Comparison of Active Filters Topologies in Medium Voltage Distribution Power Systems

V. F. Corasaniti, *Member, IEEE*, M. B. Barbieri, *Senior Member, IEEE,*
P. L. Arnera, *Senior Member, IEEE* and M. I. Valla, *Senior Member, IEEE*

Abstract--**This paper presents the design of different topologies of active power filters to compensate reactive power and harmonics in the medium voltage level of a distribution power system. One pure active filter and two hybrid topologies, are implemented. A pure active compensation is obtained with a Shunt Active Power Filter (SAPF). The shunt combination of SAPF and passive filter, form one of the hybrid topologies implemented, named Shunt Hybrid Active Power Filter (SHAPF). The other hybrid topology, called Hybrid Shunt Active Power Filter (HSAPF), connects the active filter in series with two shunt passive filters. Simulation for different load demands and distortions are performed. Finally a comparative evaluation of the different filters is carried out.**

Index Terms--**Active Filters. Distribution Power System. Harmonics. Power Quality. Reactive Power.**

I. INTRODUCTION

Non-linear loads and equipments in the consumer side and renewable energy sources in the generation side are defining the need of power electronics as an essential interface in power systems to improve Power Quality [1][2]. Voltage distortion, due to current harmonics, has become a major problem for the utilities at distribution levels. Utilities frequently encounter harmonic related problems, such as higher transformers and line losses, reactive power, and resonance problems, de-rating of distribution equipment, harmonic interactions between the utility and loads, reduced system stability and reduced safe operating margins [1][3].

The use of traditional compensation with capacitor banks and passive filters gives rise to harmonic propagation. That is harmonic voltage amplification due to resonance between line inductances and shunt capacitors. So, different active solutions have been continuously analyzed in the last years [4]-[7]. A lot of research has been followed on different topologies to improve Power Quality [8]-[10].

Among all this compensation alternatives the hybrid topologies which use passive and active filters result very attractive in distribution power systems where some passive compensation is already installed [11]-[14]. Such a combination between active and passive filters allows

reducing significantly the rating of the active filter, since its main task is to improve the filtering performance and to avoid the resonance problems introduced by passive filters. In this way it constitutes a simple and cheap solution for harmonics in distribution power systems.

A particular problem of an actual distribution power system is considered in this paper. Reconfiguration of the system imposes new constraints in different distribution substations (DS). Harmonic studies were performed considering the future configuration of the system. Voltage distortions at 13.8 kV busbar of the system and the working conditions of the capacitor banks were verified by means of harmonic flows [15]. A preliminary proposal suggested increasing the existing passive compensation with capacitor banks from 4.8 Mvar to 9.6 Mvar, but this solution introduced resonances near the 5th and 7th harmonics resulting in unacceptable distortion levels. Three active topologies connected to the medium voltage level of DS (SAPF, SHAPF and HSAPF) are proposed here to solve the particular problem of reactive power and harmonics compensation.

The paper is organized as follows. The system configuration and the harmonic problems are described in section II. The different topologies and their design are presented in section III to V. Their performances are evaluated in section VI. Finally conclusions are drawn in section VII.

II. SYSTEM DESCRIPTION

The 132 kV system, where the DS under study are connected, works meshed and connected to the 500 kV high voltage transmission system. In the future, the requirement to enhance the voltage profile at 13.8 kV level demands for new compensation in the different substations [15].

Fig. 1 shows the one line diagram of the system model adopted for the DS under test. The system is represented as an ideal voltage source of 132 kV connected to three transformers of similar characteristics, 132/34.5/13.8 kV and 15/10/15 MVA. The system is modeled by an equivalent impedance related to short circuit power at 13.8 kV. The short circuit power at 13.8 kV is approximately 200 MVA. There are no loads at the 34.5 kV level. All transformers are connected in parallel to 13.8 kV where the capacitor banks and the loads are placed. Feeders, underground cables and overhead lines, are considered at the load connection.

V. F. Corasaniti, M. B. Barbieri and P. L. Arnera are with IITREE-LAT. Facultad de Ingeniería Universidad Nacional de La Plata (FI-UNLP). (1900) 48 y 116. La Plata. Argentina (e-mail: iitree@iitree-unlp.org.ar).

M. I. Valla is with LEICI and CONICET. (FI-UNLP). La Plata. Argentina (e-mail: m.i.valla@ieee.org).
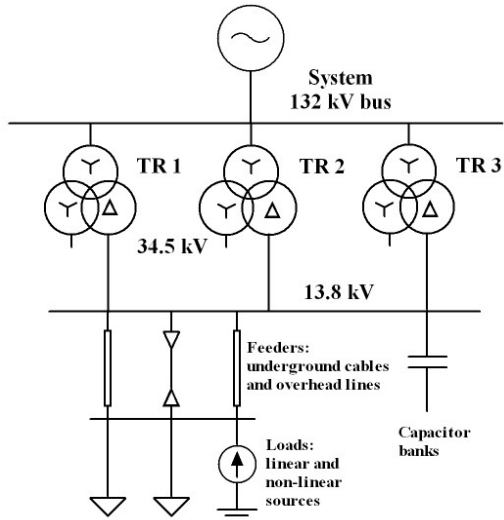
Fig. 1. One line diagram of system model.

The active and reactive power demand at the fundamental frequency is represented by a constant impedance model and the non-linear load corresponding to harmonics through sinusoidal current sources with amplitude and frequency corresponding to each harmonic.

Based on the power flow and harmonics studies performed on the system [15] the power total demand considered in this model at 13.8 kV bus system is 29.3 MVA with a PF = 0.8. The harmonics peak currents and the THD$_i$ defined by [16], are shown in Table I.

TABLE I
HARMONICS CURRENTS

i_h	i_5 (A)	i_7 (A)	i_{11} (A)	i_{13} (A)	THD$_i$ (%)
Peak values	74.9	54	24.5	18.7	5.4

A reactive compensation of 9.6 Mvar will result in PF = 0.94 at 13.8 kV bus system which is the goal for the proposed compensator.

Compensation of the reactive currents with capacitors banks of 4.8 Mvar gives rise to parallel resonances which increase the harmonics to unacceptable levels. The results of this compensation, P and Q defined by [16] together with the reactive power provided by capacitor banks (Q$_{AC}$) and the current and voltage distortion, are summarizes in Table II.

TABLE II
POWERS AND POWER FACTOR RESULTS

Q$_c$ (Mvar)	P (MW)	Q (Mvar)	V$_1$ phase (kV rms)	THD$_v$ (%)	I$_1$ line (A rms)	THD$_i$ (%)	$Pf_{tot.}$	Q$_{Ac}$ (Mvar)
0	23.4	17.7	7696	5.66	1269	5.43	0.8	-----
4.8	24.4	13.7	7865	9.65	1188	10.7	0.86	4.78
9.6	25.5	9.7	8040	9.64	1129	13.8	0.92	9.62

Table III summarizes the harmonic voltages and THD$_V$ for all cases together with the allowable limits fixed by IEEE [17] and the Argentinean regulation [18]. For Q_C = 4.8 Mvar and Q_C = 9.6 Mvar cases, the individual harmonic voltages for the 5th and the 7th harmonics and THD$_V$ are above the allowable limits, so a different compensation should be considered.

TABLE III
VOLTAGE HARMONICS RESULTS AND VERIFICATIONS

Harmonic voltages	Q$_c$ (0 Mvar)	Q$_c$ (4.8 Mvar)	Q$_c$ (9.6 Mvar)	IEEE limits	ENRE limits
V$_5$ (%)	3.29	5.47	**8.88**	3	6
V$_7$ (%)	3.32	**7.48**	3.61	3	5
V$_{11}$ (%)	2.37	2.30	0.86	3	3.5
V$_{13}$ (%)	2.14	1.42	0.56	3	3
THD$_V$ (%)	5.66	**9.65**	**9.64**	5	8

III. PURE ACTIVE FILTER

One of the most popular topologies employed in harmonic compensation is the Shunt Active Power Filter (SAPF) [19]. A general structure of the Shunt Active Power Filter (SAPF) is presented in Fig. 2.
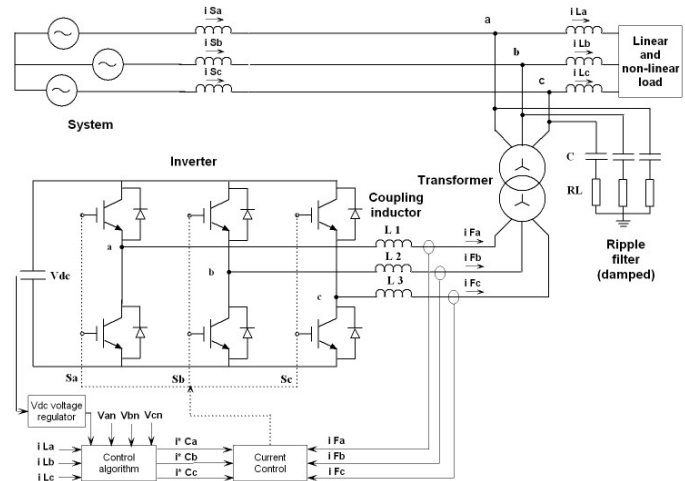

Fig. 2. General structure of the implemented SAPF.

In this case, the whole compensation is performed by the SAPF. The current harmonics are completely provided by the SAPF, while the reactive compensation is limited to 9.6 Mvar which is the goal for the proposed compensator and limits the current delivered by the SAPF.

It consists of a three phase current controlled voltage source inverter (CCVSI) connected to the grid through a coupling inductor and a transformer. In addition, a ripple filter is connected after the transformer to derive the high frequencies generated by the inverter commutation. The current references for the CCVSI are generated by the control system based on the instantaneous reactive power theory. The current loops are closed with hysteresis band controllers. The DC side of the inverter is built only with a capacitor of proper value and the active filter can build up and regulate the DC voltage on the capacitor without any external power supply.

The analysis of the SAPF is divided in two main sections: the CCVSI and the control block to obtain the desired currents and maintain the DC voltage of the CCVSI.

A. CCVSI

The CCVSI is a standard two level three phase voltage source inverter with IGBTs [1][4]. The current loops are closed with hysteresis controllers. The output current through

the coupling inductor is sampled at a fixed frequency in order to limit the switching frequency of the inverter. Its mean value is approximately equal to 10 kHz.

The value of the coupling inductor results from a trade off between filtering the high frequencies produced by switching the converter and allowing high di/dt on the inductor to follow the harmonic currents that should be damped. The switching frequencies are further filtered with a second order damped parallel filter which takes the high frequency currents away from the system [3].

The DC side capacitance is selected in order to keep the voltage ripple below 2 %. The DC value is chosen so that the converter can supply the current time derivatives demanded by the harmonics to be compensated. The DC voltage level is controlled with a proportional controller which modifies the active power reference to the converter as it will be analyzed in the next subsection.

Finally the coupling transformer adapts the voltage level of the power system (13.8 kV) to AC voltage obtained from the CCVSI with a 6.5 kV on the DC side. This transformer provides extra filtering of the switching frequencies.

B. Control System, Reference Currents Generator

The control system mainly measures the network phase voltages (V_{an}, V_{bn}, V_{cn}) and the load phase currents (i_{La}, i_{Lb}, i_{Lc}) and builds the reference currents for the CCVSI based on the instantaneous reactive power theory [5].

First, the measured variables are transformed to the stationary reference frame[α-β-0]. Then instantaneous powers are calculated

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} p_{DC} \\ q_{DC} \\ p_{0DC} \end{bmatrix} + \begin{bmatrix} p_{0AC} \\ q_{0AC} \\ p_{0AC} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_0 \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \quad (1)$$

where p is the real power, q the imaginary power and p_0 the zero sequence power.

The system under study is a three-wire system where the zero sequence may be neglected so in the sequel only p and q are considered. In the case of nonlinear loads, p and q have both DC and AC components. The mean value of the instantaneous real power (p_{DC}) equals three times the active power per phase, while the mean value of the instantaneous imaginary power (q_{DC}) equals three times the reactive power per phase. The AC components of both instantaneous powers correspond to the contribution of the harmonics and unbalances.

In the general case, the network will supply the DC value of the real power while its AC component as well as the whole imaginary power should be supplied by the SAPF. Then, the instantaneous real power is filtered in order to separate both components and to calculate the reference values p^* and q^*. Then the reference currents in the [α-β] frame are:

$$\begin{bmatrix} i_{C\alpha} \\ i_{C\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \cdot \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad (2)$$

and the phase currents of the CCVSI should be:

$$\begin{bmatrix} i_{Ca}^* \\ i_{Cb}^* \\ i_{Cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{C\alpha} \\ i_{C\beta} \end{bmatrix} \quad (3)$$

When the system voltages are distorted, the currents calculated with the previous equation will not exactly compensate the harmonics. Then, it is desirable to obtain the phase angle and frequency of the fundamental positive sequence voltage component (V_{+1}) instead of those directly measured. This is done by a Phase Locked Loop (PLL) [20] synchronous with the positive sequence of the sinusoidal phase voltages and a fundamental positive sequence voltage detector (*FPSVD*) [21] which determines the amplitude of (V_{+1}). The outputs of the *FPSVD* are pure sinusoidal phase voltages ($V'_{an}, V'_{bn}, V'_{cn}$) which are used to synchronize the filter currents and also to calculate the instantaneous powers.

A complete block diagram of the proposed control is presented in Fig. 3.
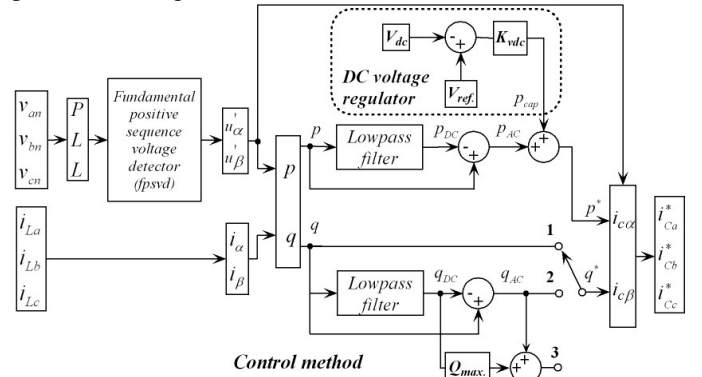

Fig. 3. Control block diagram of the SAPF.

The implemented control, show three possibilities to compensate q. Option 1 compensate the whole q, option 2 compensates only the AC components of q (q_{AC}) and option 3 compensates the AC components plus a part of the mean value of q determined by the limit $Q_{max..}$. In this analysis option 3 is selected with $Q_{max} = 9.6$ Mvar. The design parameters of SAPF are summarized in Table IV.

TABLE IV
SAPF DESIGN PARAMETERS

Inverter		Ripple filter (damped)		Transformer	
Vdc (V)	6500	R (ohm)	30	S (MVA)	15
C (uF)	7500	C (uF)	3.53	V_1 / V_2 (kV)	2.3 / 13.8
L (mH)	0.5	L (mH)	3.18	X (%)	10
		f_c (Hz)	1500	$L_{2.3kV}$ (mH)	0.112

IV. HYBRID SHUNT-SHUNT FILTER

A general structure of the Shunt Hybrid Active Power Filter (SHAPF) is presented in Fig. 4. It is formed connecting a shunt passive filter to the same general structure of SAPF show in Fig. 2. The difference lays in that the measured current not only considers the load current, but also the current consumed by the passive filter.
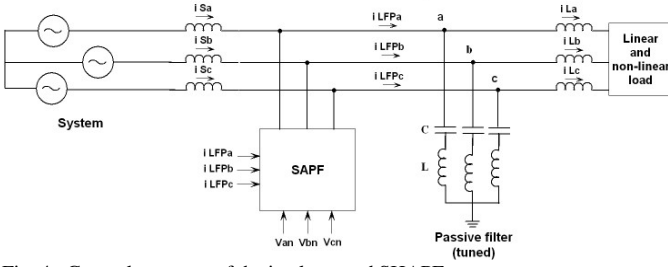
Fig. 4. General structure of the implemented SHAPF.

This topology takes advantage of the capacitor bank already installed in the DS under study. In order to avoid possible resonances with the capacitor bank, this is modified to make a passive filter. Then, 4.8 Mvar are compensated by the passive filter and less current is provided by the SAPF. It also supplies the harmonics that are not provided by the passive filter.

A. Active filter

The design of the active filter is the same of the above presented pure active topology. In this topology, the option 3 in the control system of Fig. 3 is selected, but $Q_{max.}$ is changed to 4.8 Mvar. Since the SAPF works with lower current, a smaller capacitance is required to maintain the same value of ripple of the DC voltage. The SAPF and the connection transformer are designed for a smaller power, as shown in Table V.

B. Passive filter

The passive filter consists of simple LC filter per phase tuned at 5th harmonics and 4.8 Mvar of reactive power [3]. So, defined the reactive power compensation, Q_c, the tuned harmonic frequency, f_s, and a typical quality factor, Q of each passive filter, the values of $C_f (uF)$, $L_f (mH)$, and $R_f (\Omega)$, are calculated by

$$Q_C (Mvar) = 2 \cdot \pi \cdot f \cdot V^2 \cdot C_f$$
$$f_S (Hz) = \frac{1}{2 \cdot \pi \cdot \sqrt{L_f \cdot C_f}} \qquad (4)$$
$$Q = \frac{X_o}{R_f}$$

where

f: is the system nominal frequency, 50 Hz.
V: is the system rms line voltage, 13.8 kV.
X_o: is the inductance (or the capacitance) reactance at resonance (Ω).

The design parameters of SHAPF and the passive filter are summarized in Table V. The ripple filter parameters are the same that were presented in Table IV.

TABLE V
SAPF AND PASSIVE FILTER DESIGN PARAMETERS

Inverter		Transformer		Passive filter (tuned)			
Vdc(V)	6500	S (MVA)	**10**	Q(Mvar)	4.8	C(uF)	80.2
C (uF)	**3000**	V_1/V_2(kV)	2.3/13.8	f_s (Hz)	250	L(mH)	5.05
L(mH)	0.5	X (%)	10	R(ohm)	0.17	Q	45
		$L_{2.3kV}$(mH)	0.168				

V. HYBRID SHUNT-SERIES FILTER

A general structure of the Hybrid Shunt Active Power Filter (HSAPF) is presented in Fig. 5. It consists of a three phase pulse width modulation (PWM) voltage source inverter (VSI) connected in series with one or more passive filters. They are directly connected to the system without the need of a transformer. The passive filters consist of simple LC filters per phase tuned at certain harmonic frequencies. In the same way as in SAPF and SHAPF, the switching frequencies are further filtered with the same second order parallel filter.
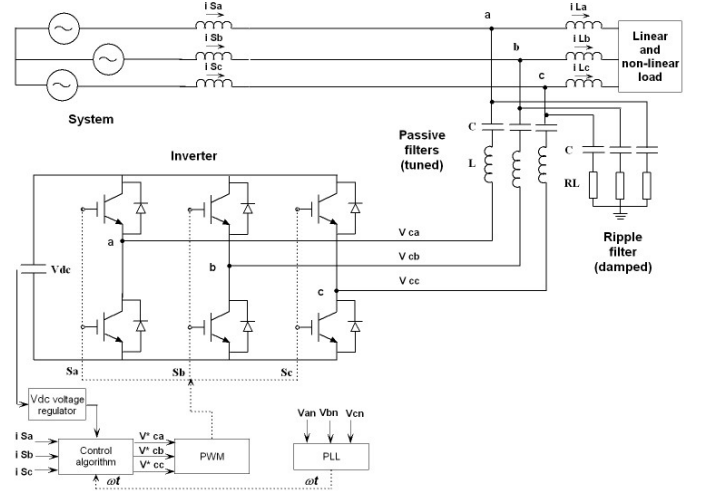

Fig. 5. General structure of the implemented HSAPF.

Basically, the active power filter acts as a controlled voltage source which forces the system line currents to become sinusoidal. The voltage references for the VSI are generated by the control system based on the measured line currents transformed to a rotating frame synchronous with the positive sequence of the phase voltages, and a close loop control of the DC voltage. This topology does not use the instantaneous powers. The active filter is used only to compensate harmonics while the 9.6 Mvar of reactive currents are damped by the passive filters.

The analysis and design of the HSAPF may be divided in three main sections: the passive filter, the PWM VSI and the control block to obtain the desired line currents and maintain the DC voltage of the PWM VSI.

A. Passive Filters

The passive filters have two main functions: reactive compensation and absorption of the harmonic currents produced by the load. Since the load of the DS is variable, it is advisable to have different levels of reactive compensation. Two passive filters tuned at 7th and 11th harmonics are proposed to provide 4.8 Mvar each. The reasons for this selection are,
• The LC filter tuned at the 7th and 11th harmonic frequency is less bulky and less expensive than one tuned at the 5th and 7th harmonic frequency.
• The filter tuned at the 11th harmonic presents lower impedance at the 13th harmonic than other tuned at the 7th harmonics.

Defined the reactive power compensation, the passive filters are design in the same way that in SHAPF topology through equations (4). Table VI summarizes the parameters of the passive filters.

TABLE VI
PASSIVE FILTERS PARAMETERS

7th Passive filter			11th Passive filter		
Q_c (Mvar)	4.8	C_f (uF)	80.2	Q_c (Mvar)	4.8	C_f (uF)	80.2
f_s (Hz)	350	L_f (mH)	2.57	f_s (Hz)	550	L_f (mH)	1.04
Q	45	R_f (Ω)	0.125	Q	45	R_f (Ω)	0.08

B. PWM Voltage Source Inverter

The PWM Voltage Source Inverter is a standard two level three phase voltage source inverter with IGBTs using a standard sinusoidal modulation with a carrier frequency of 10 kHz. The inverter is connected to the system through the passive filter. In the same way that in SAPF and SHAPF, the switching frequencies are further filtered with a second order damped parallel filter which takes the high frequency currents away from the system.

The DC side of the converter is built only with a capacitor of proper value. The capacitance is selected in order to keep the voltage ripple below 2 %. The DC value is chosen so that the converter can supply the current time derivatives demanded by the harmonics to be compensated. The active filter can build up and regulate the DC voltage on the capacitor without any external power supply or special start up circuit. The DC voltage level is controlled with a proportional controller. The inverter design values are: $Vdc = 1500$ V and $C_{dc} = 3000$ uF.

C. Control System, Reference Voltage Generator

The control system measures the three-phase supply currents (i_{Sa}, i_{Sb}, i_{Sc}), the three-phase supply voltages (V_{an}, V_{bn}, V_{cn}) and the DC voltage of the inverter to build the reference voltages for the PWM VSI.

First, the three-phase supply currents (i_{Sa}, i_{Sb}, i_{Sc}) are transformed into the instantaneous active (i_d) and reactive (i_q) components using a rotating frame synchronous with the positive sequence of the system voltage.

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} sin(\omega_s t) & sin(\omega_s t - \frac{2\cdot\pi}{3}) & sin(\omega_s t + \frac{2\cdot\pi}{3}) \\ cos(\omega_s t) & cos(\omega_s t - \frac{2\cdot\pi}{3}) & cos(\omega_s t + \frac{2\cdot\pi}{3}) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (5)$$

where $\omega_s t$ is the phase of the positive sequence of fundamental frequency of system voltage and is provided by a Phase Locked Loop (PLL).

The system under study is a three-wire system where the zero sequence may be neglected so in the sequel only i_d and i_q are considered. The active and reactive currents can be also decomposed in their DC and AC values. The mean values of the active and reactive currents $(i_{dDC}$ and $i_{qDC})$ are the fundamental active and reactive current components, while the AC components of both currents $(i_{dAC}$ and $i_{qAC})$ correspond to the contribution of active and reactive harmonics components.

It is desired that the system supplies the DC value of the active current while its AC component as well as the whole reactive current are supplied by the HSAPF. Considering the reactive current, its DC value is supplied by the passive filter while the VSI provides an AC voltage to damp the harmonics. Then, the instantaneous active and reactive currents are filtered in order to separate both components and generate the correct reference to the PWM modulator.

$$\begin{bmatrix} i_{d_{AC}} \\ i_{q_{AC}} \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} i_{d_{DC}} \\ i_{q_{DC}} \end{bmatrix} \quad (6)$$

These current components are amplified by a gain K_I to obtain the references to the power inverter.

Besides providing the harmonic currents, the control system should maintain the DC voltage of the PWM VSI to guarantee its accurate operation. It is important to notice that no active fundamental current flows through the LC filter. So the DC voltage control is obtained controlling i_q as shown in Fig. 6, where the diagram of the control system is presented.
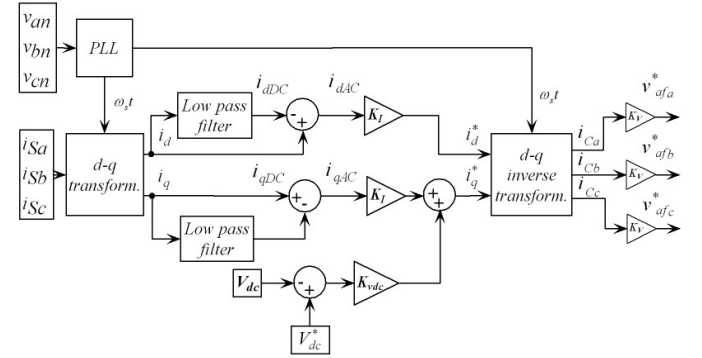

Fig. 6. Control block diagram of the HSAPF.

Then the reference currents in the [a-b-c] frame are

$$\begin{bmatrix} i_{c_a} \\ i_{c_b} \\ i_{c_c} \end{bmatrix} = \begin{bmatrix} sin(\omega_s t) & cos(\omega_s t) \\ sin(\omega_s t - \frac{2\pi}{3}) & cos(\omega_s t - \frac{2\pi}{3}) \\ sin(\omega_s t + \frac{2\pi}{3}) & cos(\omega_s t + \frac{2\pi}{3}) \end{bmatrix} \cdot \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \quad (7)$$

Each current component is amplified by a gain K_V which corresponds to the voltage gain of the PWM Inverter. The resultant signal v_{af}^* is the voltage reference produced by the control which should be synthesized by the power inverter.

VI. PERFORMANCE EVALUATION

The proposed filter topologies to compensate the DS under study are evaluated and compared in this section. The DS and filters are simulated for different load conditions. First a load and distortion equal to the 75 % of maximum demand is considered. Afterwards, the load and the harmonic distortion are increased to the maximum demand. Transient and steady state behavior are evaluated.

First the steady state compensation is considered. The three implemented topologies are compared with regards to the line voltage and current upstream the filters. The final stage of maximum demand and 9.6 Mvar reactive compensation are presented.
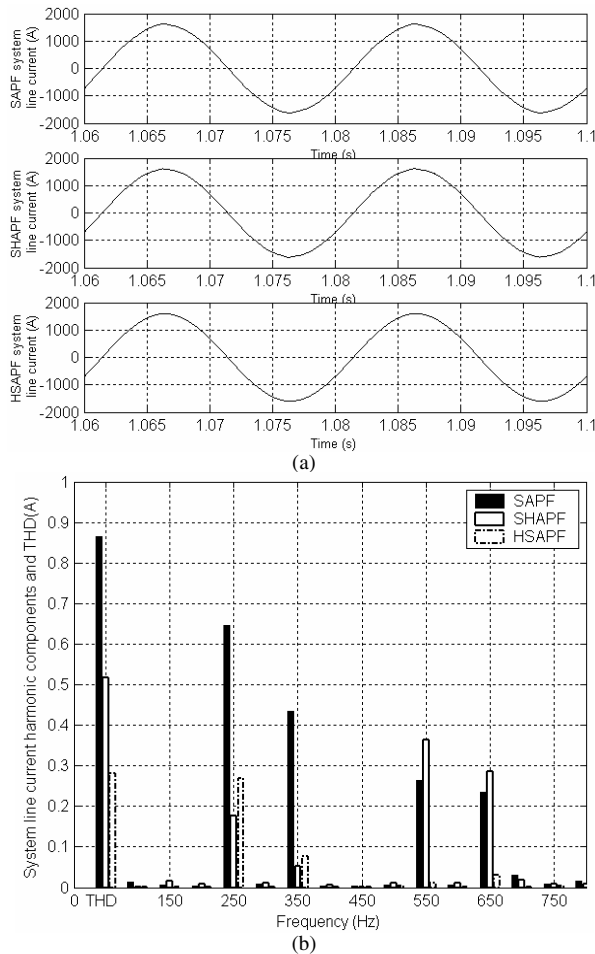

Fig. 7. System line currents of 3 topologies in 13.8 kV bus.
(a) Waveforms (b) Harmonic components and THD.

Fig. 7 a) shows the system line current waveforms at 13.8 kV bus (upstream the filters), while Fig. 7 b) presents the harmonic components together with the THD. The equivalent results corresponding to the system phase voltages are presented in Figs. 8 a) and b). In both cases, harmonic components are expressed as a percent of the fundamental value at 50 Hz.

The results of Figs. 7 and 8 show a decrease of the current and voltage harmonics and the THD with respect to compensation with capacitor banks. This is confirmed in Table VII when compared to the last row of Table II. Here the variables of the three filter topologies are presented.

TABLE VII
POWERS AND POWER FACTOR RESULTS

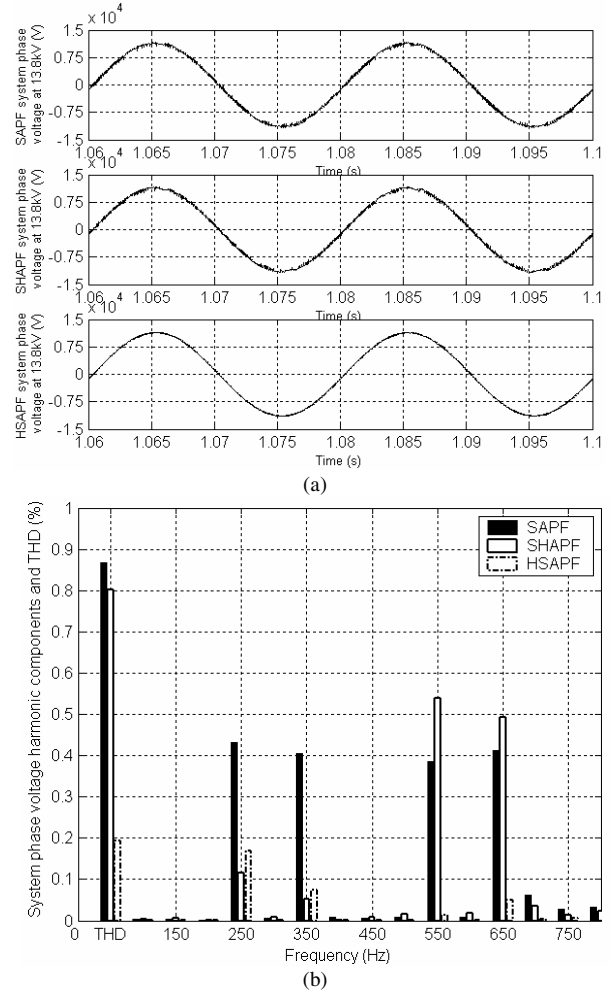| Topol.	P (MW)	Q (Mvar)	$V_{1\ phase}$ (kVrms)	THD_v (%)	$I_{1\ line}$ (Arms)	THD_i (%)	$Pf_{tot.}$	Q_{Ac} (Mvar)
SAPF	25.6	9.42	8039	0.89	1131	0.86	0.94	9.9
SHAPF	25.6	9.15	8050	0.8	1128	0.52	0.94	10.2
HSAPF	25.6	9.11	8055	0.2	1126	0.28	0.94	10.2

Fig. 8. System phase voltages of 3 topologies in 13.8 kV bus.
(a) Waveforms (b) Harmonic components and THD.

Table VIII summarizes the voltage harmonics and THD for the 3 topologies with the allowable limits like in Table III for capacitor banks. The individual harmonic voltages and THD are well below the allowable limits.

TABLE VIII
HARMONIC VOLATGE RESULTS AND VERIFICATIONS

Voltage Harmonics	SAPF	SHAPF	HSAPF	IEEE limits	ENRE limits
V_5 (%)	0.55	0.12	0.17	3	6
V_7 (%)	0.43	0.05	0.07	3	5
V_{11} (%)	0.38	0.52	0.01	3	3.5
V_{13} (%)	0.4	0.48	0.05	3	3
THD (%)	0.89	0.8	0.2	5	8

Fig. 9 a) shows the filter currents waveforms of one phase entering to 13.8 kV, while Fig. 9 b) shows their harmonic spectrum.

The results of Fig. 9 a) and b) show that its fundamental value corresponds to a reactive compensation of 4.8 Mvar (SHAPF) and 9.6 Mvar (SAPF and HSAPF). The harmonics are those required by the load in the case of SAPF and HSAPF, while the SHAPF only provides those harmonics which are not compensated by the tuned passive filter.
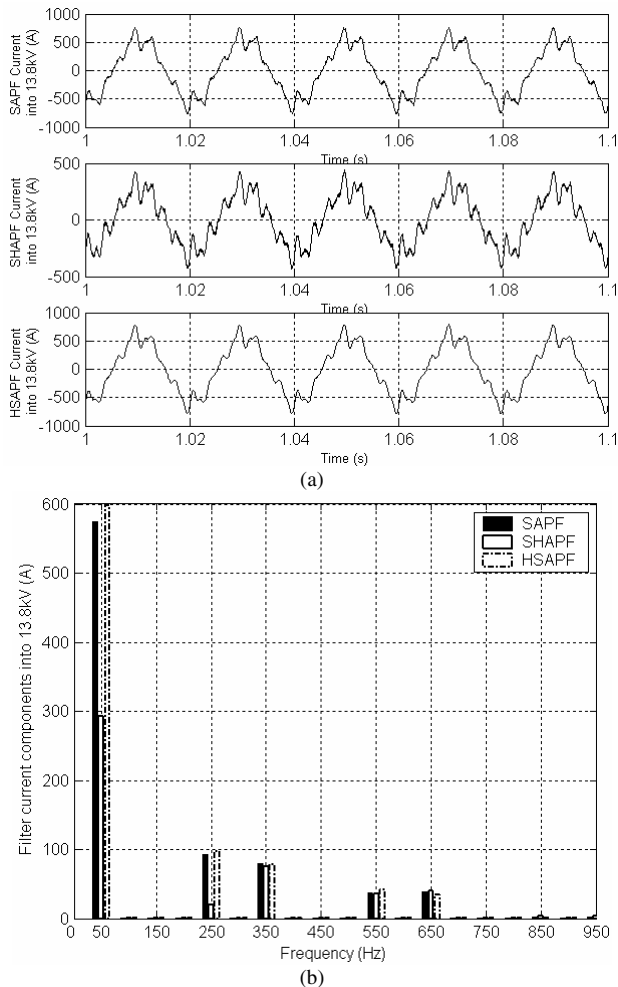
(a)

(b)

Fig. 9. Filter current components of 3 filters into 13.8 kV bus.
(a) Waveforms (b) Fundamental and harmonic components.

(a)

(b)

Fig. 10. DC voltages of 3 inverters. (a) Waveforms (b) Harmonic components.

The transient behavior is mainly evaluated through the DC bus voltage since there are no significant disturbances in the line voltages or currents. Figs. 10 a) and b) show the DC voltages waveforms and harmonic components, respectively.

The SAPF and SHAPF show very similar disturbances. In both cases the DC bus is pre-charged to 6500 V and present a slight drop when the filter starts (t = 0.25s). The DC voltage suffers a voltage drop of around 15 % when the load is increased from the 75 % the 100 % (t = 0.45s), but it reestablished its mean value in less than 100 ms. The HSAPF does not need any initialization of the DC voltage. It starts with null voltage and establishes it reference value of 1500 V in less than 2 fundamental cycles. The increment of the demand (t = 0.45s) provokes a voltage drop which is readily recovered, while the connection of the second passive filter (t = 0.75s) gives rise to a voltage increment. Neither of the disturbances is significant to the filter performance.

Fig. 10 b) shows that the 6th harmonic and its multiples dominate. This corresponds to the AC components of the instantaneous active power.

The three filters show very good performances. Regarding their complexity and component count Table IX summarizes the requirements of the three topologies.
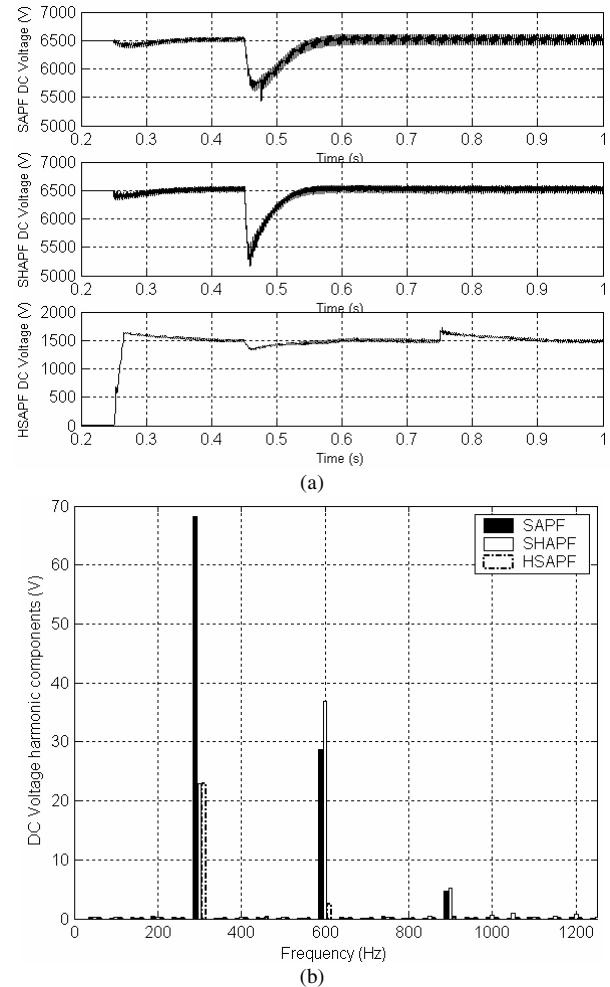
TABLE IX
SUMMARY OF TOPOLOGIES COMPONENTS

Components			SAPF	SHAPF	HSAPF
Inverter	IGBT rating	$S = \sqrt{3}/2 . V_{DC}. I_{peak}$ (MVA)	26	15	1
		Current (A peak)	4600	2600	800
	DC capacitor	Voltage (V)	6500	6500	1500
		C (uF)	7500	3000	3000
Coupling inductor			yes	yes	no
Connection transformer (MVA)			1 x 15	1 x 10	no
Passive filter (Mvar)			no	1 x 4.8	2 x 4.8
Ripple filter			yes	yes	yes

VII. CONCLUSIONS

The design of a three topologies of shunt active or hybrid filters to compensate reactive power and harmonics in the medium voltage level of a power distribution system were presented and compared in this paper. The first topology considered full compensation with the active filter, the second one used the existing capacitor bank and built the complementary compensation with the active filter, while the third one considers the active filter in series with 2 passive filters. The three proposals show very good performance. The last topology results in a more economic solution in particular when there is some passive compensation already included in the distribution system. It is rather simple and it presents a very good performance in transient and steady state operation.

VIII. REFERENCES

[1] E. Acha, V.G. Agelidis, O. Anaya-Lara, T.J.E. Miller, *Power Electronic Control in Electrical Systems*, Newnes Power Engineering Series, 2002.

[2] J. Arrillaga, N.R. Watson, S. Chan, *Power System Quality Assessment*, Wiley & Sons, Chichister, England, 2000.

[3] J. Arrillaga, N. R. Watson, *Power System Harmonics*, 2nd ed., Wiley & Sons Ltd., 2003.

[4] Narain G. Hingorani, Laszlo Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*, Wiley-IEEE Press, 1999. ISBN-0780334558

[5] H. Akagi, E. Watanabe and M. Aredes, *Instantaneous Power Theory and Applications to Power Conditioning*, IEEE Press Series on Power Engineering, 2007.

[6] H. Akagi, "Active Harmonic Filters," *Proceedings of the IEEE*, vol. 93, No. 12, pp. 2128 – 2141, December 2005.

[7] C. Zhang, Q. Chen, D. Li; Y. Zhao, "A Novel Power Quality Conditioner Applied to High Voltage Power Systems," *in Proc.2006 IEEE PES general meeting Conf.,* pp.1-5.

[8] B. Singh, K. Al-Haddad and A. Chandra, "A Review of Active Filters for Power Quality Improvement, " *IEEE Trans. Industrial Electronics*, vol. 46, No. 5, pp. 960-971, October 1999.

[9] F. Chen, H. Cheung, L. Wang, T.Mander, W.Liu, R. Cheung, "Adaptive D-based Active Power Line Filter for Industrial and Commercial Power Distribution," *in Proc.2007 IEEE PES general meeting Conf.,* pp.1-7.

[10] A. Huang, S. Bhattacharya, M. Baran, B. Chen, C. Han, " Active Power Management of Electric Power System Using Emerging Power Electronics Technology," *in Proc.2007 IEEE PES general meeting Conf.,* pp.1-7.

[11] R. Inzunza and H. Akagi, "A 6.6-kV Transformerless Shunt Hybrid Active Filter for Installation on a Power Distribution System," *IEEE Trans. Power Electronics*, vol. 20, No. 4, pp. 893-900, July 2005.

[12] D. Rivas, L. Morán, J. Dixon and J. R. Espinoza, "Improving Passive Filter Compensation Performance With Active Techniques," *IEEE Trans. Industrial Electronics*, vol. 50, No. 1, pp. 161-170, Feb. 2003.

[13] S. Srianthumrong and H. Akagi, "A Medium-Voltage Transformerless AC/DC Power Conversion System Consisting of a Diode Rectifier and a Shunt Hybrid Filter," *IEEE Trans. Industry Applications*, vol. 39, No. 3, pp. 874-882, May/Jun 2003.

[14] D. Detjen, J. Jacobs, R. W. De Doncker, and H.G. Mall, "A New Hybrid Filter to Dampen Resonances and Compensate Harmonic Currents in Industrial Power Systems With Power Factor Correction Equipment," *IEEE Trans. Power Electronics*, vol. 16, No. 6, pp. 821-827, Nov. 2001.

[15] V. F. Corasaniti, M. B. Barbieri, P. L. Arnera and M. I. Valla, "Load characterization in Medium Voltage of an Electric Distribution Utility Related to Active Filters," *in Proc.2006 IEEE PES TDC Conf.,* pp.1-7.

[16] IEEE Power Engineering Society Harmonics Working Group, "Tutorial on Harmonics Modeling and Simulation," IEEE-PES TP-125-0, 1998.

[17] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Standard 519-1992.

[18] *Base Metodológica para el Control de la Calidad del Producto Técnico*. Etapa 2. Ente Nacional Regulador de la Electricidad. Resolución ENRE 184/00, 2000.

[19] V. F. Corasaniti, M. Barbieri, P. Arnera & M. I. Valla, "Reactive and Harmonics Compensation in a Medium Voltage Distribution Network With Active Filters," *in Proc. 2007 IEEE ISIE'07*, pp. 2510-2515.

[20] L.N. Arruda, S.M. Silva, and B.J.C. Filho, "PLL structures for Utility Connected Systems," *in Proc. 2001 IEEE/IAS'01*, pp. 2655-2660.

[21] M. Aredes, J. Häfner and K. Heumann, "Three-phase four-wire shunt active filter control strategies, " *IEEE Trans. on Power Electronics*, vol.12, No. 2, pp. 311-318, March 1997.

IX. BIOGRAPHIES

Victor Fabián Corasaniti (GSM'05, M'07) He got his degree in Electrical Engineering from UNLP, Buenos Aires, Argentina, in 1999. He has been working for the IITREE-LAT FI-UNLP studying normal and transient conditions of electrical systems and technical planning since 1999. His special field of interest includes power systems operation and control, power quality and power electronics. He is an assistant professor in the EE Dept., UNLP.

Maria Beatriz Barbieri (M'97 SM'01) She got her degree in Telecommunications Engineering (with honors) from UNLP in 1984. She has been working for the IITREE-LAT FI-UNLP studying normal and transient conditions of electrical systems and in economic and technical planning since 1983. Her special field of interest includes Electrical Power Systems. She is Professor of Electricity and Magnetism at the EE Dept., UNLP. She is Argentina PES Chapter Chairman.

Patricia Liliana Arnera (M'99 SM'01) She got her degree in Electrical Engineering from the UNLP in 1981. She is Head of IITREE-LAT FI-UNLP and study transient conditions of electrical systems and working in Electromagnetic Fields and health. Her special field of interest includes Electrical Power Systems. She is Full Professor of Power System at the EE Dept., UNLP. She was Argentina PES Chapter Chairman in 2001-2002.

María Inés Valla (S'79-M'80-SM'97) She received the Electronics Engineer and Doctor in Engineering degrees from UNLP, in 1980 and 1994. She is Full Professor in the EE Department, UNLP. She is also member of Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). She is engaged in teaching and research of power converters and ac motor drives. Dr. Valla is Member of the IEEE Ethics and Membership Conduct Committee, a Senior Member of the Administrative Committee of the IEEE Industrial Electronics Society (IES). She has been a member of the organizing committees of several international conferences.