER}} &= V_{LF} \cdot I_S \\ &= 2 \cdot V_F \cdot I_S \sin\left(\frac{\phi}{2}\right). \end{aligned} \tag{6}$$

As

$S_{\mathrm{LOAD}} = V_F \cdot I_S$, it yields

$$\begin{aligned} \frac{S_{\mathrm{FILTER}}}{S_{\mathrm{LOAD}}} &= 2 \sin\left(\frac{\phi}{2}\right) \\ &= \frac{V_{LF}}{V_S}. \end{aligned} \tag{7}$$

On the other hand, the relative kilovoltampere rating of the low-power PWM converter comes from (5) and is

$$\begin{aligned} \frac{S_{\mathrm{CONV}}}{S_{\mathrm{LOAD}}} &= \frac{P_{\mathrm{CONV}}}{S_{\mathrm{LOAD}}} \\ &= \frac{P_{\mathrm{FILTER}}}{S_{\mathrm{LOAD}}} \\ &= 1 - \cos\phi. \end{aligned} \tag{8}$$

If we again consider $\phi = 29°$, it yields $S_{\mathrm{CONV}} = 12.5\%$ of that of the power load. It can be noticed that when no power-factor compensation is required, both the series filter and the small PWM converter become theoretically null. However, the small converter has to supply the power losses of the series filter (which are very small), and the series filter needs to compensate the harmonic reactive power. The low-power PWM converter is a six-pack insulated-gate-bipolar-transistor (IGBT) module, inserted into the box of the series filter.

B. Harmonic Compensation

The *kvar* requirements of the series filter for harmonic compensation are given by

$$Q^h_{\mathrm{FILTER}} = V^h_{LF} \cdot I_S \tag{9}$$

where V^h_{LF} is the rms harmonic voltage at the series filter terminals and I_S is the fundamental current passing through the filter. As the series filter is a fundamental current source, harmonic currents through this filter do not exist.

The harmonic compensation is achieved by blocking the harmonic currents from the load to the mains. As the series filter works as a fundamental sinusoidal current source, it automatically generates a harmonic voltage V^h_{LF} equal to the harmonic voltage drop V^h_F at the shunt passive filter. In this way, harmonics cannot go through the mains. Then, the rms value of V^h_{LF} can be evaluated through the harmonic voltage drop at the shunt passive filter:

$$\begin{aligned} V^h_{LF} &= V^h_F \\ &= \sqrt{\sum (V^j_F)^2} \end{aligned} \tag{10}$$

where V^j_F represents the rms value of the voltage drop produced by the jth harmonic in the shunt passive filter. This voltage drop is related with the jth harmonic impedance of the filter and the jth harmonic current:

$$V^j_F = I^j_F \cdot Z^j_F. \tag{11}$$

Assuming a *six-pulse thyristor rectifier load,* with a shunt passive filter like the one shown in Fig. 1, the jth harmonic current can be evaluated in terms of the fundamental I_S:

$$I^j_F = \frac{I_S}{j} \quad (j = 6n \pm 1, \text{ with } n = 1, 2, 3 \cdots). \tag{12}$$

Replacing (10)–(12) into (9) yields

$$Q^h_{\mathrm{FILTER}} = (I_S)^2 \cdot \sqrt{\sum \left(\frac{Z^j_F}{j}\right)^2}. \tag{13}$$

The impedance Z^j_F, will depend on the parameters of the filter (C_f, L_f, R_f), and is very small for the fifth and seventh harmonics. On the other hand, Z^j_F takes a constant value for high-order harmonics (high-pass filter) and, for this reason, when j is large, the terms $(Z^j_F/j)^2$ in the summation in (13) can be neglected ($j > 60$). With these assumptions, the term represented by the square root in (13), can be as small as 3%–10% of the load base impedance. Then,

$$\frac{Q^h_{\mathrm{FILTER}}}{S_{\mathrm{LOAD}}} = 3\% - 10\%. \tag{14}$$

The small size of series filters, compared with the shunt active filters (30%–60% of S_{LOAD}), is one of the main advantages of this kind of solution. The small size of series filters also helps to keep the power losses at low values [4].

C. Power Losses

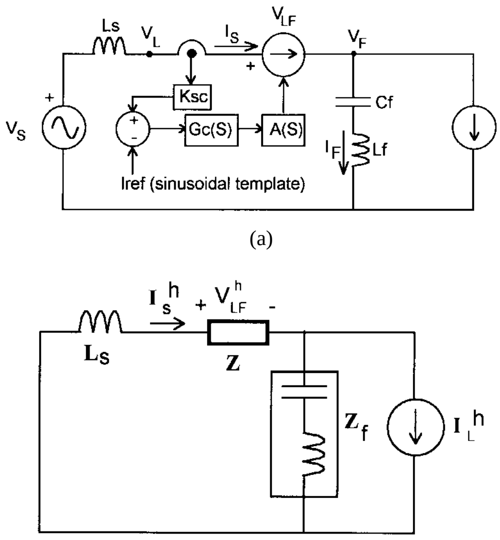
The power losses of the series active filter depend on the inverter design. In this paper, the series filter was implemented using a three-phase PWM modulator, based on IGBT switches. With this type of power switches, efficiencies over 96% are easily reached. Then, 4% power losses can be considered for the series filter, based on its nominal kilovoltampere. Now, if the filter works only for harmonic compensation, its rating power will be between 3%–10% of the nominal load rating (14). Then, power losses of the series filter represent only 0.12%–0.4% (less than 1%) of that of the kilovoltampere rating of the load [4]. However, if the series filter is also designed for power-factor compensation ($\cos\phi_{\mathrm{MAX}} = 0.875$ or $S_{\mathrm{FILTER}} = 0.5\, S_{\mathrm{LOAD}}$), the relative power losses can be as high as 2%.

III. STABILITY ANALYSIS

A. Harmonic Analysis

The following assumptions will be made to analyze the stability due to harmonics.

1) The source voltage V_s is a pure fundamental waveform.
2) The load is represented by a harmonic current source, I^h_L.



(a)

(b)

Fig. 3. (a) Single-phase equivalent circuit. (b) Harmonics equivalent circuit.

With these assumptions, the equivalent harmonic circuit for the system is shown in Fig. 3(b), where the series active filter is represented by the impedance Z. Ideally, this impedance should have an infinite value to all harmonics, because the filter is assumed to work as a sinusoidal, fundamental current source. However, as the filter is made with real components with limited gains, that is not true and, hence, it is required to know the amount of impedance the series filter is able to generate, to attenuate the harmonics going from the load to the source.

According to Fig. 3(a), the voltage V_{LF} generated by the series filter is given by

$$V_{LF} = (I_S \cdot K_{sc} - I_{\rm ref}) \cdot A(s) \cdot G_C(S) \tag{15}$$

where

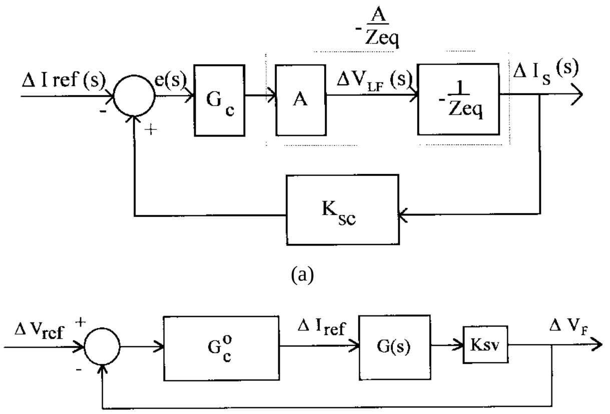
I_S	source current (controlled by the series filter);
K_{SC}	current sensor gain;
$I_{\rm ref}$	sinusoidal template, in phase with the mains supply;
$A(s)$	transfer function of series active filter and CT's;
$G_C(S)$	$= K(1 + K_i(s))$ proportional-integral gain (PI controller).

The sinusoidal template $I_{\rm ref}$ is controlled to keep only the in-phase fundamental value of the total load current. Then $I^h_{\rm ref} = 0$, and the harmonic voltage V^h_{LF} can be evaluated from (15), yielding

$$V^h_{LF} = I^h_S \cdot K_{sc} \cdot A(s) \cdot G_C(S). \tag{16}$$

From (16), the impedance Z the filter is able to generate operating as a current source is given by

$$\begin{aligned} Z &= \frac{V^h_{LF}}{I^h_S} \\ &= K_{sc} \cdot A(s) \cdot G_C(S). \end{aligned} \tag{17}$$



(a)

(b)

Fig. 4. Control loops of the series active filter. (a) For the line current I_S. (b) For the load voltage V_F.

Then, the larger the value of (17), the better the series filter. The relation between the harmonics going through the line supply (I^h_S) and the harmonics generated by the load (I^h_L) can be obtained with the help of Fig. 3(b). From this figure, the transfer function I^h_S/I^h_L is

$$\frac{I^h_S}{I^h_L} = \frac{Z_f}{Z_S + Z_f + Z} \tag{18}$$

where

$$Z_S = sL_S$$

and

$$Z_f = \frac{s^2 \cdot L_f \cdot C_f + 1}{C_f s}.$$

Modeling $A(s)$ in a simplified form, just as a proportional gain "A," and replacing "Z" from (17) into (18), yields

$$\frac{I^h_S}{I^h_L} = \frac{b_2 \cdot s^2 + b_1 \cdot s + b_0}{a_2 \cdot s^2 + a_1 \cdot s + a_0} \tag{19}$$

where

$$\begin{aligned} b_2 &= L_f * C_f \\ b_1 &= 0 \\ b_0 &= 1 \\ a_2 &= C_f * (L_f + L_S) \\ a_1 &= K_{sc} * A * K * C_f \\ a_0 &= K_{sc} * A * K * K_i * C_f + 1. \end{aligned}$$

Applying the Routh–Hurwitz criterion for stability, the system is stable when all the coefficients of the characteristic equation have the same sign, or $a_i > 0$. As this condition is always satisfied, the system is stable for the harmonic components.

B. Fundamental Analysis

The control implemented for the fundamental has two control loops, which have to accomplish the following two well-defined objectives.

1) The line current has to follow the reference, which has been designed to be a pure sinusoidal (fundamental),

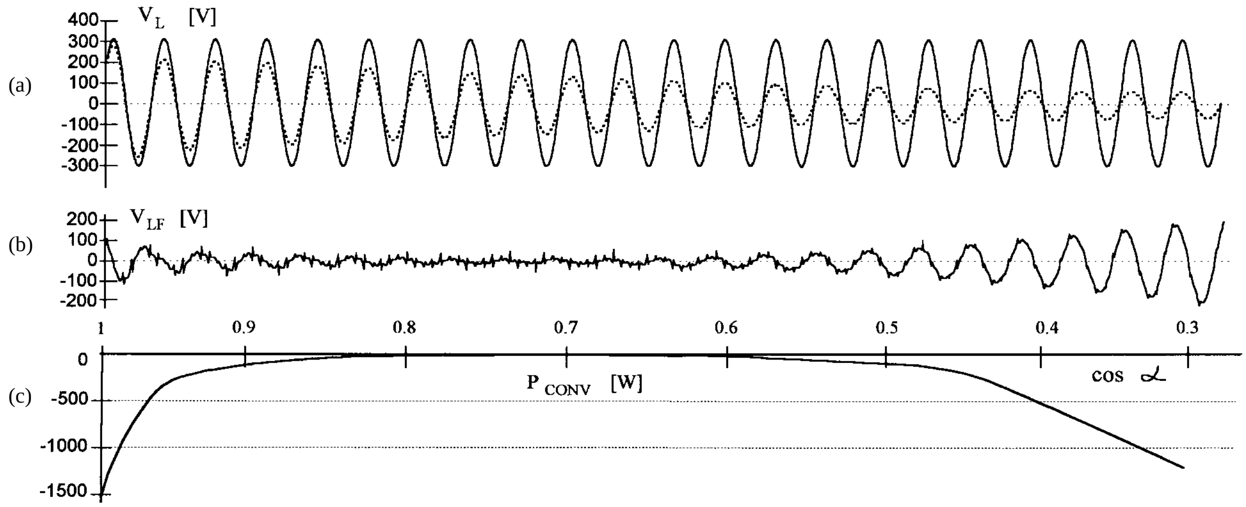


Fig. 5. Simulation results for a smooth change in the firing angle α (50 Hz). (a) Line voltage V_L [100 V/div] (220 V phase to neutral). (b) Series filter voltage V_{LF} [100 V/div]. (c) Active power through the small PWM rectifier.

in phase with the mains voltage (unity-power-factor operation) and with variable amplitude.

2) The module of the load voltage V_F has to keep the nominal value of the mains voltage V_S (zero regulation operation).

These two control loops are now described.

1) Line Current Control: The control loop implemented for the line current is shown in Fig. 4(a). From this figure, the following equations are obtained:

$$\frac{\Delta I_S(s)}{\Delta I_{\mathrm{ref}}(s)} = \frac{\dfrac{A\cdot G_C(S)}{Z_{eq}}}{1+\dfrac{A\cdot K_{SC}\cdot G_C(S)}{Z_{eq}}} \tag{20}$$

$$\frac{\Delta I_S(s)}{\Delta I_{\mathrm{ref}}(s)} = \frac{A\cdot G_C(S)}{Z_{eq}+A\cdot K_{SC}\cdot G_C(S)} = T(s)$$

with

$$G_C(S) = K\left(1+\frac{K_i}{s}\right). \tag{21}$$

In these equations, Z_{eq} is the total equivalent impedance of the load, which is comprised of the nonlinear load and the shunt passive filter. Under steady state ($s \approx 0$) $G_c \approx \infty$ and, hence, $T(s) \approx 1/K_{sc}$. This means that the current follows the reference template. However, it is important to note that (21) is strongly dependent on the load, which is included in the term Z_{eq}.

2) Load Voltage Control V_F: The control loop for the load voltage V_F is shown in Fig. 4(b), where K_{sv} is the gain of the voltage sensor and G_C^0(S) is a PI controller. To get the complete transfer function of the control loop, it is necessary to obtain the transfer function of $G(s)$. Let

$$\Delta V_F(s) = Z_{eq}\cdot \Delta I_S(s) \Rightarrow \Delta I_S(s) = \frac{\Delta V_F(s)}{Z_{eq}}. \tag{22}$$

Now, from (21) and (22),

$$\Delta I_{\mathrm{ref}}(s) = \left(\frac{1}{Z_{eq}\cdot T(s)}\right)\cdot \Delta V_F(s) \tag{23}$$

and from Fig. 4(b)

$$\frac{\Delta V_F}{\Delta I_{\mathrm{ref}}} = Ksv\cdot G(s). \tag{24}$$

Equating (23) and (24) finally yields

$$G(s) = \frac{Z_{eq}\cdot T(s)}{Ksv}. \tag{25}$$

Finally, the equations for the complete control loop are obtained:

$$\frac{\Delta V_F(s)}{\Delta V_{\mathrm{ref}}(s)} = \frac{G_c^o(S)\cdot T(s)\cdot Z_{eq}}{1+G_c^o(S)\cdot T(s)\cdot Z_{eq}}. \tag{26}$$

It can be noticed from (26) that the control loop is strongly dependent on the load impedance, because it is included in the term Z_{eq}. Then, both the loops have to consider the load effect in the design of the series active filter.

IV. SIMULATIONS AND EXPERIMENTAL RESULTS

For the simulations and experiments, a shunt passive filter with a quality factor $Q = 6$ was used. The high-pass filter (HPF) shown in Fig. 1 was not connected. That means the passive filter being used presents a higher impedance to harmonics than normal industrial filters. The source inductance $L_S = 1$ mH. In simulations, 220-V phase-to-neutral line supply was used, and the load was a six-pulse thyristor rectifier. In experiments, only 70-V phase-to-neutral supply was used, and the load was a diode rectifier, instead of thyristor converter. The dc-link voltage at the experimental series filter was set at 300-V dc (max). As the turns ratio of the TC's was 3.4, the maximum V_{LF} generated at the line side was around 40-V rms. For this reason, only 70 V were used in the power supply for the experiments. Otherwise, power-factor compensation could not be shown. Table I shows the values of C and L used in the shunt passive filter.

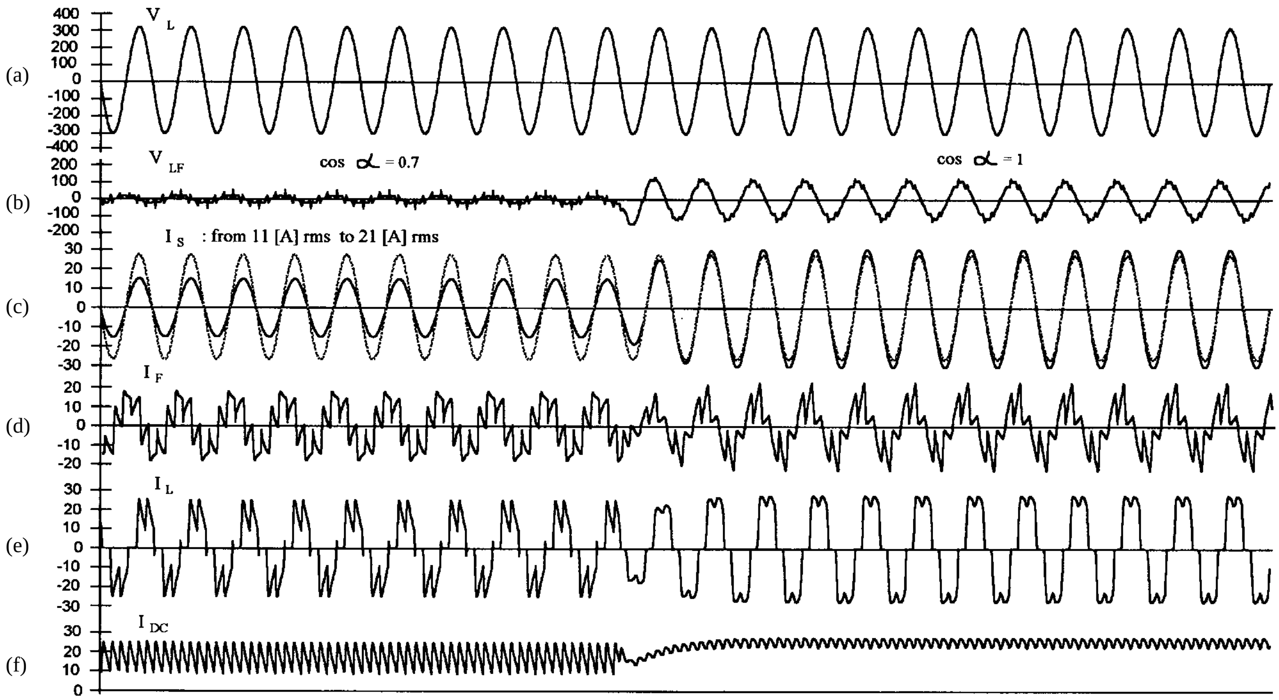


Fig. 6. Simulation results for a step change in the firing angle α (50 hz). (a) Line voltage V_L [100 V/div] (220 V phase to neutral). (b) Series filter voltage V_{LF} [100 V/div]. (c) Line current I_S [10 A/div]. (d) Filter current I_F [10 A/div]. (e) Load current I_L [10 A/div]. (f) Thyristor rectifier current I_{DC} [10 A/div].

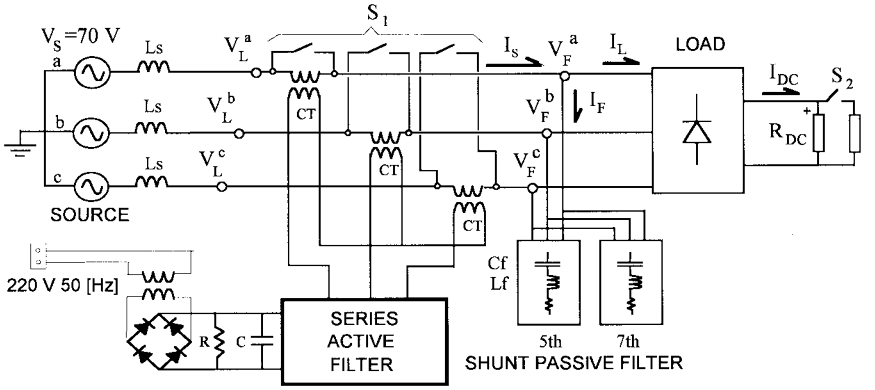


Fig. 7. Circuit implemented for the experiments.

TABLE I
PASSIVE FILTERS USED

	C [uF]	L[mH]
Fifth filter	120	3.3
Seventh filter	18	11

A. Simulations

Fig. 5 shows the simulation results obtained when the firing angle α changes smoothly from 0° to 72° $(\cos\alpha = 1$ to $\cos\alpha = 0.3)$. The dc load $R_{\mathrm{DC}} = 20\ \Omega$ [see Fig. 1(b)]. The first oscillogram [Fig. 5(a)] shows the line voltage V_L and the source current I_S (in dotted lines). Both the waveforms are in phase at all angles. The second oscillogram [Fig. 5(b)] shows the series filter voltage V_{LF}, and the third [Fig. 5(c)] shows the active power returned to the system by the small PWM converter. As it was stated in Section II, power-factor compensation requires that some amount of active power comes into the series filter. This active power is then returned to the system by the small PWM converter shown in Fig. 1. It can be observed that, due to the reactive power generation of the shunt passive filter, unity power-factor operation requires almost negligible active power through the series filter in the interval $\cos\alpha = 0.95$–$\cos\alpha = 0.5$. At $\cos\alpha = 1$, the amount of active power passing through the series filter and returned to the mains is around 1500 W, which represents about 10% of that of the thyristor rectifier (14.8 kVA). However, at $\cos\alpha = 0.95$, P_{CONV} quickly decreases to less than 300 W. For this particular example, power-factor compensation for $\cos\alpha < 0.3$ is not recommended, because the power required by the small PWM rectifier becomes important. The fundamental rms value of V_{LF} is directly related to the amount of active power flowing into the series filter, and this situation can also be observed in Fig. 5.

Fig. 6 shows the simulation results obtained when the firing angle of the thyristor bridge suddenly changes from $\cos\alpha = 0.7$ to $\cos\alpha \approx 1$. The load is exactly the same as in Fig. 5

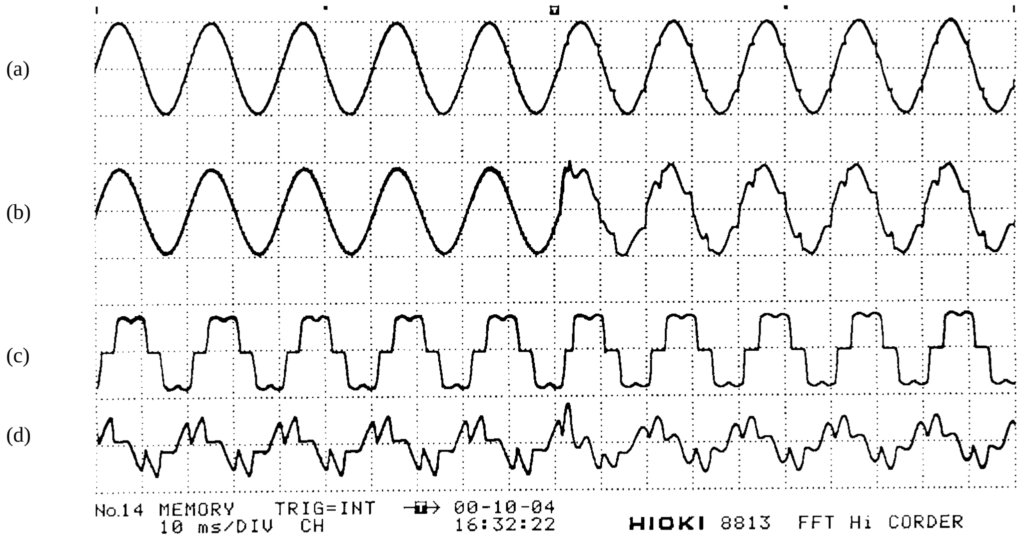
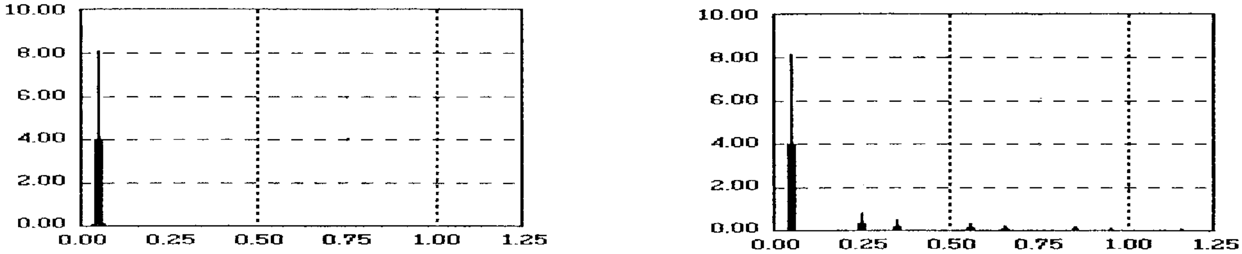


Fig. 8. The series filter is suddenly disconnected from the system. (a) Line voltage V_L [100 V/div] (70 V phase to neutral). (b) Line current I_S [10 A/div]. (c) Load current I_L [10 A/div]. (d) Filter current I_F [10 A/div].



(a)

(b)

Fig. 9. Spectrum of the input line current I_S. (a) With the proposed series active filter. (b) Without the series filter.

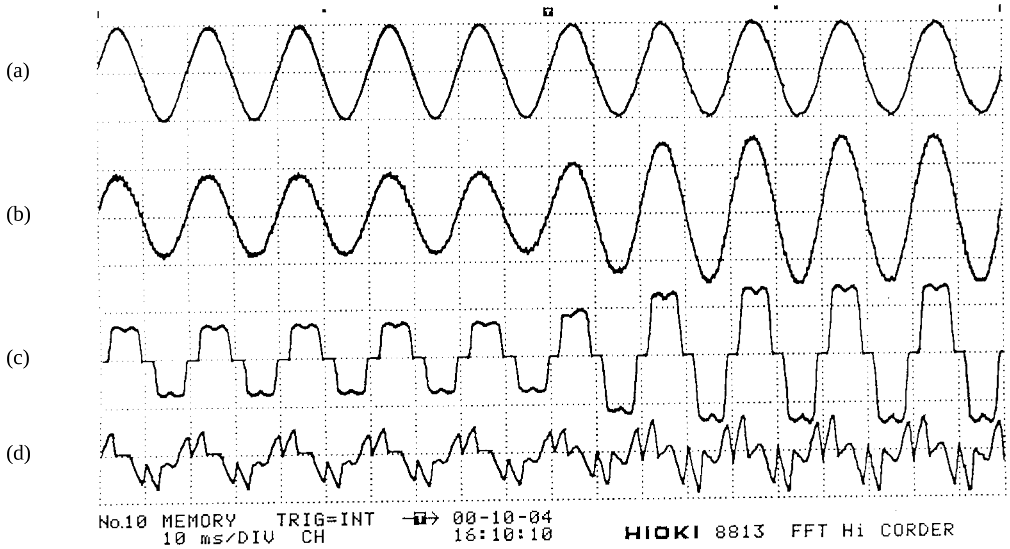


Fig. 10. Transient response for a sudden change in the dc load current. (a) Line voltage V_L [100 V/div] (70 V phase to neutral). (b) Line current I_S [10 A/div]. (c) Load current I_L [10 A/div]. (d) Filter current I_F [10 A/div].

($R_{\mathrm{DC}} = 20\,\Omega$). The first oscillogram [Fig. 6(a)] shows the line voltage V_L. The second [Fig. 6(b)] shows the filter voltage V_{LF}, and the third [Fig. 6(c)] shows the source current I_S. In Fig. 6(c), the line voltage waveform is also displayed to show the unity power-factor operation. It can be observed that I_S is perfectly sinusoidal and in phase with the voltage V_L. On the other hand, the voltage V_{LF} shown in (b) increases when $\cos\alpha = 1$, because under these conditions the series filter has to compensate the leading power-factor operation of the load, due to the reactive power generated by the shunt passive filter. At $\cos\alpha = 0.7$, the load (thyristor rectifier plus shunt passive filter) is working near unity power factor and, hence, the fundamental of the voltage V_{LF} is close to zero. The oscillograms in Fig. 6(d)–(f) show the filter current I_F, the thyristor rectifier input current I_L, and the thyristor rectifier output current I_{DC}, respectively. The complete set of oscillograms in Fig. 6 show the good dynamic response of the proposed system.

B. Experiments

The proposed series filter was implemented and tested using a 2-kVA IGBT three-phase inverter. Fig. 7 shows the circuit implemented for the experiments. A diode bridge rectifier, instead of a thyristor rectifier, was used. Due to voltage limitations of the dc-link electrolytic capacitors (350-V dc), the dc-link voltage in the series active filter was limited to 300-V dc. As was already explained, this restriction limited the voltage V_L to 70-V rms (phase to neutral). For simplicity, the small PWM converter was replaced by a single-phase diode rectifier, directly connected to the dc link of the series filter. Therefore, the power going through the series filter cannot be returned to the system, and is dissipated in "R." The experiments displayed in the paper are: 1) series filter disconnection and 2) step increase of power at the dc link of the diode rectifier.

Fig. 8 shows the experimental results obtained when the series filter is suddenly disconnected from the system by closing the switch S_1 in Fig. 7. It can be observed that, when the filter is connected, the waveform of the line current I_S is almost sinusoidal. After the removal of the active filter, the current I_S deteriorates. This experimental result clearly demonstrates the effectiveness of the series active filter. The oscillograms of Fig. 8 show the following: Fig. 8(a) the line voltage V_L (70-V rms); Fig. 8(b) the line current I_S (6-A rms); Fig. 8(c) the load current I_L (diode rectifier); and Fig. 8(d) the shunt passive current I_F.

Fig. 9 shows the spectrum of the input line current I_S, with and without the proposed series active filter. Without the series filter, some amount of fifth, seventh, eleventh, and thirteenth harmonics go through the power system. With the series filter, these harmonics almost disappear from the line. They are forced to go through the shunt passive filter.

Fig. 10 presents the transient response obtained for a sudden change in the dc load current, by closing the switch $S2$ in Fig. 7. The resistance R_{DC} changes from 20 to 10 Ω. The oscillograms correspond to the following: Fig. 10(a) line voltage V_L; Fig. 10(b) line current I_S; Fig. 10(c) load current I_L; and Fig. 10(d) shunt passive filter current I_F. It can be noticed that, after two cycles, the line current reaches its steady state, keeping its sinusoidal waveform (the line current has changed from 8 to 16 A peak). In the experiments, the switching frequency of the series filter is about 12 kHz.

V. CONCLUSIONS

A series active power filter, working as a sinusoidal current source, in phase with the mains voltage, has been developed and tested. The amplitude of the fundamental current in the series filter is controlled through the error signal generated between the load voltage and a preestablished reference. The control allows an effective correction of power factor, harmonic distortion, and load voltage regulation. In the experiments, it has been demonstrated that the filter responds very fast under sudden changes in the load conditions, reaching its steady state in about two cycles of the fundamental. Compared with other methods of control for a series filter, this method is simpler to implement, because it is only required to generate a sinusoidal current, in phase with the mains voltage, the amplitude of which is controlled through the error in the load voltage.

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