Improving Passive Filter Compensation Performance With Active Techniques

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***Abstract*—This paper presents the performance analysis of a hybrid filter composed of passive and active filters connected in series. The analysis is done by evaluating the influence of passive filter parameters variations and the effects that different active power filter's gain have in the compensation performance of the hybrid scheme. The compensation performance is quantified by evaluating the attenuation factor in a power distribution system energizing high-power nonlinear loads compensated with passive filters and then improved with the connection of a series active power filter. Finally, compensation characteristics of the hybrid topology are tested on a 10-kVA experimental setup.**

***Index Terms*—Active power filter, current harmonics, power factor, power filter, reactive power.**

I. Introduction

PASSIVE filters have always been considered a good alternative for current harmonics compensation and displacement power-factor correction. In general, passive tuned filters have been used to minimize low-frequency current harmonics while high-pass units have been connected to attenuate the amplitude of high frequency current components. However, high-pass filters present disadvantages due to the resistance connected in parallel to the inductor, which increases the filter losses and reduces the filtering effectiveness at the tuned frequency.

Technical disadvantages of passive filters have been extensively discussed in previous literature. The most critical aspects of passive filters are related to the fact that they cannot modify their compensation characteristics following the dynamic changes of the nonlinear load, the performance dependence they present with the power system parameters, and the probability of series resonances with the power system's equivalent reactance. Another technical disadvantage of passive filters is related to the small design tolerances acceptable in the values of L and C. Small changes in the value of L or C modify the filter resonant frequency. For example, a 5% difference in the selected value of L or C in a second-order LC filter tuned at 250 Hz (fifth harmonic) modifies the required resonant frequency in 7% with respect to the selected design value, affecting the filter current harmonic compensation performance. Also, the passive filter generates at fundamental frequency reactive power that changes the system voltage regulation, and if the filter is not designed properly or disconnected during low load operating conditions, overvoltages can be generated at its terminals.

Hybrid topologies composed of passive LC filters connected in series to an active power filter have already been proposed and discussed in technical papers [1]–[6]. Hybrid topology improves the compensation characteristics of passive filters, and allows the use of active power filters in high-power applications at a relatively low 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. Most of the technical disadvantages of passive filters described before can be eliminated if an active power filter is connected in series to the passive approach as shown in Fig. 1.

Papers dealing with hybrid topologies have focussed their analysis on the control scheme, principles of operation, and design criteria used in the active power filter [1]–[6]. In all technical papers, the compensation characteristics have been tested in simple systems consisting of an ideal voltage source and a nonlinear load. In this paper, a complete analysis of the influence of the passive filter parameters, and the active power filter gain in the compensation performance of the hybrid scheme is presented. Also, simulated results illustrate how the compensation characteristics of a passive filter used to eliminate current harmonics in a large industrial power distribution system can be improved by connecting an active power filter. Finally, the compensation performance of the hybrid scheme is tested on a 10-kVA laboratory prototype for nonlinear load compensation, and the operation with distorted line voltages.

II. Principles of Operation

The hybrid active power filter topology presented in this paper is shown in Fig. 1 and is implemented with a three-phase pulsewidth modulation (PWM) voltage-source inverter operating at fixed switching frequency (the active power filter), and connected in series to the passive filter through coupling transformers. The principles of operation of the control scheme are presented and analyzed in [6]. Basically, the active power filter acts as a controlled voltage source and forces the utility line currents to become sinusoidal and in phase with the respective phase to neutral voltage by pushing all current harmonics to

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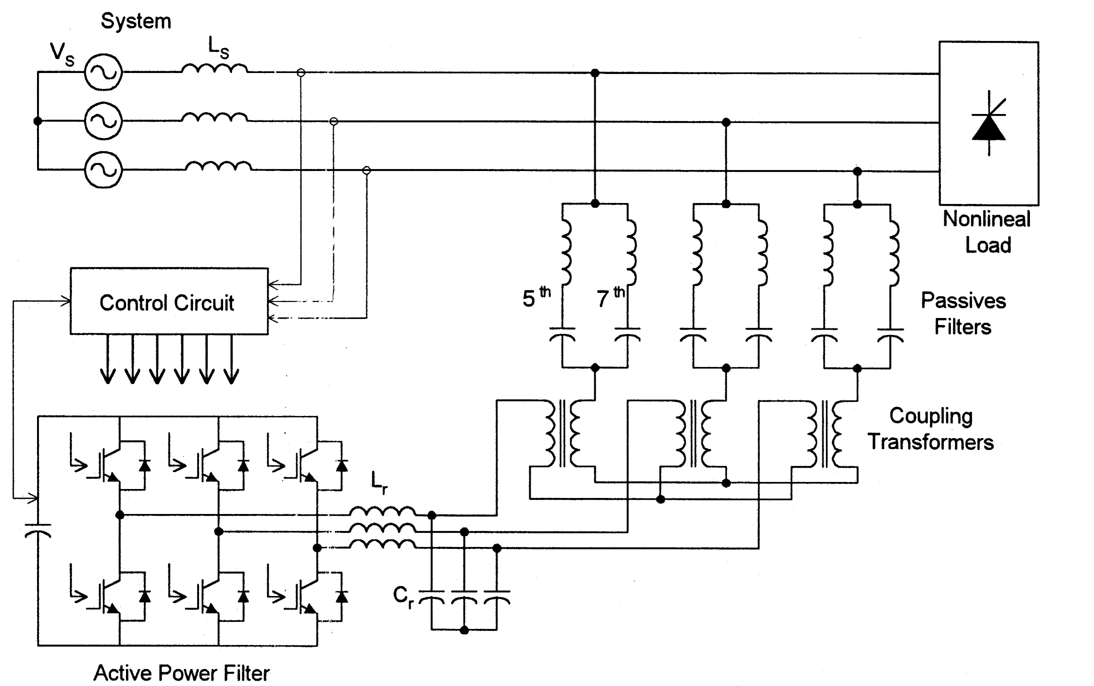


Fig. 1. Hybrid active power filter configuration.

circulate through the hybrid scheme. In other words, because the active power filter is connected in series to the passive filter through coupling transformers, it imposes a voltage signal at the primary terminals that forces the circulation of current harmonics through the passive filter, improving its compensation characteristic, independently of the variations in the selected resonant frequency or filter parameters.

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

A. Current Harmonic Compensation

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

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

where I_{Sh} is the harmonic content of the line current to be compensated, and $\boldsymbol{K}$ is the active power filter gain. The coupling transformer changes the secondary current waveform generated by the PWM voltage-source inverter, in a voltage signal V_{Ch} induced between the primary terminals.

If the ac mains voltage is purely sinusoidal, the ratio between the harmonic component of the nonlinear load current and the harmonic component of the ac line current (attenuation factor, γ) is obtained from Fig. 2(a) and is equal to

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

Equation (2) shows that the attenuation factor γ defines the filtering characteristic of the hybrid topology (I_{Sh}/I_{Lh}), which depends on the value of the passive filter equivalent impedance Z_F, the active power filter gain $\boldsymbol{K}$, and the system impedance Z_S. To improve the attenuation factor (i.e., better compensation performance), $\boldsymbol{K}$ must be increased because Z_S and Z_F are constant.

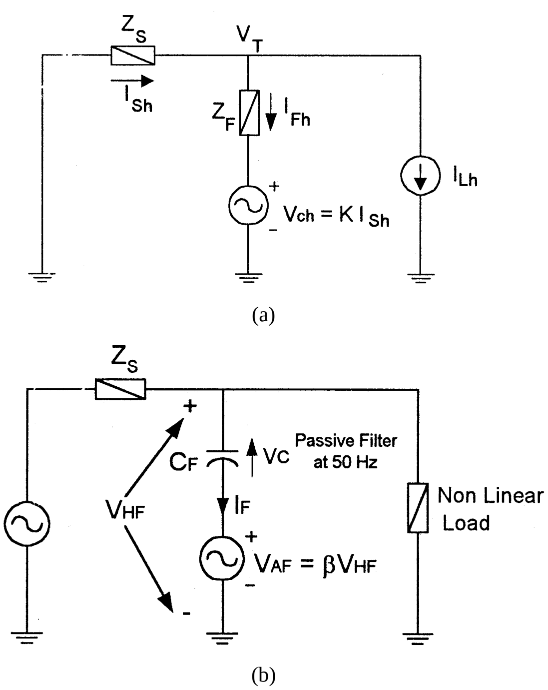


Fig. 2. Single-phase equivalent circuit of the hybrid active power filter scheme. (a) For current harmonic compensation. (b) For displacement power-factor compensation.

B. Displacement Power-Factor Compensation

Hybrid power filters can also be used to control the load displacement power factor. In fact, displacement power-factor correction can be achieved by controlling the fundamental voltage component drop across the passive filter capacitor V_C, [2]. In order to do that, a voltage component at fundamental frequency, V_{AF}, and in phase with the capacitor filter voltage V_C is generated at the coupling transformer primary terminals featuring an amplitude equal to

$$V_{AF} = \beta \cdot V_{HF}. \tag{3}$$

On the other hand, at fundamental frequency the passive filter equivalent impedance is capacitive, as shown in Fig. 2(b), and the voltage across the hybrid filter is equal to

$$V_{HF} = V_C + V_{AF} \tag{4}$$

which shows that the voltage across the capacitor C_F can be changed by adjusting the active power filter output voltage amplitude V_{AF} in phase with V_C. The hybrid filter fundamental current is defined by the following expression:

$$i_F = C_F \frac{dv_C}{dt} = C_F \frac{d}{dt}(v_{HF} - \beta v_{HF}) = (1-\beta) C_F \frac{dv_{HF}}{dt}. \tag{5}$$

Considering that V_{HF} and i_F are the voltage and current, respectively, at the hybrid filter terminals, (5) suggests that, by defining

$$C_\gamma = (1-\beta) C_F \tag{6}$$

the hybrid filter can be considered as an equivalent capacitor $C\gamma$. Moreover, (6) shows that if β is positive the hybrid filter reduces the reactive power that flows to the load, and conversely, if β is negative the hybrid filter increases the reactive power that flows to the load. According to (3), modifying β means that the voltage across the active filter is changed and hence the voltage across the pasive filter is inversely changed as indicated by (4), assuming that V_{AF} is mainly constant.

III. Hybrid Filter Compensation Performance

Current harmonic compensation is achieved by reducing the impedance of the hybrid filter and, thus, forcing the current harmonic to follow the low-impedance trajectory instead of circulating through the power system [Fig. 2(a)]. To accomplish this task, the hybrid filter must present a wide bandwidth and a very small impedance at the frequency of the harmonics that are being compensated. The hybrid filter bandwidth depends on the passive filter parameters and on the active power filter gain $\boldsymbol{K}$. The passive filter impedance value at the resonant frequency depends on the tuned factor δ.

The tuned factor δ in per unit with respect to the resonant frequency ω_r is defined by

$$\delta = \frac{\omega - \omega_r}{\omega_r} \tag{7}$$

where ω is the passive filter real resonant frequency, and ω_r the designed value. The tuned factor δ defines the magnitude in which the passive filter resonant frequency changes due to the variations in the power system frequency and modifications in the passive filter parameters L and C. The values of L and C can change due to aging conditions, temperature variations, or design tolerances. The tuned factor δ can also be defined in terms of frequency and parameter variation, such as

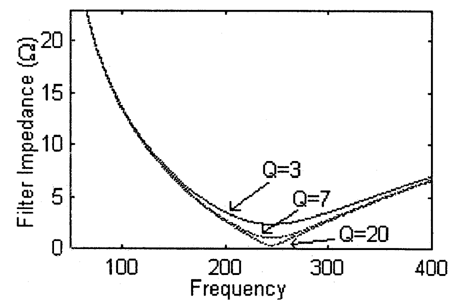


Fig. 3. Frequency response of the passive filter equivalent impedance for different quality factor values.

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\left(\frac{\Delta L}{L_n} + \frac{\Delta C}{C_n}\right) \tag{8}$$

where Δf is a frequency variation around the nominal value f_n, ΔL is an inductance variation around the nominal value L_n, and ΔC is a capacitance variation around the nominal value C_n. The influence of each of these parameters in the hybrid filter compensation performance is analyzed in this section. The results are used to determine the parameters values that optimize the hybrid filter compensation performance.

A. Effects of the Passive Filter Quality Factor

An important parameter that must be considered in the passive filter design and that has a strong influence in the hybrid scheme compensation performance is the quality factor Q. The quality factor Q of a passive filter is defined by

$$Q = \frac{1}{R_f}\sqrt{\frac{L_f}{C_f}} \tag{9}$$

where R_f, L_f, and C_f are the resistance, inductor, and capacitor values of the passive filter. The passive filter quality factor Q defines the passive filter bandwidth, as shown in Fig. 3. A passive filter with a small bandwidth $(Q < 5)$ presents a high impedance for current harmonics with a frequency that is not equal to the resonant value. This characteristic affects the compensation performance of nonlinear loads. The filter resistance and capacitor must be increased to make the filter bandwidth wider. However, by increasing R_F and C_F, the passive filter costs and losses become greater.

Fig. 3 shows that a high value of the quality factor Q defines a large bandwidth of the passive filter and low impedance at the resonant frequency, which improves the attenuation of current harmonics. On the other hand, a low value in the quality factor and/or a large value in the tuned factor reduces the passive filter bandwidth and increases the impedance at the resonant frequency, forcing an increase in the amplitude of the voltage generated by the active power filter required to keep the same compensation effectiveness, and therefore increasing the active power filter rated power. Moreover, since the tuned factor δ and the quality factor Q modify the filter bandwidth and the passive filter harmonic equivalent impedance at the resonant frequency, their values must be carefully selected in order to maintain the

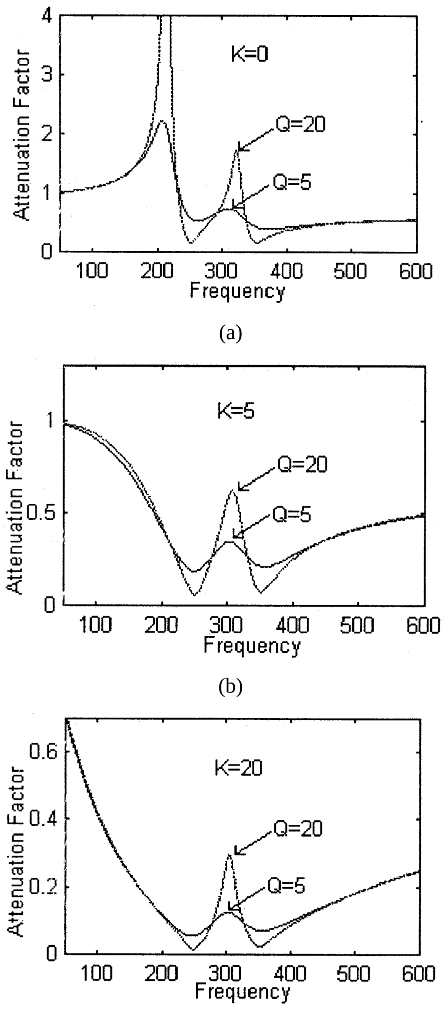


Fig. 4. Hybrid filter frequency response for different values of active power filter gain K and passive filter quality factor Q. (a) Frequency response of the passive filter. (b) Frequency response of the hybrid topology with $K = 5$. (c) Frequency response of the hybrid topology with $K = 20$.

compensation effectiveness of the hybrid topology. A better hybrid filter bandwidth can be achieved by modifying the active power filter gain as discussed below.

B. Effects of the Active Power Filter Gaing

Fig. 4 shows how the active power filter gain $\boldsymbol{K}$ changes the harmonic attenuation factor of the line currents γ. The attenuation factor of the line current harmonics expressed as a percentage is obtained from (2), and is shown in Fig. 4 for a power distribution system with two passive filters tuned at fifth and seventh harmonics. The filter parameters used in this analysis are: $C_5 = 100\ \mu$F, $L_5 = 5$ mH, $C_7 = 50\ \mu$F, and $L_7 = 4.79$ mH. The tuned factor δ selected for the filters are 0.1 for the fifth and 0.07 for the seventh.

Fig. 4 shows that the hybrid filter bandwidth can be modified by changing the active power filter gain. Large values of $\boldsymbol{K}$ improve the hybrid filter compensation performance by reducing the equivalent impedance for different values of frequency, that is, by increasing the hybrid filter bandwidth. Fig. 4 also illustrates that the effect of low values in passive filter quality factors Q can be compensated with the adequate selection of the

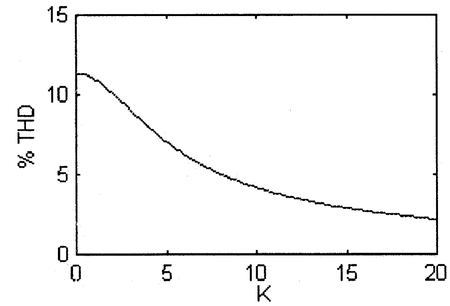


Fig. 5. System line current THD versus active power filter gain $\boldsymbol{K}$.

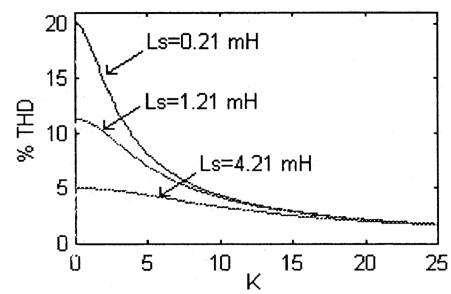


Fig. 6. Relation between the THD of the line current versus the active power filter gain $\boldsymbol{K}$ for different values of the system equivalent impedance.

active power filter gain $\boldsymbol{K}$. Similarly, Fig. 4 indicates that large values of $\boldsymbol{K}(\boldsymbol{K} > 15)$ improve hybrid filter compensation performance.

The total harmonic distortion (THD) of the line current depends on the value of $\boldsymbol{K}$, as shown in (10)

$$\text{THD}i = \frac{\sqrt{\sum_{h=2} \left(I_{Lh} \cdot \frac{Z_F}{Z_S + Z_F + K} \right)^2}}{I_{S1}}. \qquad (10)$$

Equation (10) indicates that the total harmonic distortion of the line current decreases if $\boldsymbol{K}$ increases. In other words, a better hybrid filter compensation is obtained for larger values of voltage harmonic components generated by the active power filter. However, Fig. 5 shows that no significant improvement is obtained for $\boldsymbol{K}$ greater than 15.

Figs. 4 and 5 illustrate that the tuned frequency and quality factor of the passive filter directly modify the compensation characteristics of the hybrid topology. If these two factors are not properly selected, the active power filter gain must be increased to maintain the same compensation performance.

C. Effects of the Power System Equivalent Impedance

The influence of the power system equivalent impedance on the hybrid filter compensation performance is related to its effects on the passive filter. In fact, if the system equivalent impedance is lower compared to the passive filter equivalent impedance at the resonant frequency, most of the load current harmonics will mainly flow to the power distribution system. In order to compensate this negative effect on the hybrid filter compensation performance, $\boldsymbol{K}$ must be increased, as shown in (2), increasing the active power filter rated power.

Fig. 6 shows how the system equivalent impedance affects the relation between the system current THD with the active filter

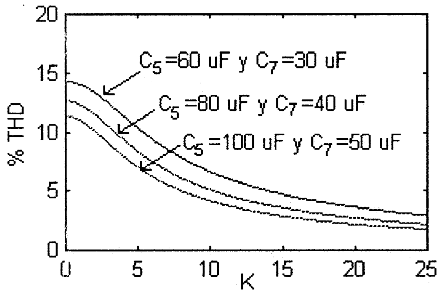


Fig. 7. THD of the system line current versus the $\boldsymbol{K}$ factor for different values of filter capacitor.

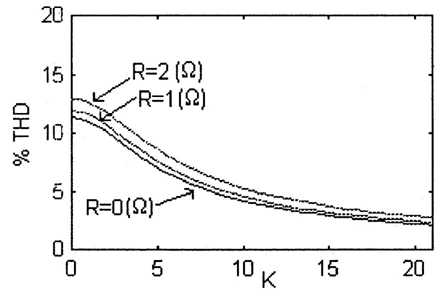


Fig. 8. THD of the system line current versus the $\boldsymbol{K}$ factor for different values of filter resistor.

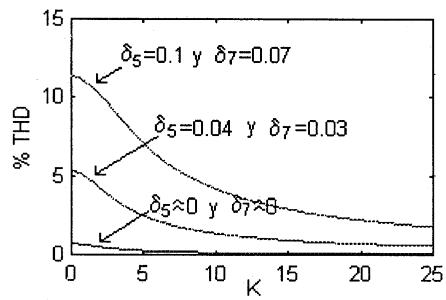


Fig. 9. THD of the system line current versus the $\boldsymbol{K}$ factor for different values of tuned factor, $\boldsymbol{\delta}$.

gain $\boldsymbol{K}$ in a power distribution system with passive filters tuned at the fifth and seventh harmonics. Fig. 6 also shows that if L_S decreases, the current system THD increases, so in order to keep the same THD in the line currents, the active power filter gain $\boldsymbol{K}$ must be increased. If L_S is high, it is not necessary to increase $\boldsymbol{K}$ to ensure a low THD value in the system current. This is due to fact that it is always easier to compensate current harmonics in weak power distribution systems (large value of L_S) than in bulky systems (small value of L_S).

Finally, Fig. 6 also illustrates that hybrid filters with large values of $\boldsymbol{K}$ are not sensitive to power system inductance variations, therefore, compensation performance of the hybrid scheme is guaranteed if $\boldsymbol{K}$ is larger than 15.

D. Effects of the Passive Filter Components

Although by decreasing R_F or C_F the passive filter quality factor is improved, and the bandwidth increases, each component produces a different effect in the hybrid filtering behavior. For example, by increasing R_F, the filter equivalent impedance at the resonant frequency becomes larger, affecting the current harmonic compensation characteristics at this specific frequency. On the other hand, by increasing C_F, the reactive power generated at rated frequency becomes larger, overloading the hybrid filter and generating large amount of reactive power, creating voltage regulation problems.

Fig. 7 illustrates how the system current THD changes with different values of C_F, while keeping the filter tuned factor δ constant. It is important to note that the larger values of C_F provide better compensation characteristic of the hybrid scheme.

Figs. 7 and 8 prove that large values of the active power filter gain, improve the hybrid filter compensation performance, independently on the values of C_F and R_F. This is an important characteristic since it gives more flexibility in the design of the passive filter, and allows a significant reduction in the respective cost (small values of C_F and R_F are required).

E. Effects of the Passive Filter Tuned Factor

The tuned factor δ affects the hybrid scheme performance, especially at the passive filter resonant frequency. This is due to the fact that δ defines the changes in the system frequency, changing the value of the passive filter resonant frequency. Fig. 9 shows how the system line currents THD changes with respect to the active power filter gain $\boldsymbol{K}$ for different values of passive filter tuned factors. Large values of δ deteriorate the filtering performance of the hybrid filter, but it can be overcome if $\boldsymbol{K}$ is chosen larger than 15.

The analysis presented in this section shows that by using an active power filter with a low gain $(\boldsymbol{K} < 10)$, the compensation performance of the hybrid scheme depends on the passive filter design characteristics. By using $\boldsymbol{K} > 15$, most of the disadvantages of passive compensation disappear, and the hybrid scheme behaves like an ideal filter. In this case, the hybrid compensation performance does not depend on the passive filter parameter values neither on the power system equivalent impedance. According to this analysis, a practical value for $\boldsymbol{K}$ is equal to 20.

IV. Analysis of the Hybrid Filter Performance Compensating a Distribution System

This section will show how passive filter compensation performance can be improved by connecting and active power filter in series. The power distribution system energizes four six-pulse controlled rectifiers, each of 18 MW rated power. Each converter is connected to the secondary of a delta/wye and a delta/delta transformer simulating a 12-pulse rectifier. The single-phase diagram of the power distribution system shown in Fig. 10 only considers the nonlinear loads and passive filters used to compensate current harmonics distortion. The other part of the power distribution system is connected to different bus voltages and is not considered in this analysis.

Each 12-pulse rectifier is connected to passive filters tuned at the fifth, seventh, 11th, and 13th frequency harmonic, plus a high-pass filter. Although for the power distribution system the rectifiers behave as an equivalent 12-pulse converter, the two passive filters tuned at the fifth and seventh harmonics are connected in case one of the rectifiers does not operate, leaving only one six-pulse unit connected to the bus.

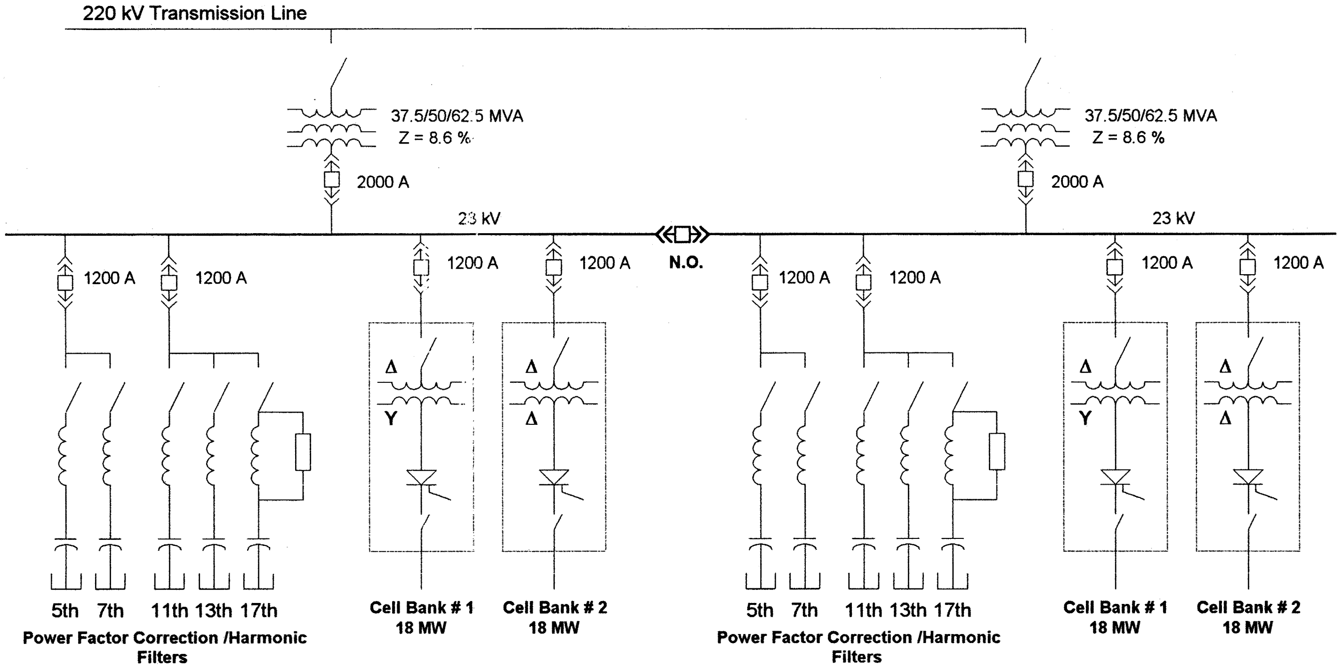


Fig. 10. Single-phase line diagram of the power distribution system under study.

TABLE I
POWER SYSTEM AND PASSIVE FILTER PARAMETERS

	L (mH)	C (μF)	R (mΩ)	kVAR
System	2.8	---		
5th harm. Filter	9.85 ± 2 %	42.8 ± 3 %	760	13800
7th harm. Filter	5.85 ± 2 %	36.4 ± 3 %	630	10200
11th harm. Filter	3.07 ± 2 %	27.8 ± 3 %	520	7800
13th harm. Filter	2.19 ± 2 %	27.8 ± 3 %	440	7800
17th harm. Filter	1.28 ± 2 %	27.8 ± 3 %	25000	7800

The analysis presented in this section will consider the worst operating condition which is defined when only one 18-MW converter is connected to the power system. The power system and passive filter parameters are shown in Table I. The active power filter used in this example is rated at 750 kVA, since it will compensate for current harmonics only, with coupling transformers turns ratio equal to 20, semiconductors rated current equal to 250 A, and 1200 V rated voltage and connected to the passive filters as shown in Fig. 11.

The first analysis is done for cases where the two converters operate in each bus voltage. The active power filter starts to compensate at $t = 300$ ms. The active power filter gain selected in this case is equal to 20. Before the active power filter starts to compensate the current system THD is equal to 4.42%, proving the adequate design of the passive filters. However, with the active power filter in operation, the compensating performance of the hybrid topology is improved, as shown in Fig. 12. After the active power filter starts to operate, the THD of the system line current is reduced to 1.2%. Moreover, the hybrid scheme operation reduces the fundamental component of the filter current, due to the power factor compensation done with the active scheme.

The previous approach to compensate requires several passive filters that increases the cost, and produces over voltage regulation due to the large amount of reactive power supplied to the system. For these reasons it is convenient to consider a lesser number and rated power of passive filters connected to the system. If the passive filters tuned at the 11th and 13th harmonics are eliminated, as shown in Fig. 13, the current waveforms obtained for this case are shown in Fig. 14.

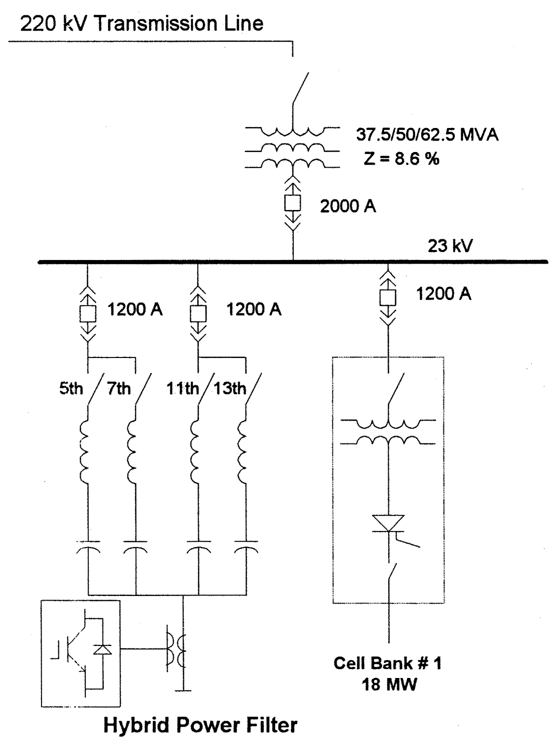


Fig. 11. Single-phase equivalent system with hybrid compensation and for the worst operating condition: only one six-pulse converter is connected to the bus.

Fig. 14 shows that the THD of the line current before active compensation starts is equal to 7.51%. Once the hybrid topology

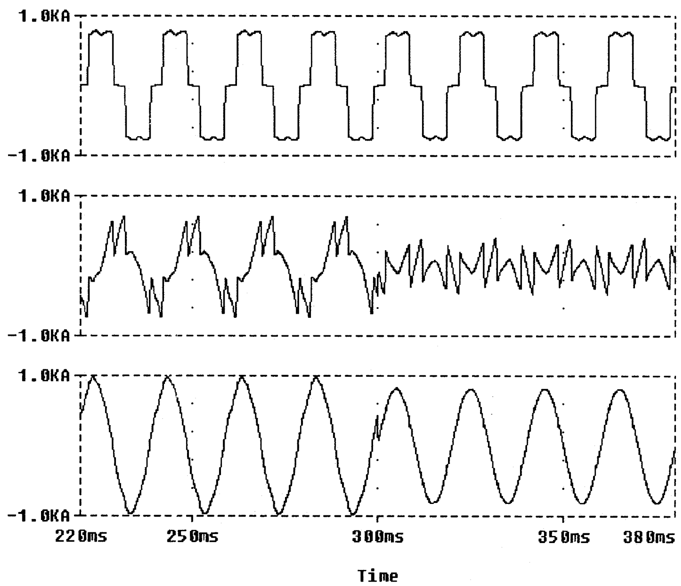


Fig. 12. Simulated current waveforms for hybrid filter compensation (active power filter compensation starts at 300 ms). Top: simulated load current; middle: simulated hybrid filter current; bottom: simulated system line current.

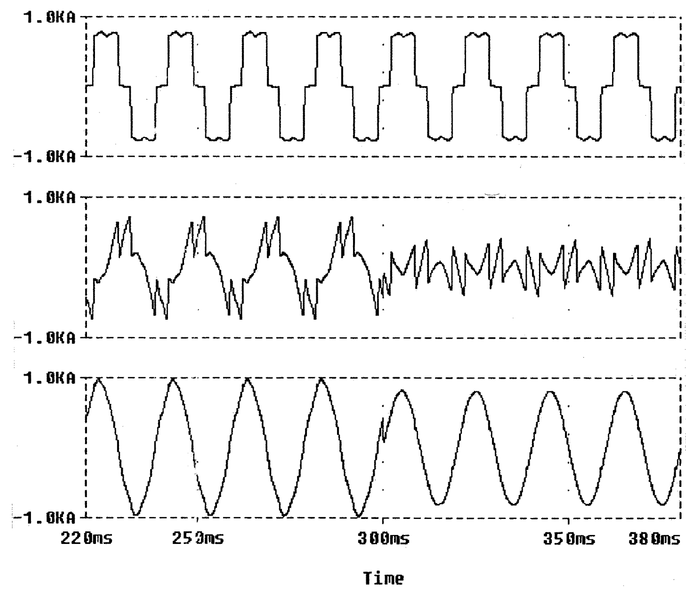


Fig. 14. Simulated current waveforms for hybrid filter compensation (active power filter compensation starts at 300 ms). Top: simulated load current; middle: simulated hybrid filter current; bottom: simulated system line current.

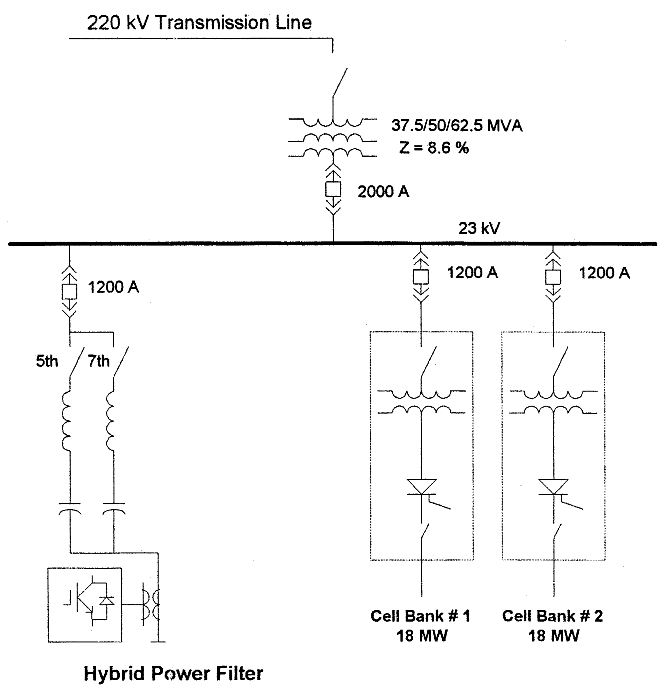


Fig. 13. Single-phase equivalent system with hybrid compensation and the worst operating condition: only one six-pulse converter is connected to the bus and passive filters tuned at fifth and seventh harmonic connected.

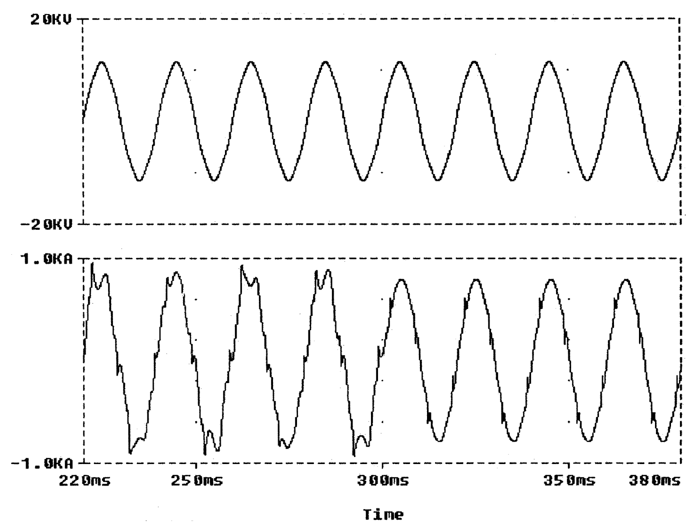


Fig. 15. Simulated waveforms for steady-state operating conditions and system voltage waveform distorted. Top: voltage source waveform with 3% of fifth harmonic; bottom: system line current (active power filter compensation starts at $t = 300$ ms).

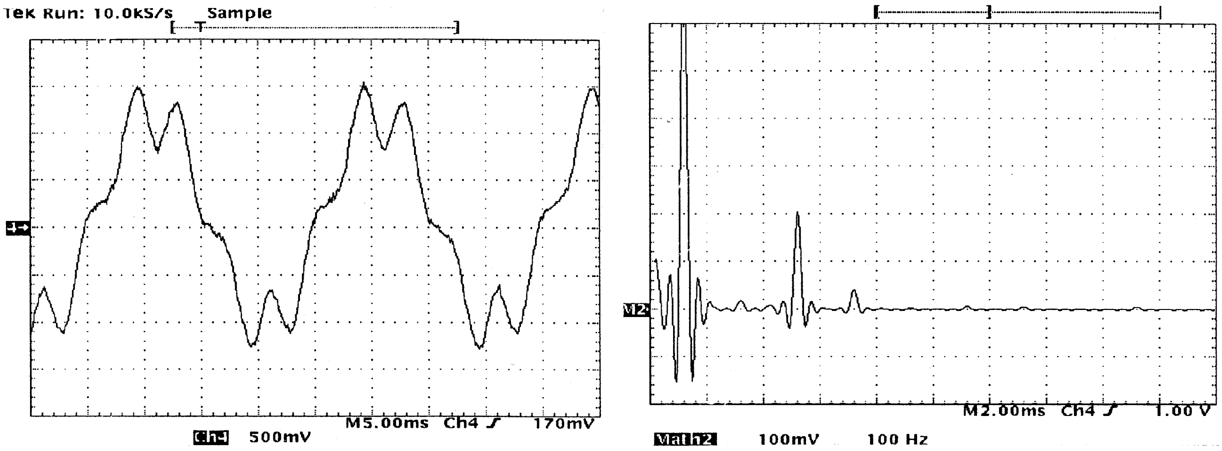
operates $(t = 300 \text{ ms})$, the system line current THD is reduced to 4.7%.

Voltage distortion in the power distribution system affects the compensation characteristics of passive filters, as shown in Fig. 15. If a small harmonic distortion exists in the voltage waveform, for example a 3% of fifth harmonic, the passive filter compensation performance is significantly reduced. In this case the THD of the line currents increases to 15.2%. In order to avoid these types of problems, the active power filter is connected, and the THD of the line current is reduced to 4.8%. Moreover, the operation of the active power filter protects the passive filter from an overload condition, in case a resonance is generated at 250 Hz.

The simulated results shown in this section test the compensation effectiveness of hybrid active power filters, and the possibility of improving passive filter compensation performance.

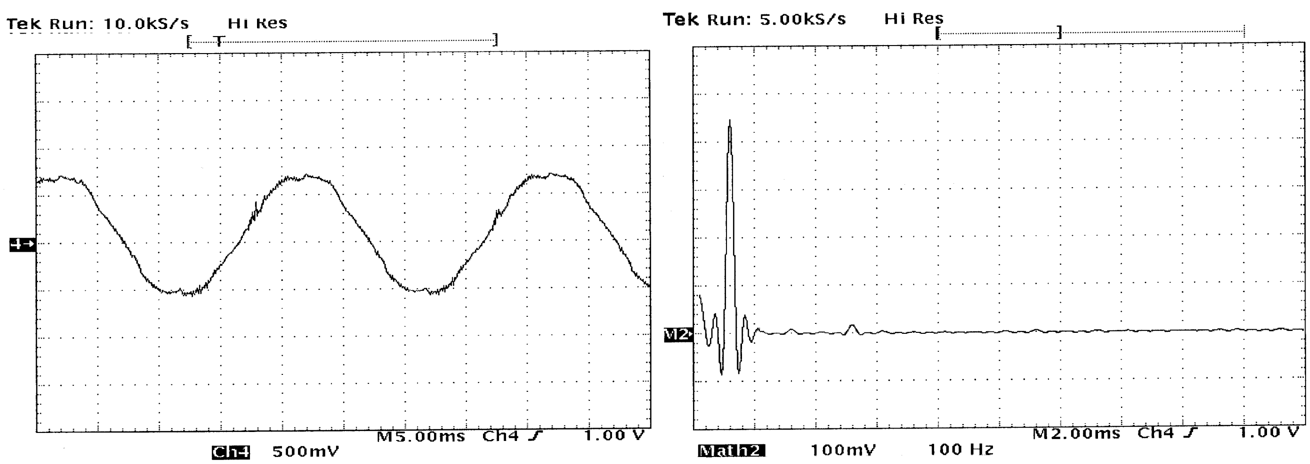
V. Experimental Results

A laboratory prototype using insulated gate bipolar transistor (IGBT) switches was implemented and tested in the compensation of a six-pulse controlled rectifier. The inverter was operated at 4-kHz switching frequency and was connected in series to a passive filter through a coupling transformer with turns ratio equal to 15. The passive filter was tuned at the fifth harmonic (250 Hz). The passive filter used in the experimental setup was implemented with $C_5 = 110$ μF, $L_5 = 3.6$ mH, and quality



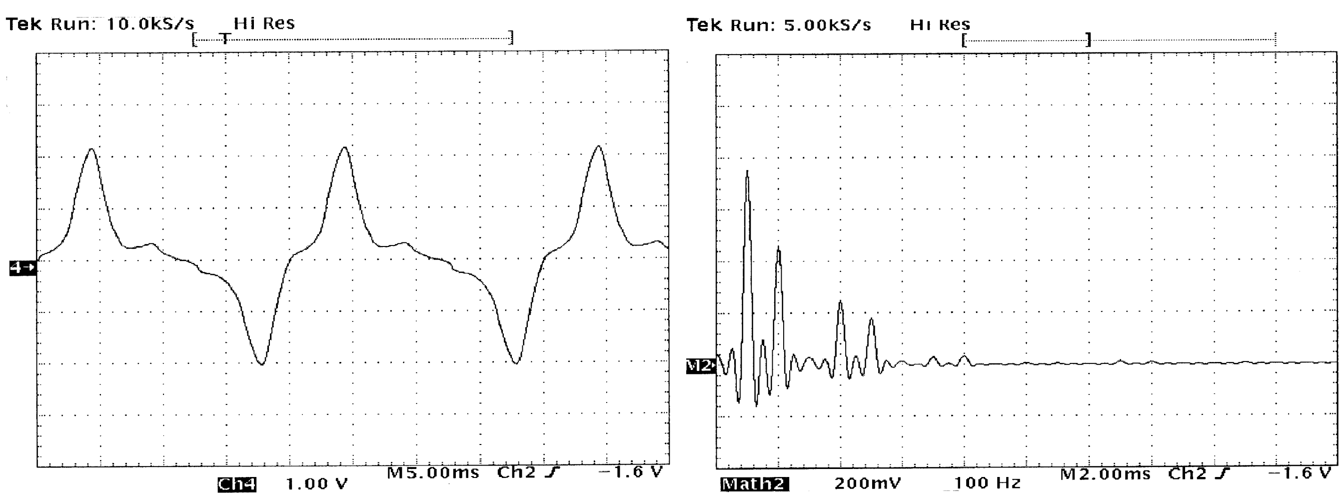
(a) (b)

Fig. 16. Experimental ac line current waveform with passive filtering compensation. (a) Line current waveform ($\mathrm{THD} = 24\%$). (b) Line current frequency spectrum.



(a) (b)

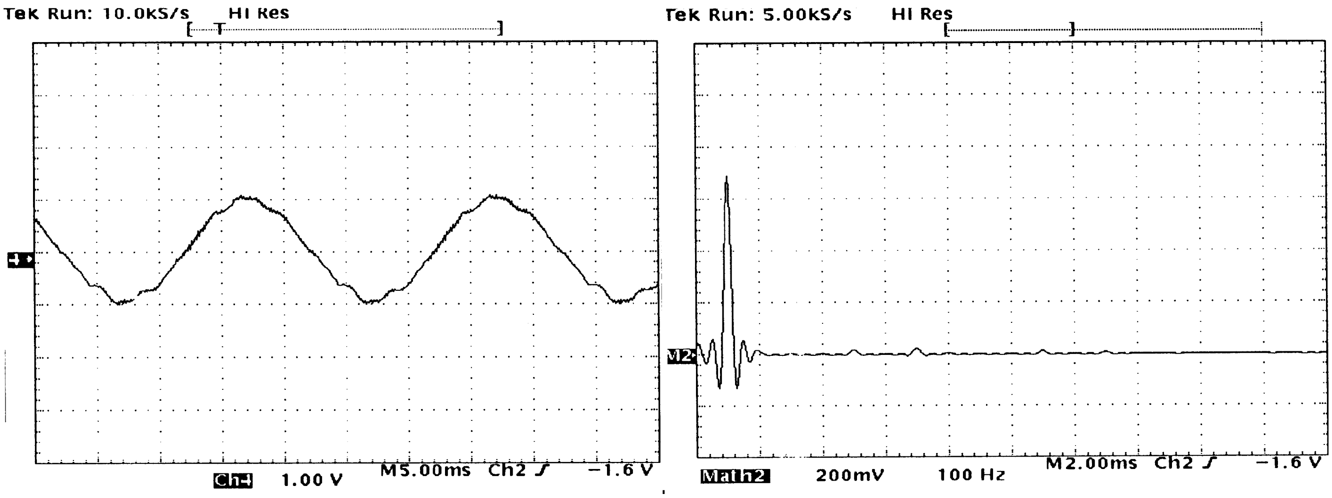
Fig. 17. Experimental ac line current waveform with hybrid filter compensation. (a) Line current waveform ($\mathrm{THD} = 6.3\%$). (b) Associated frequency spectrum.



(a) (b)

Fig. 18. Experimental ac line current waveform for resonant compensation. (a) Line current waveform ($\mathrm{THD} = 60\%$). (b) Associated frequency spectrum.

factor equal to 7. Steady-state experimental results are illustrated in Figs. 16–19. In particular, Fig. 16(a) shows the system line current when only the passive filter is connected; the associated frequency spectrum is shown in Fig. 16(b). In this case, the line current THD is equal to 24%. With active compensation, the system ac line current is reduced to 6.3% as shown in Fig. 17. In Fig. 18, the nonlinear load resonates with the passive filter generating an ac line current with 60% THD. Once the ac-



(a) (b)

Fig. 19. Experimental ac line current waveform with hybrid topology compensation. (a) Line current waveform $(\mathrm{THD} = 4.9\%)$. (b) Associated frequency spectrum.

tive filter starts to compensate (hybrid topology) the resonance is effectively attenuated and the associated THD is reduced to 4.9% as shown in Fig. 19.

VI. Conclusion

The compensation performance of a hybrid filter was presented and analyzed. The hybrid active power filter combines the compensation characteristics of resonant passive and active power filters. It was proved that the proposed hybrid scheme is able to compensate displacement power factor and current harmonics simultaneously. The combination of passive and active power filters allows for better performance compensation of high voltage nonlinear loads. The compensation performance of the hybrid scheme was analyzed for different parameter variation and active power filter's gain. It was concluded that large values of active power filter's gain improves compensation effectiveness, independently of the passive filter performance. It is recommended that, for this type of application, the active power filter's gain must be greater than 15. The technical viability of the proposed scheme was verified by simulation using Pspice and with an experimental setup of 10 kVA.

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