A simple control scheme for hybrid active power filter

D. Rivas, L. Morán, J. Dixon and J. Espinoza

Abstract: A simple control scheme for hybrid active power filters connected in parallel is presented and analysed. The hybrid active power filter combines the compensation characteristics of resonant passive and active power filters. The series active power filter is implemented with a three-phase pluse-width modular (PWM) voltage-source inverter. The proposed scheme is able to compensate displacement power factor and current harmonics simultaneously. The combination of passive and active power filters allows a better performance compensation of high-power nonlinear loads. The proposed control scheme is discussed in terms of principles of operations under steady-state and transient conditions. The design and implementation of the power and control circuits are reported. Finally, key predicted results are verified experimentally on a 5 kVA prototype model.

1 Introduction

Active power filters have been shown to be an interesting alternative to compensate power distribution systems. Series and shunt topologies have already been presented and discussed in the technical literature. Shunt active power filters are more suitable to compensate current harmonic components and the displacement power factor, while series topologies present better characteristics to compensate voltage distortions. Hybrid topologies composed of passive LC filters connected in series to an active power filter have already been proposed and discussed previously [1–5]. Hybrid topology significantly improves the compensation characteristics of simple passive filters, making the active power filter available for high-power applications, at a relative lower cost. Moreover, compensation characteristics of already installed passive filters can be significantly improved by connecting a series active power filter at its terminals, giving more flexibility to the compensation scheme.

Control schemes for the active power filter are normally based on the instantaneous reactive power reference [1] or synchronous reference frame [4], requiring complex circuitry for their implementation, or a DSP to implement digitally. Also, compensation characteristics of both schemes depend significantly on the voltage waveform distortion. A simple control scheme implemented with analogue technology was presented in [5]. Although the reported control scheme was simple and easy to implement, the compensation characteristics were not good enough due to the frequency response of the passive filter used to obtain the control reference waveforms.

The hybrid active power filter topology presented is shown in Fig. 1. The active power filter is implemented with a three-phase PWM voltage-source inverter, operating at fixed switching frequency, and connected in series to the passive filter through a coupling transformer. The proposed control scheme shown in Fig. 2 generates the reference signals required to compensate current harmonic components and the displacement power factor of high power nonlinear loads. The active power filter forces the utility line currents to become sinusoidal and in phase with the respective phase-to-neutral voltage, improving the compensation characteristics of the passive filter.

2 Principles of operation

Passive filters have been extensively used to compensate current harmonics and the displacement power factor in power distribution systems. However, the poor flexibility of passive filters to adapt to variable load compensation requirements constitutes a major disadvantage. This results in power factor overcompensation in the case of low-load power operation, or in poor harmonic filtering in case the frequency spectrum of the load current changes in magnitude or in frequency. In the hybrid topology (Fig. 1), since the active power filter is connected in series to the passive filter through a coupling transformer, it imposes a voltage signal at its primary terminals that forces the circulation of current harmonics through the passive filter, improving its compensation characteristics, independently of the variations in the selected resonant frequency of the passive filter. By changing the voltage waveform at the terminal of the primary winding of the coupling transformer, the compensation characteristics of the passive scheme are changed. By adjusting the amplitude of the voltage fundamental component, the amount of reactive power required by the load can be controlled precisely. If current harmonic compensation must be improved, the active power filter generates a voltage component at the terminal of the coupling transformer primary winding, changing the passive filter frequency response, and therefore increasing the harmonic compensation performance.

The principles of operation for current harmonic and power factor compensation are explained with the single-phase equivalent circuit shown in Fig. 3.

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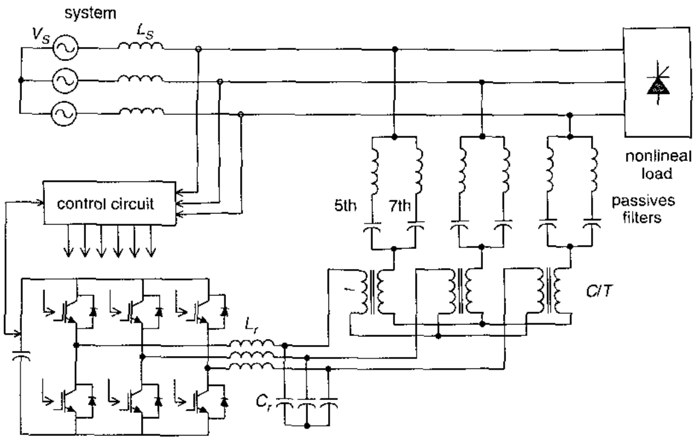


Fig. 1 *Hybrid active power filter configuration*

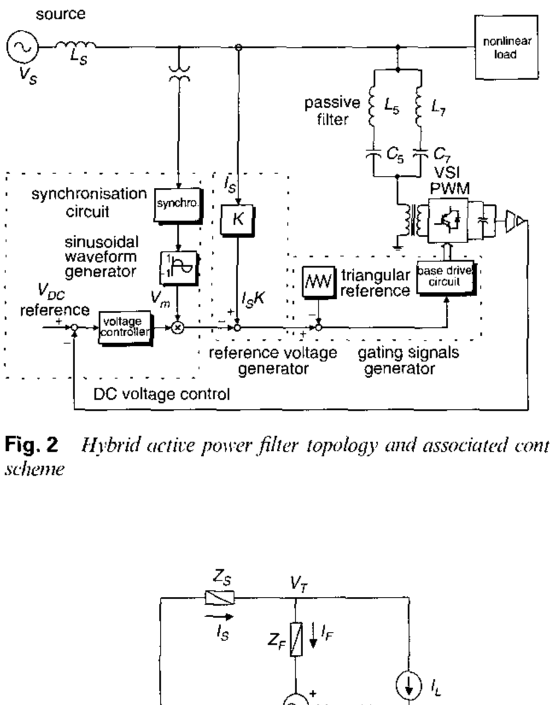


Fig. 2 *Hybrid active power filter topology and associated control scheme*

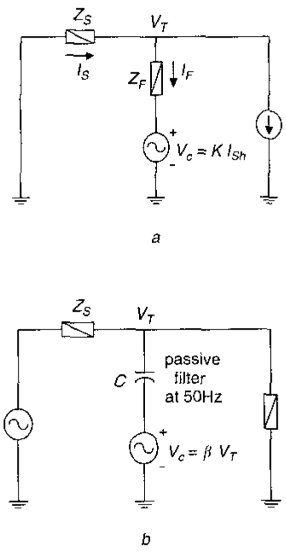


Fig. 3 *Single-phase equivalent circuit of the proposed hybrid active power filter scheme*
(*a*) current harmonic compensation
(*b*) displacement power factor compensation

In the current harmonic compensation mode, the active filter improves the filtering characteristic of the passive filter by imposing a voltage harmonic waveform at its terminals with an amplitude value equal to

$$V_{Ch} = K \cdot I_{Sh} \tag{1}$$

where I_{Sh} is the harmonic content of the line current. If the AC mains voltage is pure sinusoidal, perfect harmonic compensation is achieved if the voltage drop across the capacitor is equal to the voltage imposed by the series active power filter. The ratio between the harmonic component of the nonlinear load current and the harmonic component of the AC line current is obtained from Fig. 3 and is equal to

$$\frac{I_{Sh}}{I_{Lh}} = \frac{Z_F}{K + Z_F + Z_S} \tag{2}$$

Fig. 3 shows that the filtering characteristics of the hybrid topology (I_{Sh}/I_{Lh}) depends on the value of the passive filter equivalent impedance Z_F. Moreover, since the tuned factor and the quality factor can modify the filter band width and the passive filter harmonic equivalent impedance, their values must be carefully selected to maintain the compensation effectiveness of the hybrid topology. In particular, a high value of the quality factor defines a large band width of the passive filter, improving the compensation characteristics of the hybrid topology. However, a low value in the quality factor and/or a large value in the tuned factor increases the required voltage generated by the active power filter necessary to keep the same compensation effectiveness, which increases the active power filter rated power.

Fig. 4 shows how the *K* factor (1) influences the harmonic attenuation factor of the line currents. The attenuation factor of the line current harmonics expressed in percentage is obtained from (2), and is illustrated in Fig. 4, for a power system with two passive filters tuned at the fifth and seventh harmonics as the one shown in Fig. 1.

Also, the *K* factor shown in (1) affects the total harmonic distortion (THD) of the line current, as it is described in (3).

$$THDi = \frac{\sqrt{\sum\limits_{h=2} \left(I_{Lh} \cdot \frac{Z_F}{Z_S + Z_F + K} \right)^2}}{I_{S1}} \tag{3}$$

Equation (3) indicates that the THD of the line current decreases if *K* increases. In other words, the larger the voltage harmonics generated by the active power filter, the

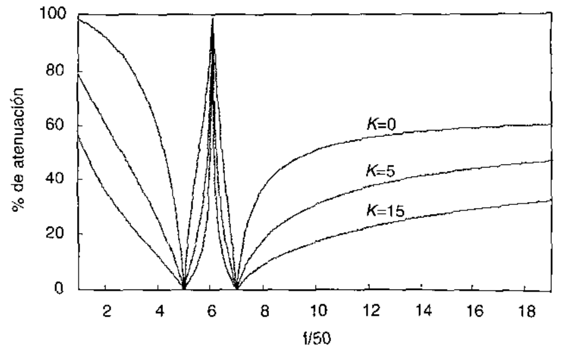


Fig. 4 *Attenuation factor of the line current harmonics*

better the hybrid filter compensation obtained. Also, it is shown that the compensation capability of the hybrid filter depends on the compensation characteristic of the passive filter, that is the filter impedance value and tuned factor will affect the active filter rated power required to satisfy the system compensation requirements. Fig. 5 shows the relation between the system line current THD and the K factor for a power distribution system connected to a high-power six-pulse rectifier with passive filters tuned at the fifth and seventh harmonics.

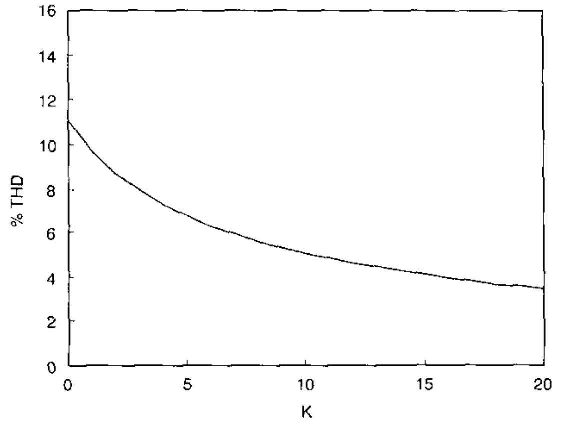


Fig. 5 *AC line current THD against K factor*

Displacement power factor correction can be achieved by controlling the voltage drop across the passive filter capacitor. In that way, the voltage across the passive filter capacitor changes, modifying the amount of generated reactive power. To do that a voltage at fundamental frequency is generated at the inverter AC terminals, with an amplitude equal to

$$V_C = \beta \cdot V_T \tag{4}$$

Displacement power factor control can be achieved since at fundamental frequency the passive filter equivalent impedance is capacitive, as shown in Fig. 2*b*. The reactive power generated by the passive filter is obtained by changing the fundamental voltage imposed by the active power filter across the passive filter capacitor terminals. The passive filter fundamental current component is defined by the following expression:

$$i_F = C\frac{d}{dt}(v_T - \beta v_T) = (1-\beta)C\frac{dv_T}{dt} = C_\gamma\frac{dv_T}{dt} \tag{5}$$

where $C_\gamma = (1-\beta)C$. (5) proves that the equivalent capacitance at fundamental frequency C_γ, can be modified by changing β. The reactive power generated by the active filter is β times the reactive power generated by the capacitor passive filter and can be defined by

$$Q_\gamma = V_C \cdot I_F = \beta V_T I_F = \beta Q \tag{6}$$

Equation (6) shows that if β is positive the active power filter generates a voltage at fundamental frequency in phase with V_T, reducing the reactive power that flows to the load. If β is negative, the active power filter generates a voltage at fundamental frequency phase shifted by 180° with respect to V_T, increasing the reactive power that flows to the load. In other words, by selecting a β positive or negative the hybrid topology can generate or absorb reactive power at fundamental frequency, compensating for a leading or lagging displacement power factor of the nonlinear load.

3 Control circuit

The block diagram of the proposed control scheme shown in Fig. 2 consists of three modules: the DC voltage control, the voltage reference generator and the inverter gating signals generator.

The voltage reference waveform required by the inverter control scheme is obtained by adjusting the amplitude of a sinusoidal reference waveform in phase with the respective phase-to-neutral voltage and then subtracting the respective AC line current (Fig. 2). The sinusoidal reference signal can be obtained from the voltage system (in the case of low voltage distortion) or it can be generated from an EPROM synchronised with the respective phase-to-neutral voltage. The amplitude of this reference waveform controls the inverter DC voltage and the AC mains displacement power factor. The inverter DC voltage varies according to the amount of real power absorbed by the inverter, while the AC mains power factor depends on the amount of reactive power generated by the hybrid filter, which can be controlled by changing the amplitude of the fundamental component of the inverter output voltage.

Simulated results for steady-state operating conditions proves the feasibility of the proposed control scheme. In particular, Fig. 6 shows simulated results of the hybrid scheme which compensates a six-pulse controlled rectifier. The system line currents are shown for the case of a rectifier connected directly to the voltage source, then connected through a shunt passive filter and finally with the proposed hybrid scheme. Simulated results prove the effectiveness of the proposed compensation scheme. The THD of the line current is reduced from 28%, in the case of a direct connection (Fig. 6*a*), to 14.4% in the case where only the passive filter operates (Fig. 6*b*), to only 4.04%, for active compensation with the hybrid topology (Fig. 6*c*).

The transient response of the proposed hybrid scheme is shown in Fig. 7. The active power filter is connected at $t = 400$ ms. Simulated results prove the good transient response of the hybrid topology. Fig. 7*b* shows that the passive filter rms current is reduced due to the connection of the active filter, while Fig. 7*c* illustrates that the connection of the active power filter at $t = 400$ ms reduces the line current THD. The transient response of the hybrid scheme is less than 5 ms.

If the load current is changed (Fig. 8), the compensation effectiveness of the proposed scheme is not affected, as

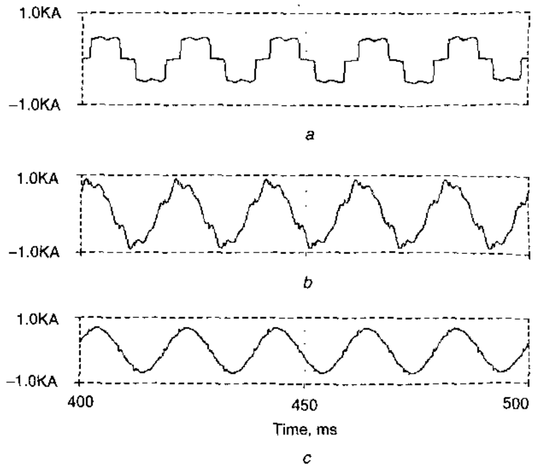


Fig. 6 *Simulated AC line current waveforms for different types of compensation*
(*a*) without filter
(*b*) only with passive filter
(*c*) with the proposed hybrid filter

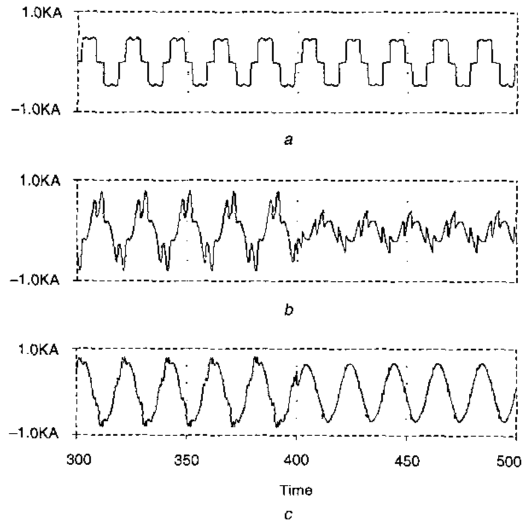


Fig. 7 *Simulated current waveforms for transient operating conditions at $t = 400\,ms$*
(*a*) nonlinear load current
(*b*) passive filter current
(*c*) AC line current

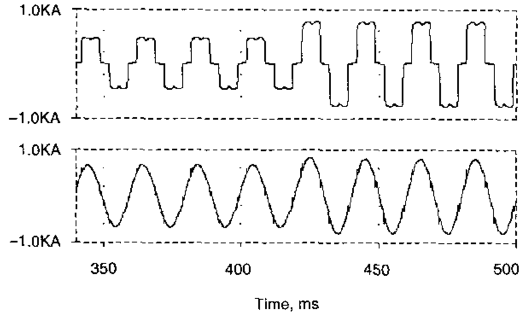


Fig. 8 *Simulated current waveforms for transient change in the load current at $t = 400\,ms$*
(*a*) nonlinear load current
(*b*) system AC line current

shown in Fig. 8*b*. In this case, the amplitude of the line current is increased (Fig. 8*a*) as well as the system line current. However, the system line current THD is not affected by transient changes in the load current.

These Figs. confirm that the transient response scheme is fast enough to compensate rapid changes in the load current.

4 Experimental results

A 5 kVA laboratory prototype using IGBT switches was implemented and tested in the compensation of a six-pulse controlled rectifier. The implemented passive filter has the following parameters:

	fifth order filter	seventh order filter
L[mH]	6.22	3.17
C[μF]	65	65

The Q factor in both filters is equal to ten. The coupling transformer turn ratio is equal to four. The active filter DC voltage is set at 200 V. The inverter modulation index is 0.9. The nonlinear load used in the experimental setup is a 2.5 kVA six pulse controlled rectifier. The inverter was operated at 4 kHz switching frequency. Steady-state experimental results are shown in Figs. 9–12.

The THD of the rectifier input current is 28.1%. Once the passive filters are connected, the system line current THD is reduced to 24% (Fig. 9*a*). It is clear that the compensation effectiveness of the passive filter is not adequate. However, if the proposed active power filter is connected, the system line current THD is reduced to 6.9% (Fig. 10*a*). The associated frequency spectrum shown in Fig. 10*b* indicates that the fifth harmonic is not fully compensated. This is due to the presence of a fifth harmonic

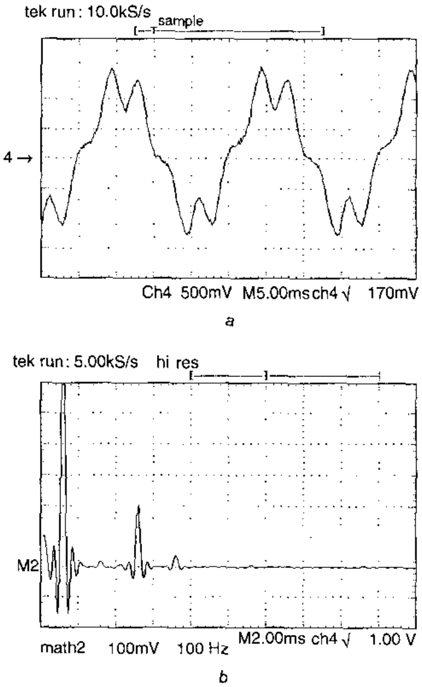
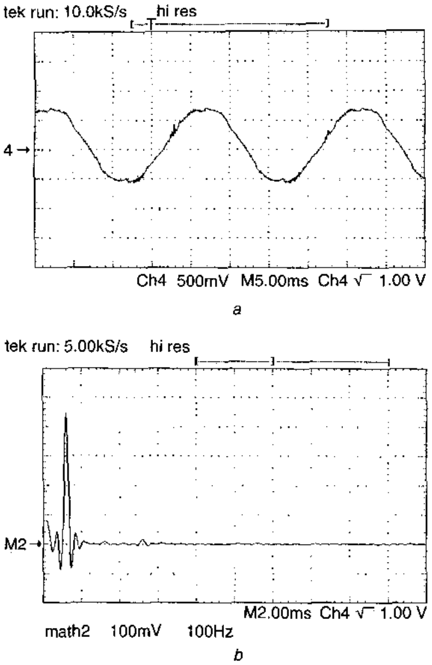


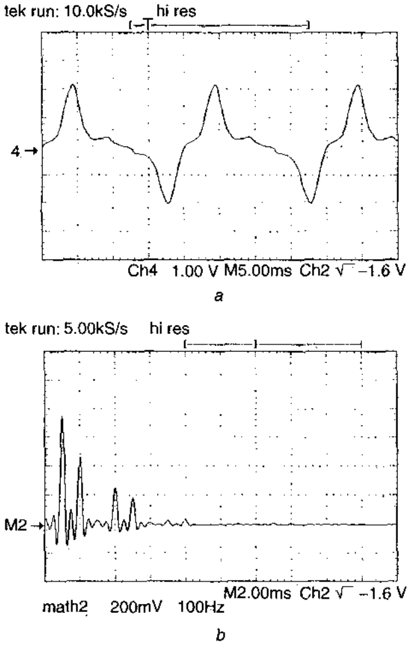
Fig. 9 *Experimental AC line current waveform without active filtering compensation*
(*a*) system line current waveform (THD = 24%)
(*b*) line current frequency spectrum



a

b

Fig. 10 *Experimental AC line current waveform with hybrid filter compensation*
(*a*) system line current waveform (THD = 6.3%)
(*b*) associated frequency spectrum



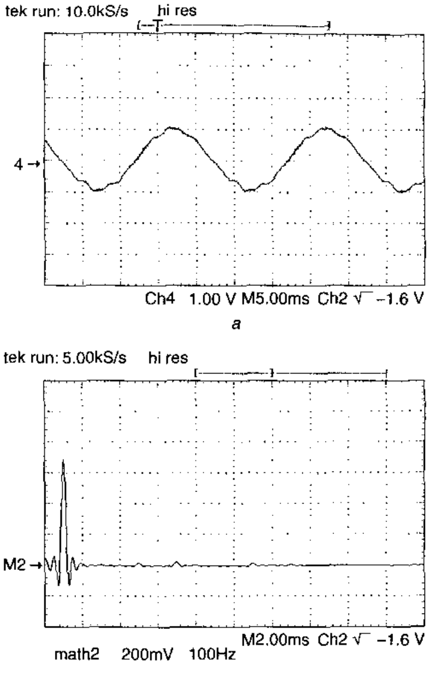
a

b

Fig. 11 *Experimental AC line current waveform with passive compensation and resonant operating condition*
(*a*) system line current waveform (THD = 60%)
(*b*) associated frequency spectrum

in the system voltage that affects the compensation performance of the hybrid topology.

By increasing the system voltage operation with a variac, a resonance is created between the system equivalent impedance and the passive filters. The resonance increases the system line current THD to 60% (Fig. 11*a*). The resonant frequency is located between the second and fourth component (Fig. 11*b*). By connecting the series active filter (hybrid compensation) the resonance is completely eliminated, and the system line current THD is reduced to 4.9% (Fig. 12*a*). In this case, the associated system line current frequency spectrum shows the fundamental component and low-amplitude high-frequency component that are not completely attenuated by the active filter.



a

b

Fig. 12 *Experimental AC line current waveform with hybrid topology compensation*
(*a*) system line current waveform (THD = 4.9%)
(*b*) associated frequency spectrum

5 Conclusions

A simple control scheme for hybrid active power filters connected in parallel has been presented and analysed. The hybrid active power filter combines the compensation characteristics of resonant passive and active power filters connected in series. It was proved that the proposed scheme is able to compensate the displacement power factor and current harmonics simultaneously. The combination of passive and active power filters allows better performance compensation of high-power nonlinear loads.

The technical viability of the proposed scheme was verified by simulation using Pspice and with an experimental setup of 5 kVA. The close agreement between the analytical and the experimental results proves the validity of the analysis and the feasibility of the proposed control scheme.

6 Acknowledgment

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