A Control System for a Three Phase Active Power Filter which Simultaneously Compensates Power Factor and Unbalanced Loads

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Abstract - The efectiveness of an active power filter depends basically on three characteristics: a) the modulation method used, b) the design characteristics of the PWM modulator and c) the method implemented to generate the reference template. For the last characteristic there are many methods, most of them complicated and hence difficult to implement and adjust. In this paper, a new method, which its main characteristic is its simplicity, is presented. This method is useful for shunt active power filters and is capable to eliminate harmonics, compensate power factor and correct unbalance problems simultaneously. Experimental results, with the reference template obtained with the method, are presented in the paper.

INTRODUCTION

Active power filters play an important role in reducing harmonic contamination in power lines. In the past twenty years, the proliferation of nonlinear loads such as static power converters, arc furnaces and others, have resulted in a variety of undesirable phenomena in the operation of power systems, which in many cases cannot be solved with passive LC filters. The basic difference between LC filters and active filters is that the active filters have the capability to compensate randomly varying currents.

One of the most popular principles of operation used to implement topologies for active power filters is the "Shunt Active Power Filter", shown in Figure 1. A current source is connected in parallel with the nonlinear load and controlled to generate the harmonic currents needed for the load. In this form, the mains only needs to generate the fundamental current, avoiding contamination problems along the power line. In most cases, the load also needs reactive power, which also can be generated by the same current source, reducing the amount of fundamental current from the mains. Then, this kind of filter can simultaneously compensate harmonics and power factor problems [1-3]. In three-phase umbalanced loads it is also possible to redistribute and equilibrate the mains phase-currents, providing that the total amount of power coming from the mains is the same as the amount required for the load. In this form, the filter can solve three problems at once: a) elimination of unwanted harmonics, b) power factor compensation and c) redistribution of power to keep the system balanced.

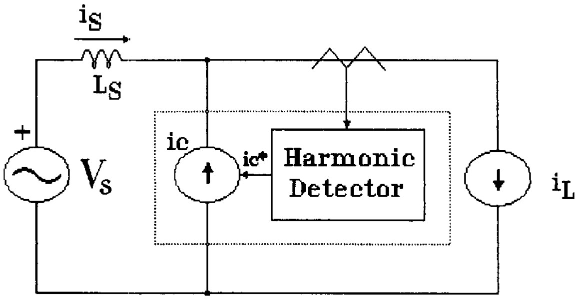

Figure 1. Operation principle of shunt active power filter

In the practical implementation of this kind of filter, force commutated, current-controlled voltage-source inverters (CC-VSI), as the one shown in Figure 2, are widely used. Three aspects have to be considered in the design of such a solution [4,5]: a) the parameters of this inverter such as type of power switches and the values of link inductances; b) modulation method used and c) the control method used to generate the harmonic reference template. This last aspect is analysed in this paper and a very simple and eccurate solution has been developed. This solution, based on Sample and Hold circuits (S&H), eliminates complicated transformations and mathematical operations such as multiplications and divisions.

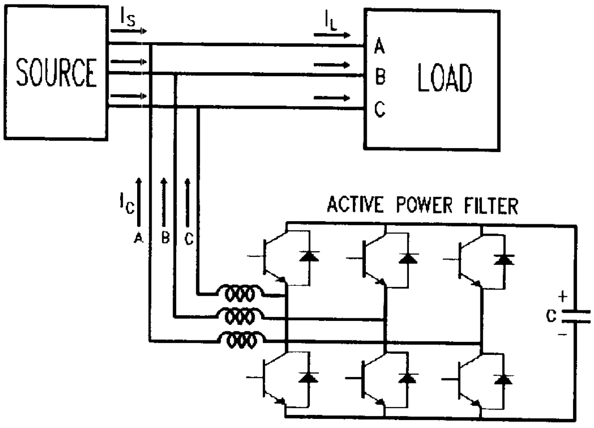

Figure 2. Current-controlled VSI as a shunt active power filter.

Most of the methods proposed to generate the current reference waveform for active power filters are based on the theory of instantaneous reactive power [6,7,8]. This theory gives a very precise solution to get the reference template, and permits to obtain a clear differentiation between instantaneous active and

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reactive power. However, there are some particularities in this method. First, in many cases, and from the mains point of view, is more convenient the separation of the average active power in a defined period instead of the instantaneous active power, because the first solution avoids flikers in the mains. Another problem is the complication of the electronic circuit necessary to obtain the reference, which includes transformations, multiplications and divisions, making it difficult to implement and adjust.

THE PROPOSED METHOD

The method proposed to generate the compensation currents is very simple and permits a good transient response. It is explained with the help of Figure 3.

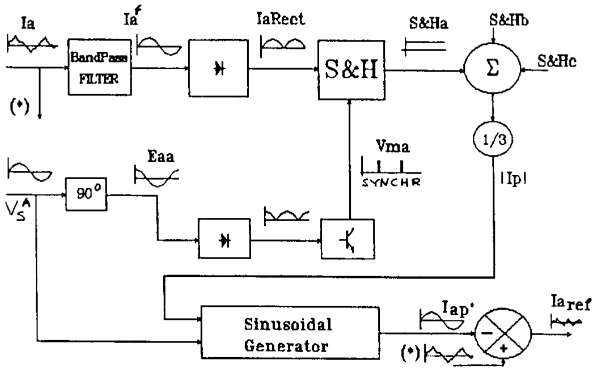

Figure 3. Control block of the proposed method.

The current in each phase of the load is filtered to get the fundamental phase-current. A "sample and hold" circuit, synchronized with the peak value of the phase-to-neutral voltage, allows to get three dc signals, which are proportional to the amplitude of the active component of the current for each phase. These three dc signals, with the information of the total active power in the load, are averaged to balance the system. Then, by multiplying the averaged dc signal for a set of balanced reference waveforms (in phase with the mains voltage), three in-phase balanced currents for each phase are obtained. Finally, these currents are sustracted from the real load currents to get the compensation currents mentioned above. These compensation currents are then able to correct the harmonic distortion, the power factor and the umbalances of the load. In this form, the mains see the load as a pure balanced resistance.

The proposed method avoids multiplications, divisions and transformations, and is based on the recovering of the fundamental active currents (in-phase currents) in the load. Once this currents are obtained, they are substracted to the total load currents to get the desired reference waveform.

Let to assume that I_L is the total load current in one phase. This current contains basically three components:

$$I_L = I_P + I_Q + I_H \qquad (1)$$

where I_P, I_Q and I_H are the fundamental active current (in-phase component), the in-quadrature fundamental (reactive component) and the harmonic component (also reactive) respectively. The active filter has to be capable to eliminate, from the source point of view, I_Q and I_H. This objective can be reached in two different forms: a) by evaluating I_Q and I_H, or b) by substracting I_p from I_L. The last method is developed in this work, using a simple method to obtain I_P.

First, the load currents are sensed and filtered to eliminate the armonics (I_H), and then the total fundamental currents (one for each phase) are obtained. These currents have to be separated in their active and reactive components (in-phase and in-quadrature currents respectively):

$$I = I_P + I_Q \qquad (2)$$

where $$I_P = |I|\cos\phi \qquad (3)$$

represents the required magnitude of the in-phase fundamental current. Eq.(3) allows, through the knowledge of the phase angle "ϕ" of the current, evaluate I_P for each phase. However, the angle "ϕ" does not need to be known, because the term "$|I|\cos\phi$" can be obtained from the time function of the fundamental when the mains voltage reaches its maximum value. Let:

$$v_S(wt) = V_M \sin(wt) \qquad (4)$$

be the instantaneous phase-to-neutral source voltage, and:

$$i_L^f(wt) = |I|\sin(wt+\phi) \qquad (5)$$

the instantaneous fundamental load current. At the instant (angle) $wt=\pi/2$:

$$v_S(wt) = V_M \qquad (6)$$

and

$$i_L^f(wt) = |I|\sin(\pi/2+\phi) = |I|\cos\phi = I_P \qquad (7)$$

Then, the instantaneous value of $i_L^f(wt)$, at $wt=\pi/2$ is exactly the magnitude of the in-phase fundamental current. This value is reached when $v_S(wt)=V_M$ and hence I_P can be obtained each time the mains voltage reaches its maximum value. Figure 4 explains graphically the idea.

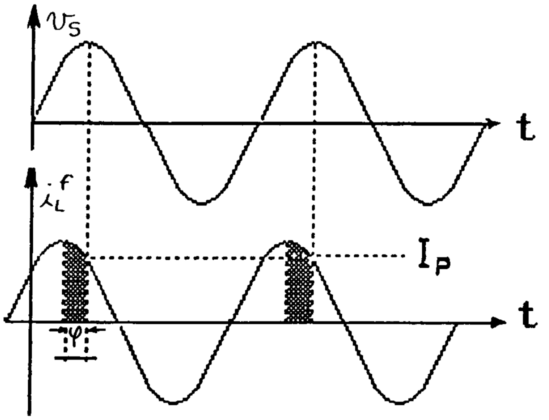

Figure 4. Method used to capture I_P.

Then, following the method explained graphically in figure 4, I_P is captured and "stored" until the next sample of I_P is obtained to replace the old one. This action is executed with the help of "Sample and Hold" (S&H) circuits, which are synchronized with the mains and permit to "actualize" I_P in each half a cycle. The synchronization pulses to trigger the S&H circuits are generated through the "zero-crossing" signals, obtained from a set of "in-quadrature voltages". These "in-quadrature voltages" are generated in the control block with a three-phase, Dz0 conection, signal transformer. It is convenient to say that it has been assumed that the mains is a perfectly balanced three-phase power supply.

With the method explained above, I_P is captured in a form of a "dc signal" per each phase. Now, if the load is balanced, the three values of I_P obtained, I_P^A, I_P^B and I_P^C are identical. However, they will not be the same in the general case and then, the umbalanced characteristics of the load will be transfered to the source. To avoid it, the three magnitudes of I_p can be averaged, because the total amount of power remains the same. Let:

$$P_L = |V_S^A| I_P^A + |V_S^B| I_P^B + |V_S^C| I_P^C \qquad (8)$$

be the total active power to the load. As the power source is balanced,

$$|V_S^A| = |V_S^B| = |V_S^C| = V_S \qquad (9)$$

it yields:

$$P_L = V_S(I_P^A + I_P^B - I_P^C) \qquad (10)$$

Let now to get the averaged value of I_P, I_P^*:

$$I_P^* = (I_P^A + I_P^B + I_P^C)/3 \qquad (11)$$

Replacing (11) in (10) and because of (9):

$$|V_S^A| I_P^A + |V_S^B| I_P^B + |V_S^C| I_P^C = 3V_S I_p^* \qquad (12)$$

Then, the averaged value of I_P does not change the amount of active power. This is important because most of the active power filters cannot produce active power. Now, the averaged current I_P^*, have to be transformed from a dc signal to a mains frequency sinusoidal waveform. To do that it is required to get a sinusoidal waveform in phase with the mains and multiply it by I_P^*. The multiplication can be avoided, using a simple transistor, fed with the dc signal I_P^*, which acts as a power supply. The base of the transistor is then activated with a fundamental waveform in phase with the mains (this waveform does not need to be perfectly sinusoidal). The output of the transistor will be a square wave with an amplitude proportional to I_P^*. This output is then filtered with a band-pass filter and a sinusoidal waveform, proportional to I_P^* is obtained. The Figure 5 shows the circuit used to implement this "multiplier".

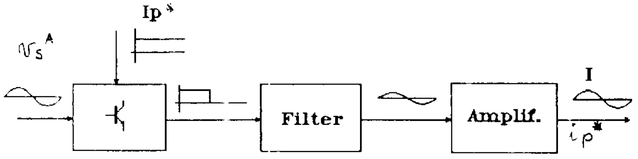

Figure 5. Circuit to obtain the sinusoidal active component.

The circuit of figure 5 is implemented for each one of the three phases to get three sinusoidal waveforms, which are proportional to the fundamental active power. Finally, these three sinusoidal waveforms are substracted from the load current to get the desired current reference templates:

$$I_{REF}^A = I_L^A - I_P^* \qquad (13)$$

$$I_{REF}^B = I_L^B - I_P^* \qquad (14)$$

$$I_{REF}^C = I_L^C - I_P^* \qquad (15)$$

The control circuit also has the capability to avoid flickers and transient phenomena in the source, produced by sudden changes in the load current. To do this, the control system makes soft variations of I_P^* during these moments. However, this action will require to have energy storage components in the active power filter. Hence, the design of the control system have to take in account the characteristics of the power filter.

SIMULATIONS AND EXPERIMENTAL RESULTS

A number of simulations with different operating conditions were developed. The figure 6 shows the resultant reference template obtained for the phase "A", when the load current has the waveform shown in this figure. The calculated source current results perfectly sinusoidal.

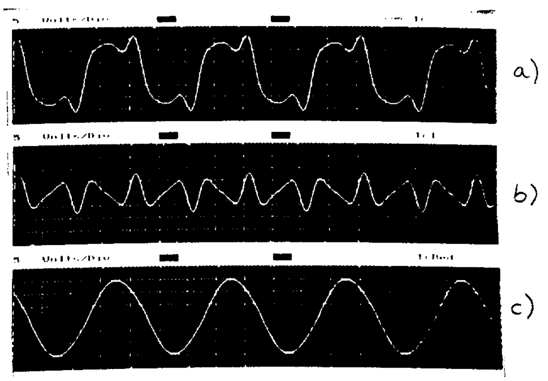

Figure 6. Current waveforms for a normal operation
a) total load current I_L^A
b) reference template I_{REF}^A
c) resultant source current

The figure 7 shows a simulation of a step change in the phase angle. The angle "ϕ" changes from 65° to 0°. It can be observed that the amplitude of the source current increases to supply the higher amount of active power required. The angle of the source current remains at $\phi = 0°$.

To get experimental results, a three-phase control board was implemented and tested with the help of the circuit shown in figure 8. The lost of one phase, with balanced resistive load and source voltage with harmonic distortion was implemented. The oscillograms of figure 9 show the lost phase (I_L^A), the three reference templates generated by the control block (I_{REF}^A, I_{REF}^B and I_{REF}^C) and the resultant source currents. It can be noted that these currents remain sinusoidal and perfectly balanced but their amplitudes decrease slowly. As it was mentioned above, this is convenient for the source because flickers and transient phenomena are avoided.

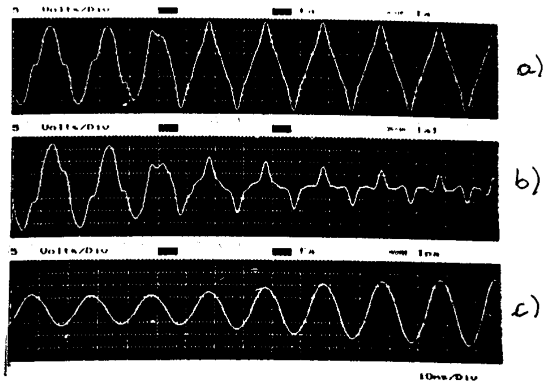

Figure 7. Current waveforms for a step change in phase angle
a) total load current I_L^A
b) reference template I_{REF}^A
c) resultant source current

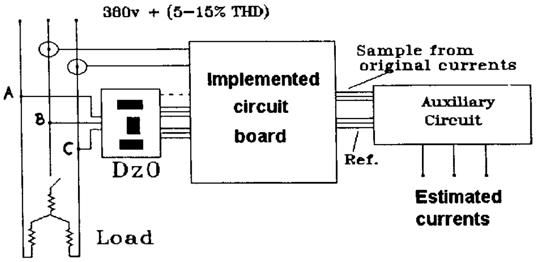

Figure 8. Experiment for lost of one phase

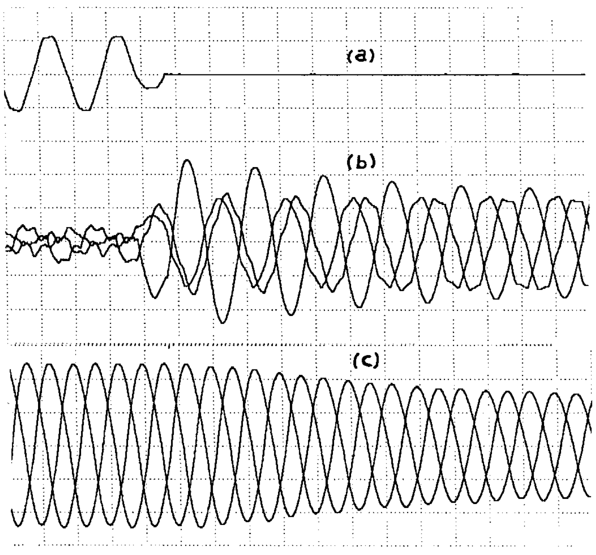

Figure 9. Step response for lost of one phase
a) total load current I_L^A
b) reference templates I_{REF}
c) resultant source currents

A second experiment, to simulate a sudden phase change was implemented with a synchronous machine, which also contributed with the generation of slot harmonics. To realize this experiment, the resistive load shown in figure 8 was changed and replaced by the synchronous machine. The machine was operated at constant power and the excitation current was suddenly interrupted. The results of this experiment are shown in figure 10. It can be noted that source current remains in phase with the voltage and the magnitude does not change.

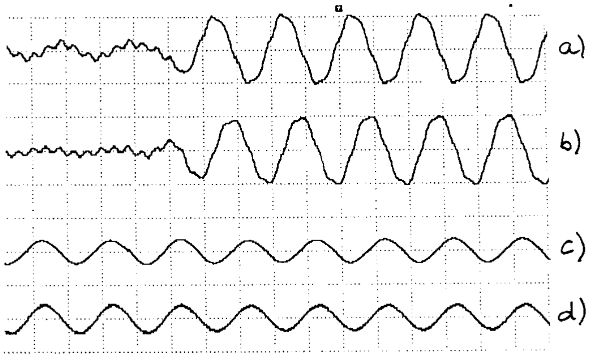

Figure 10. Currents for a step change in phase angle
a) machine current I_L^A
b) reference template I_{REF}^A
c) resultant source current
d) source voltage V_S^A

CONCLUSIONS

A simple and efficient control block, to generate current reference templates for active power filters has been implemented and tested. The control allows the elimination of unwanted harmonics, correction of power factor and correction of desequilibrium in the load currents. The device also avoids that sudden changes of the active power load be transmitted to the power source. Another interesting characteristics of the proposed method of control is that multiplications, divisions and transformations are eliminated, making the control system cheap, simple and more reliable. To be able to take full advantage of this control board, it would be required to have a very fast power converter and an appropiate modulation method to switch the semiconductors.

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