

A SERIES ACTIVE POWER FILTER BASED ON A SINUSOIDAL CURRENT CONTROLLED VOLTAGE SOURCE INVERTER.

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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 pre-established reference. The control allows an effective correction of power factor, harmonic distortion, and load voltage regulation.

I. INTRODUCTION

The harmonic contamination, due to the increment of non-linear loads, such as power converters, rectifiers and arc furnaces, has become a serious problem in power systems. These problems were partially solved in the past with the help of LC passive filters. However, this kind of filters cannot solve random variations in the load current waveform, produced by spikes or sudden amplitude variations. To solve these problems, shunt active power filters have been developed [1,2], which are today widely investigated. These filters work as a current sources, connected in parallel with the non-linear load, generating the harmonic currents the load requires. In this form the mains only needs to supply the fundamental, avoiding contamination problems along the transmission lines. Besides, with an appropriated control strategy, it is also possible to correct power factor and unbalanced loads [3].

However, the shunt filter has some drawbacks, because until now it is difficult to implement in large scale and the cost is high. For these reasons, different solutions are being proposed to reduce the cost of the active filters. One of them is the use of series active filters, which need to be designed only for a fraction of the total load power [4,5], because most of the harmonics are forced to go through a shunt LC passive filter, connected in parallel with the non-linear load. In previous works, the control strategy implemented for these series filters, make them work as a voltage sources [6].

In this work, the series filter works as a sinusoidal current source, with the following advantages: a) the control system is simpler because only a sinusoidal current needs to be modulated, b) the modulation method to control the current becomes simpler for the same reason, and c) it controls the voltage at the load allowing good regulation characteristics.

II. GENERAL DESCRIPTION OF THE SYSTEM

A. Basic Principle

The circuit of figure 1 shows the main components of the series filter implemented in this work.

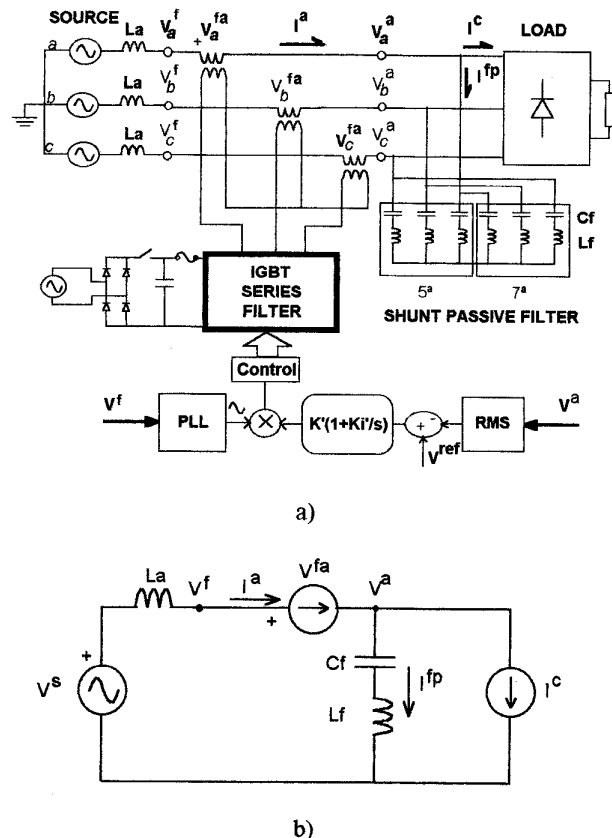


Figure 1. Main components of the series active filter.

- a) three-phase diagram
 b) single-phase equivalent circuit

In this figure, I^c is the total load current, I^{fp} is the current passing through the LC passive filter, and I^a the source current, which is forced to be sinusoidal because of the series active filter represented by the current source I^a .

This series active filter has been implemented with an IGBT inverter.

The passive filter presents a low impedance path for the load current harmonics and also helps to correct partially the power factor. On the other hand, the series active filter, working as a sinusoidal current source in phase with the mains supply, completes the correction of the power factor and presents a very high impedance for current harmonics, allowing an effective elimination of harmonics going through the mains.

The correct operation of the active filter must ensure a good regulation at the load point. Then, the load voltage V^a is kept constant and with the same magnitude of the mains voltage V^f . This operation is reached by phase-shifting the power angle between V^f and V^a without changing the magnitudes. This action is shown in the circle diagram of Fig. 2

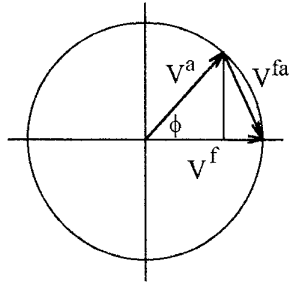


Figure 2. Circle Diagram of the Series Filter

Then, to have an adequate power factor compensation in the power system, the series active filter must be able to generate a voltage V^{fa} whose magnitude is calculated through the circle diagram of Fig. 2 according with:

$$V^{fa} = 2 \cdot |V^a| \cdot \sin \frac{\phi}{2} \quad (1)$$

Then, if for example the series filter has the capability to generate a voltage whose magnitude is 25% of the fundamental amplitude, the maximum phase-shift should be 15° , which poses a limit in the ability to compensate power factor.

To get the sinusoidal current reference template for the series filter, a sinusoidal waveform, in phase with the mains supply is generated. The magnitude of this sinusoidal template is controlled with the error signal obtained in the control block, which compares the load voltage with a reference magnitude. This reference magnitude is adjusted to be equal to the amplitude of the mains voltage. Finally, a PI controller takes the error signal to ensure an excellent voltage regulation at the load terminals.

To control the series filter, the magnitude of the sinusoidal template is compared with the filter current and forced to follow the template. Then, the series filter will be generating a sinusoidal current in phase with the mains

supply, acting as a high impedance path for the harmonic currents. To do that, the series filter has to generate the fundamental voltage V^{fa} , described in eq.(1), plus the harmonic voltage V^{fa}_h required to produce the high impedance effect.

Let's call Z_{eq} the total equivalent impedance of the load, which comprises the non-linear load, and the shunt passive filter. Then, the following equation can be written:

$$V^{fa} = V^f - Z_{eq} I_a \quad (2)$$

By linearizing eq(2) around an operating point, it yields:

$$\Delta V^{fa} = -Z_{eq} \Delta I_a \quad (3)$$

Eq.(3) gives the relation between the error current and the necessary error voltage being generated for compensation purposes. The higher the impedance Z_{eq} , the smaller the error current. This equation also shows that the error current is proportional to the negative value of the error voltage.

III. STABILITY ANALYSIS

A. Harmonic Analysis.

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

- i) The source V^s is a pure fundamental waveform.
- ii) The load is represented by a harmonic current source.

With these assumptions, the equivalent harmonic circuit for the active filter, can be represented with the help of figure 3.

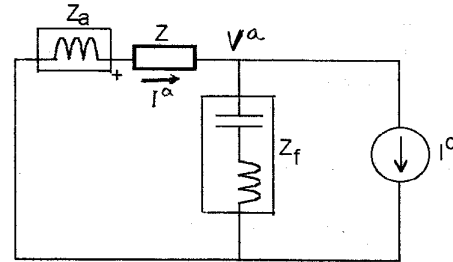


Figure 3. Harmonics equivalent circuit.

The series active filter is represented by the impedance Z in figure 3. 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 current source is able to generate, to attenuate the harmonics going from the load to the source.

The internal loop (current control) of the current source can be represented by:

$$V^{fa} = (I^a \cdot K_{sc} - I^{ref}) \cdot A(s) \cdot K \cdot \left(1 + \frac{K_i}{s}\right) \quad (4)$$

where:

K_{sc} = current sensor gain.

$A(s)$ = transfer function of inverter and transformers.

V^{fa} = voltage generated by the current source.

$K (1 + K_i/s)$ = proportional-integral gain.

I^{ref} = sinusoidal template, in-phase with mains supply.

The amplitude of I^{ref} is controlled to keep only the in-phase fundamental value of the total load current. Then, the harmonic voltage that the series active filter has to produce, to avoid the circulation of current harmonics through the series filter, can be deducted through eq.(4), yielding:

$$V_{harmonic}^{fa} = I_{harmonic}^a \cdot K_{sc} \cdot A(s) \cdot K \cdot \left(1 + \frac{K_i}{s}\right) \quad (5)$$

where:

$$I_{harmonic}^a = I^a \cdot K_{sc} - I^{ref} \quad (6)$$

Then, the impedance the inverter is able to generate, operating as a current source is given by:

$$Z = K_{sc} \cdot A(s) \cdot K \cdot \left(1 + \frac{K_i}{s}\right) \quad (7)$$

With this, the transfer function, deducted through figure 3, and with the value of Z given by eq. (7) is:

$$\frac{I^a}{I^c} = \frac{Z_f}{Z_a + Z_f + Z} \quad (8)$$

where: $Z_a = sL_a$

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 filling eq.(8) with the values of (7), it yields:

$$\frac{I^a}{I^c} = \frac{b_2 \cdot s^2 + b_1 \cdot s + b_0}{a_2 \cdot s^2 + a_1 \cdot s + a_0} \quad (9)$$

with:

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

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 two well defined objectives:

a) The line current has to follow the reference, which has been designed to be a pure sinusoidal (fundamental), in phase with the mains voltage, and with variable amplitude.

b) The module of the load voltage V^a , has to keep the nominal value of the mains voltage.

These two control loops are described now:

a) Line current control.

The control loop implemented for the line current is shown in figure 4.

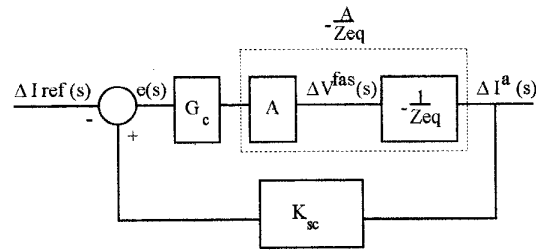


Figure 4. Control loop for the line current.

From this figure, the following equations are obtained:

$$\frac{\Delta I^a(s)}{\Delta I_{ref}(s)} = \frac{A \cdot G_c}{1 + \frac{A \cdot K_{sc} \cdot G_c}{Z_{eq}}} \quad (10)$$

$$G(s) = \frac{Z_{eq} \cdot T(s)}{K_{sv}} \quad (16)$$

$$\frac{\Delta I^a(s)}{\Delta I_{ref}(s)} = \frac{A \cdot G_c}{Z_{eq} + A \cdot K_{sc} \cdot G_c} = T(s) \quad (11)$$

$$\text{with } G_c = K \left(1 + \frac{K_i}{s} \right)$$

Then, 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 eq.(11) is strongly dependent of the load, which is included in the term Z_{eq} .

b) Load voltage control, V^a

The control loop for the load voltage is shown in the figure 5:

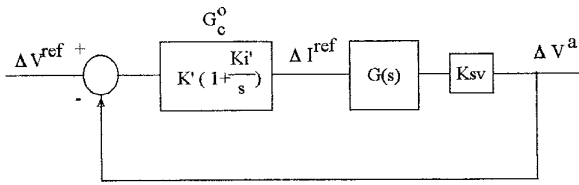


Figure 5. Control loop of the load voltage, V^a

In figure 5, K_{sv} is the gain of the voltage sensor. To get the complete transfer function of the control loop, it is required to obtain the transfer function of $G(s)$. Let:

$$\Delta V^a(s) = Z_{eq} \cdot \Delta I^a(s) \Rightarrow \Delta I^a(s) = \frac{\Delta V^a(s)}{Z_{eq}} \quad (12)$$

Now, from eqs.(11) and (12):

$$\Delta I_{ref}(s) = \left(\frac{1}{Z_{eq} \cdot T(s)} \right) \cdot \Delta V^a(s) \quad (13)$$

and from figure 5:

$$\Delta I_{ref} = G_c^0 \cdot (\Delta V^{ref} - \Delta V^a) \quad (14)$$

$$\frac{\Delta V^a}{\Delta I_{ref}} = K_{sv} \cdot G(s) \quad (15)$$

Equaling (13) and (15), it finally yields:

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

$$\frac{\Delta V^a(s)}{\Delta V^{ref}(s)} = \frac{G_c^0 \cdot T(s) \cdot Z_{eq}}{1 + G_c^0 \cdot T(s) \cdot Z_{eq}} \quad (17)$$

It can be noticed from eq.(17), that the control loop is strongly dependent of 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. That means that the passive filter being used, presents a higher impedance to harmonics than normal industrial filters. TABLE 1 shows the values of C and L used in the shunt passive filter.

	C [uF]	L[mH]
5 th filter	120	3.3
7 th filter	18	11

Table 1. Passive filters used

Some simulations were performed to verify the feasibility of the series filter proposed. The figure 6 shows the results obtained when the filter is suddenly connected to the system.. The first oscillogram (a) shows the load current I^c . The second (b), shows the current through the shunt passive filter I^{fp} , and the third (c) shows the line current I^a .

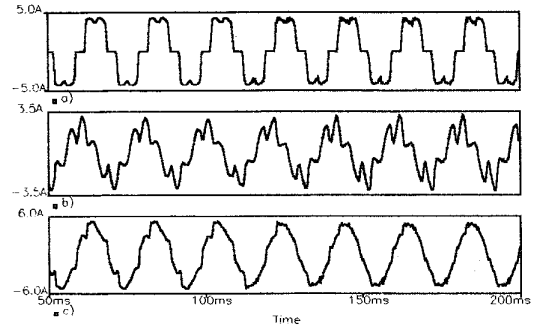


Figure 6. Simulation results for a line current $I^a = 4[A]$
a) load current I^c
b) passive filter current I^{fp}
c) line current I^a

It can be observed that the waveform of the line current improves, becoming almost sinusoidal after two cycles. On the other hand, the current through the LC filter (shunt passive filter), results more distorted because after the connection of the series active filter, all the harmonics generated for the load (rectifier), have to go through the LC filter.

The proposed circuit was implemented and tested, using a 2 kVA, IGBT, three-phase inverter. The figure 7 shows two oscillograms. The first one without the series active filter, and the second one with the filter installed. In both the cases, the amplitude of the current is 8 [A]. Each oscillogram displays: a) the line voltage, b) the line current, and c) the load current. The figures clearly show the great improvement in the line current when the series active filter is connected.

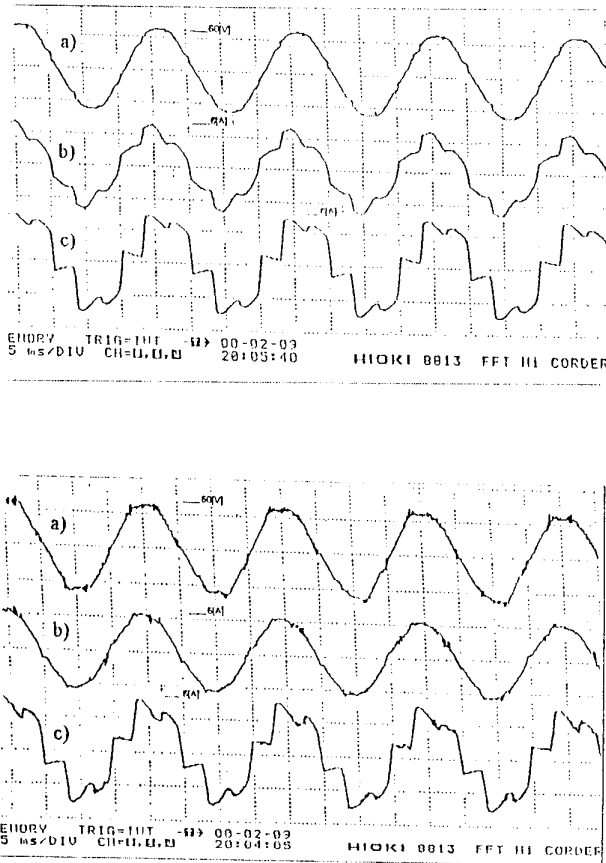


Figure 7. Line current improvement.
 First oscillogram: *without series filter*
 Second oscillogram: *with series filter*
 a) Phase-to-neutral source voltage (60 [V])
 b) line current (8 [A] peak)
 c) load current (9 [A] peak)

The figure 8 shows the implementation of the power circuit to get transient results, by changing the level of the load current.

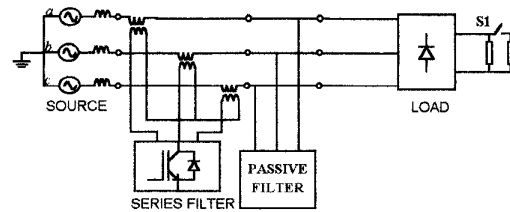


Figure 8. Power circuit for transient results.

The figure 9 presents the transient response, obtained for a sudden change in the load current, by closing the switch S1 in figure 8. Again the oscillograms correspond to: a) line voltage, b) line current, and c) load current. It can be noticed that after two cycles, the line current reaches its sinusoidal waveform, with an amplitude a little higher (the line current has changed from 6 to 8 [A] peak). The line voltage appears a little distorted due to the PWM produced by the series filter. This drawback can be attenuated using higher switching frequencies. In the experiments, the switching frequency is about 2 [kHz].

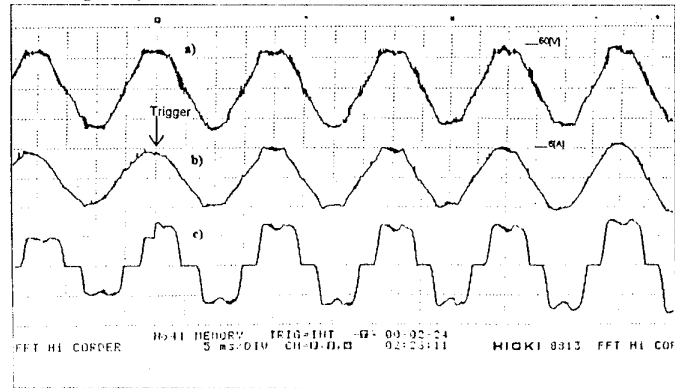


Figure 9. Transient response for a sudden load change.
 a) source voltage
 b) line current
 c) load current.

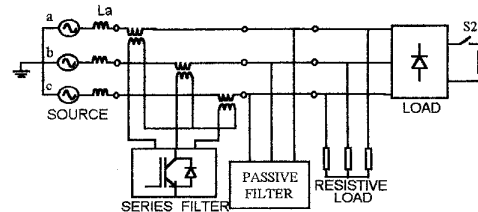


Figure 10. Power connection for a mixed load.

The figure 10 shows the circuit used for a change in the load type, from only resistive to a load combined with a rectifier.

The figure 11 shows the experimental result obtained, using the circuit of figure 10. It can be seen that the load current begin to be distorted after the connection of the rectifier, but the line current, after two cycles of transient phenomena, remains sinusoidal. The level of the line current has changed from 7 to 8 [A].

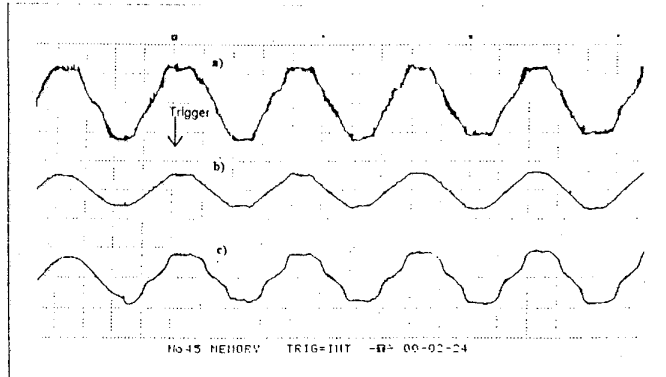


Figure 11. Transient response changing the type of load
a) Phase-to-neutral source voltage
b) line current
c) load current

The transient experiments show that the system responds reaching steady state in about two cycles, which is fast enough for most of the industrial applications. The parameters used in the experiments were not optimized, and hence it is feasible to get better results.

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 pre-established 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 around two cycles of the fundamental. Compared with other methods of control for series filter, this method is simpler to implement because it is only required to generate a sinusoidal current, in phase with the mains voltage, whose amplitude is controlled through the error in the load voltage.

One of the drawbacks of the system is that the PWM pulsations produce voltage distortion. To reduce this problem, a higher switching frequency is recommended.

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