A SIMPLE CONTROL SCHEME FOR HYBRID ACTIVE POWER FILTER

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Abstract **- A simple control scheme for hybrid active power filters connected in parallel is presented and analyzed in this paper. 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 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 voltage non linear 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.

I. INTRODUCTION

Active power filters have 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 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 improves significantly the compensation characteristics of simple passive filters, making the use of 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, given more flexibility to the compensation scheme.

Control scheme of the active power filter are normally based on the Instantaneous Reactive Power Reference [1] or on the 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 analog technology was presented in [5]. Although the reported control scheme was simple and easy to implement, compensation characteristics was not good enough due to frequency response of the passive filter used to obtain the control reference waveforms.

The hybrid active power filter topology presented in this paper 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. 5 generates the reference signals required to compensate current harmonic components and displacement power factor of high power non linear loads. Basically, 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.

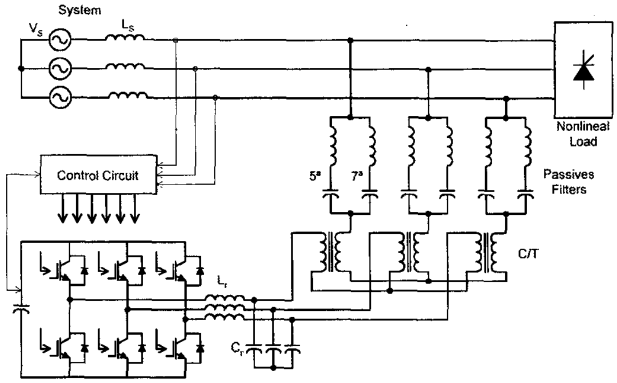

Fig. 1. The hybrid active power filter configuration.

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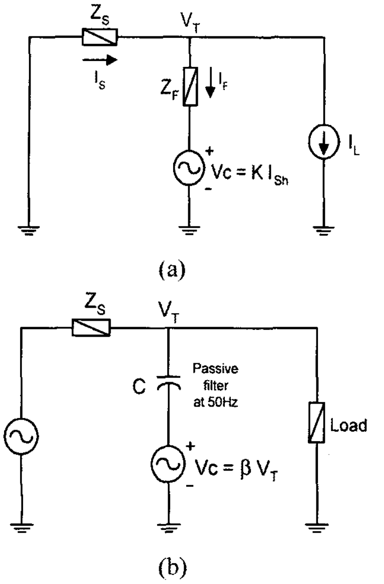
II. PRINCIPLES OF OPERATION

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.

The principles of operation for current harmonic and power factor compensation are explained with the single-phase equivalent circuit shown in Fig. 2.



(a)

(b)

Fig. 2. 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 equals 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, the ratio between the harmonic component of the non linear load current and the harmonic component of the ac line current is obtained from Fig. 1-b and is equal to:

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

Figure 2 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 being carefully selected in order 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. On the other hand, 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.

Figure 3 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 equation (2), and is illustrated in figure 3, for a power system with two passive filters tuned at 5th and 7th harmonics.

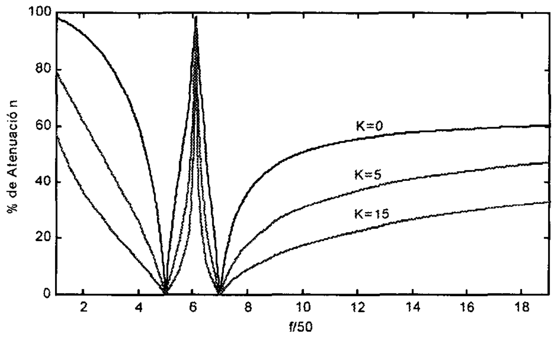


Fig. 3. The attenuation factor of the line current harmonics.

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

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

Equation 3 indicates that the total harmonic distortion of the line current decreases if K increases. In other words, the larger the voltage harmonics generated by the active power filter a better hybrid filter compensation is 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. Figure 4 shows the relation between the line current THD and the K factor for a power distribution system connected to a high power six pulses rectifier and passive filters tuned at 5th and 7th harmonics.

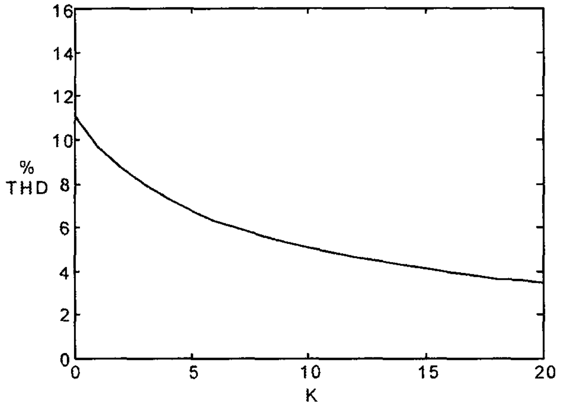


Fig. 4. Ac line current THD v/s K factor.

Displacement power factor correction can be achieved by controlling the voltage drop across the passive filter capacitor. In order to do that a voltage at fundamental frequency is generated at the inverter ac terminals, with an amplitude equals to:

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

Displacement power factor control can be achieve 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:

$$i_F = C\frac{d}{dt}\left(v_T - \hat{a}\, v_T\right) = \left(1 - \hat{a}\right)C\frac{dv_T}{dt} = C\tilde{a}\frac{dv_T}{dt} \tag{5}$$

Equation 5 proves that the equivalent capacitance at fundamental frequency Cγ, can be modified by changing β. The reactive power generated by the active filter is β times the reactive power generated by the passive filter and can be defined by:

$$Q_{\tilde{a}} = V_C \cdot I_F = \hat{a}\, V_T I_F = \hat{a}\, Q_{\tilde{a}} \tag{6}$$

Equation (6) shows that if β>0 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<0 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 leading or lagging displacement power factor of the non linear load.

III. CONTROL CIRCUIT

The block diagram of the proposed control scheme shown in Fig. 5 consists of three modules: the dc voltage control, the voltage reference generator and the inverter gating signals generator.

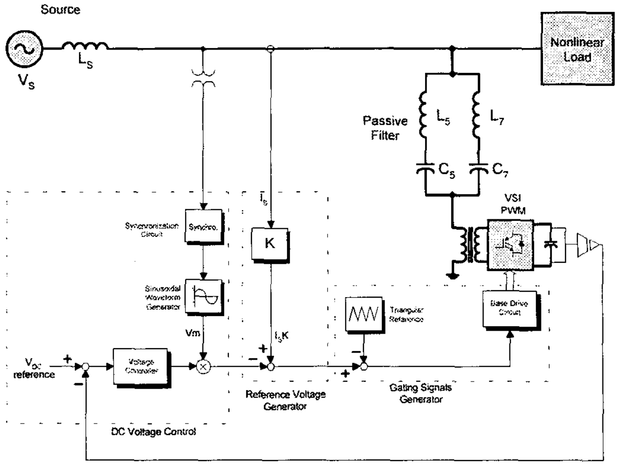


Fig. 5. The hybrid active power filter topology and associated control scheme.

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. 5). The sinusoidal reference signal can be obtained from the voltage system (in case of low voltage distortion) or it can be generated from an EPROM synchronized 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 with 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 while compensates a 6 pulses controlled rectifier. 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 total harmonic distortion of the line current (THD) is reduced from 28 %, in the case of 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 compensation with the hybrid topology (Fig. 6-c).

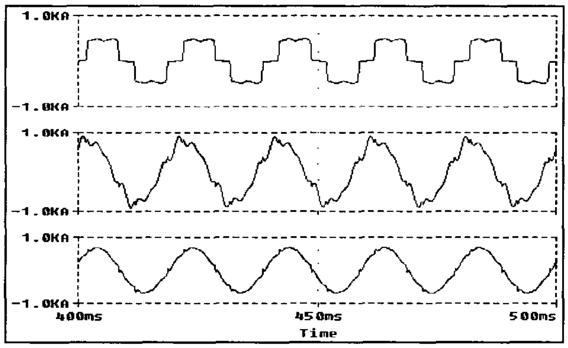


Fig. 6. Simulated ac line current waveforms for different types of compensation. a) Without filter. b) Only with passive filter. c) With the proposed hybrid filter.

The trasient response of the proposed hybrid scheme is shown in Fig. 7. The active power filter is connected at t = 400 ms. Simulated results proves the good transient response of the hybrid topology, which allows the circulation of a sinusoidal line current waveform even when the current load changes its amplitude. Specially, figure 7 c) shows that the transient response of the control scheme is lower than 5 ms.

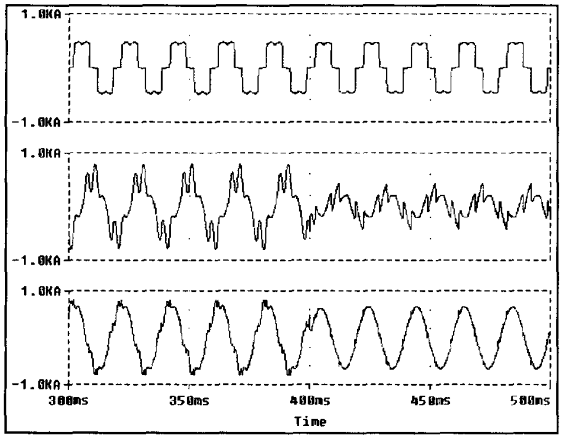


Fig. 7. Simulated current waveforms for transient operating conditions. a) Nonlinear load current. b) Passive filter current. c) Ac line current.

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

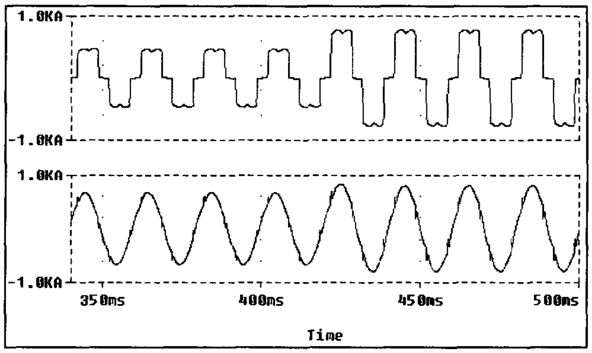


Fig. 8. a) Nonlinear load current and b) Ac line current.

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

IV. EXPERIMENTAL RESULTS

A laboratory prototype using IGBT switches was implemented and tested in the compensation of a six-pulses controlled rectifier. The inverter was operated at 4 kHz switching frequency. Steady state experimental results are illustrated in figure 9 and 10.

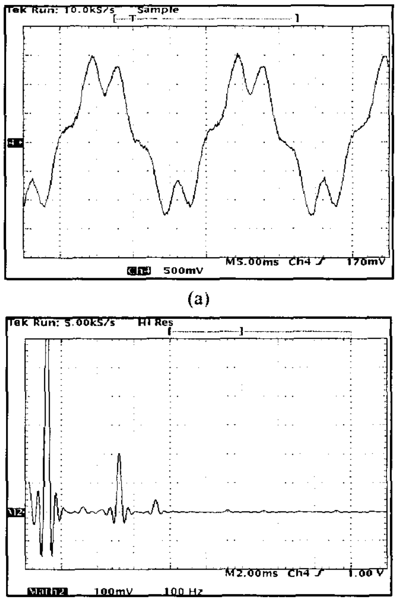


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Fig. 9. Experimental ac line current waveform without filtering compensation. a) Line current waveform. b) Line current frequency spectrum.

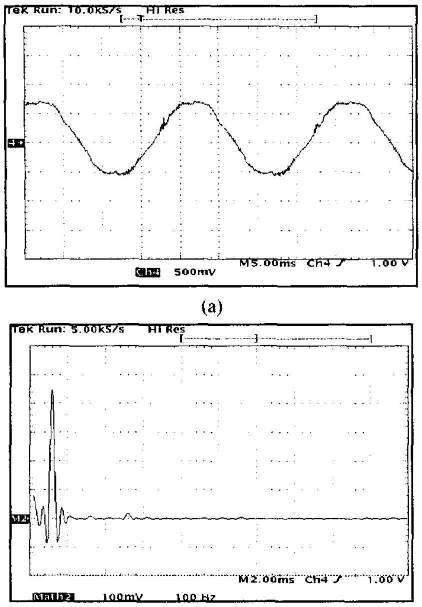

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Fig. 10. Experimental ac line current waveform with hybrid filter compensation. a) Line current waveform. b) Associated frequency spectrum.

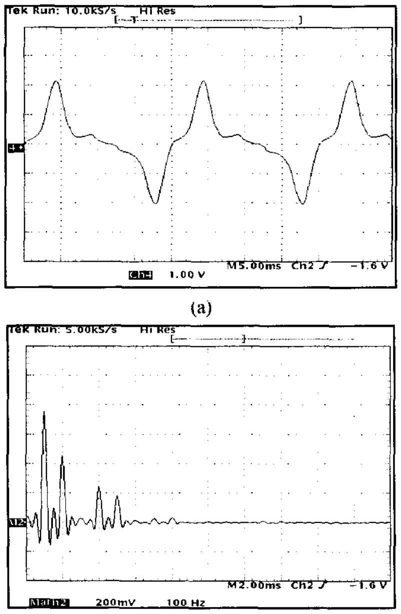

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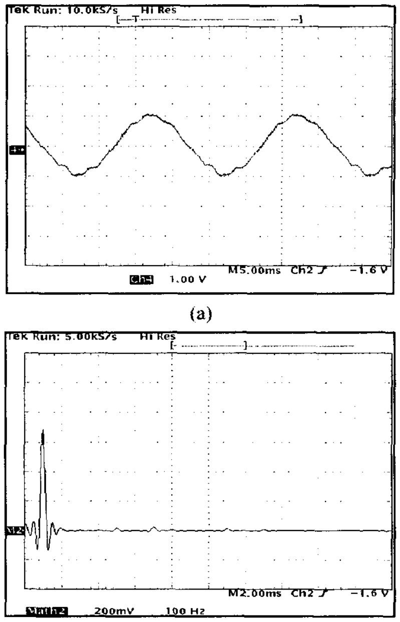
Fig. 11. Experimental ac line current waveform with hybrid filter compensation. a) Line current waveform. b) Associated frequency spectrum.



(a)

(b)

Fig. 12. Experimental ac line current waveform with hybrid topology compensation. a) Line current waveform. b) Associated frequency spectrum.

V. CONCLUSION

A simple control scheme for hybrid active power filters connected in parallel has been presented and analyzed in this paper. The hybrid active power filter combines the compensation characteristics of resonant passive and active power filters. It was proved that 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 voltage non linear loads.

The technical viability of the proposed scheme was verified by simulation using Pspice and whit 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.

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