Comparison of power filter topologies for reducing the customer-generated disturbances caused by non-linear loads

M. I. Milanés[1], E. Romero[1] and F. Barrero[1]

[1] Department of Electronic and Electromechanical Engineering
School of Industrial Engineering
University of Extremadura
Apdo. 382, 06071 Badajoz (SPAIN)
phone:+34 924289600, fax:+34 924289601,
e-mail: milanes@unex.es, eromero@unex.es, fbarrero@unex.es

Abstract. This paper presents a study of different power filter topologies used to compensate the customer-generated disturbances caused by a non-linear load connected at the point of common coupling (PCC). The advantages and drawbacks of each topology are analyzed and an evaluation is performed by means of computer simulation under different conditions. The rating of the equipment and the *THD* in the source current have been carried out for comparison purposes. Finally, it is proposed a criterion for the selection of the most appropriate topology depending on the type of harmonic-producing load.

Key words: Passive filters, active filters, hybrid filters, IEEE-519, harmonics, unbalance.

1. Introduction

Proliferation of non-linear loads has contributed to decrease power quality in power distribution systems due to harmonic distortion in the voltage at the PCC. Besides, the harmonic currents demanded by this type of loads cause line losses, reactive power, resonance problems, harmonic interactions among customers or between the utility and load, etc. Some power filters have been developed as solutions to reduce these disturbances [1].

For a non-linear customer, the distortion at the PCC can be caused by the harmonic currents it injects or by the utility or other receptors connected at the same or near point of coupling. In this paper some power filters topologies are studied in detail. They are all installed in parallel with the load and try to keep the customer-generated harmonics within acceptable limits. The disturbances not produced by the own receptor have not been taken into account as aims of compensation, although the behaviour of the power filters in those situations has been studied.

The four analyzed topologies are:

1) *Parallel Passive Filters (PPF)*
2) *Parallel Active Filter (PAF)*
3) *Hybrid Filters: Active Filter in parallel with Passive Filters (AFPPF)*
4) *Hybrid Filter: Active Filter in series to Passive Filters (AFSPF)*

A neutral-pointed-clamped (NPC) voltage source inverter is used as active filter in all topologies formed by an active component. Passive components are parallel LC filters tuned to the dominant frequencies.

2. Parallel solutions for reducing the customer-generated disturbances at the PCC

In this section a brief study about the compensation capability of each topology is presented. In case of active or hybrid topologies the control strategies have been performed in order to achieve harmonic elimination, displacement power factor correction and balancing of non-linear loads. Typical control strategies for hybrid filters [2]-[5] do not compensate dynamic variation of fundamental reactive power nor unbalance. Novel strategies that improve the operation of these hybrid topologies are proposed.

A. Parallel Passive Filters (PPF)

Passive filters have been traditionally used to absorb harmonic currents and correct the displacement power factor. Each filter is formed by an inductor L_{PF} connected in series to a capacitor C_{PF} and designed so that its tuned frequency f_{PF} equals a dominant frequency in the load current. If at the tuned frequency its impedance Z_{PF}^{hPF} (mainly due to the resistor of the filter R_{PF}) is smaller than the source impedance Z_S^{hPF}, the passive filter offers a low-impedance path to the harmonic load current, preventing its derivation to the utility. The equivalent circuit of a system with a parallel passive filter is shown in Fig. 1. The source current, passive filter current and voltage at the PCC at the tuned frequency are:

$$i_{Sh_{PF}} \simeq \frac{u_{Sh_{PF}}}{Z_S^{h_{PF}}}, \quad (1)$$

$$i_{PFh_{PF}} \simeq i_{Lh_{PF}} - \frac{u_{Sh_{PF}}}{Z_S^{h_{PF}}}, \quad (2)$$

$$u_{PCCh_{PF}} \simeq R_{PF} \cdot \left(i_{Lh_{PF}} - \frac{u_{Sh_{PF}}}{Z_S^{h_{PF}}} \right). \quad (3)$$

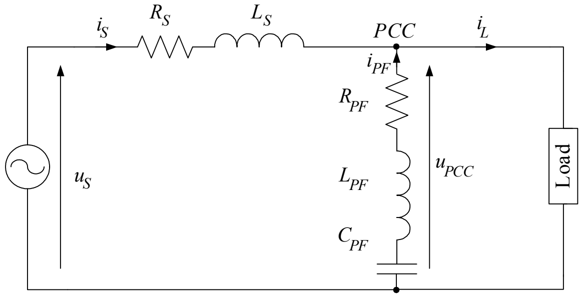


Fig. 1. Compensation with a parallel passive filter

From these equations, it could be concluded that there will only be tuned frequencies in the source current if the utility voltage contains this harmonic component, so the passive filter acts adequately because this disturbance is not a customer-generated pollution. However, this solution has got many drawbacks, summarized in Table II.

B. Parallel Active Filters (PAF)

Fig. 2 shows a PAF connected at the PCC operating as a controlled source that injects a current i_{AF}.

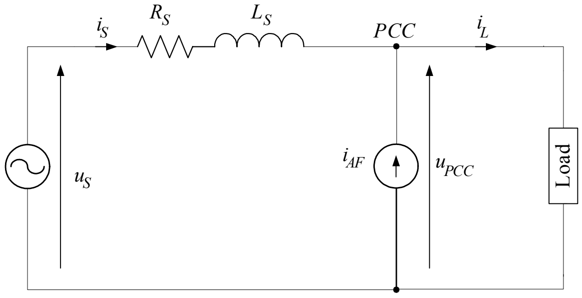


Fig. 2. Compensation with a PAF

The reference current for the PAF is determined by:

$$i_{AFref} = i_L - i_{Sref}\,, \quad (4)$$

where i_{Sref} is the reference source current whose calculus depends on the control strategy. For three-phase four-wire systems with harmonics and/or unbalance the best control strategy for getting the desired compensation objectives is Perfect Harmonic Cancellation (PHC) [6], that proposes a reference source current in phase with the positive-sequence fundamental voltage at the PCC $\mathbf{u}_{PCC1}^{+}$:

$$\mathbf{i}_{Sref} = \mathrm{K} \cdot \mathbf{u}_{PCC1}^{+} = \frac{\overline{p}_L}{\left(U_1^{+}\right)^2}\mathbf{u}_{PCC1}^{+} \quad (5)$$

where $\overline{p}_L$ is the constant instantaneous active power demanded by the load and calculated as the mean value of the product $u_{PCCa} \cdot i_{La} + u_{PCCb} \cdot i_{Lb} + u_{PCCc} \cdot i_{Lc}$ and U_1^{+} the modulus of the space vector $\mathbf{u}_{PCC1}^{+}$.

As it is indicated in Table II, PAF operates suitably for any utility voltage or load current conditions, but they require a large inverter rating.

C. Active Filter in parallel with Passive Filters (AFPPF)

An AFPPF is formed by an active filter in parallel with one or more passive filters, as it is shown in Fig. 3. The passive equipment is in charge of one or more dominant harmonics suppression and displacement power factor improvement. The AF acts as a controlled source current reducing the higher harmonics in the load current and mitigating the problems of passive filters working alone.

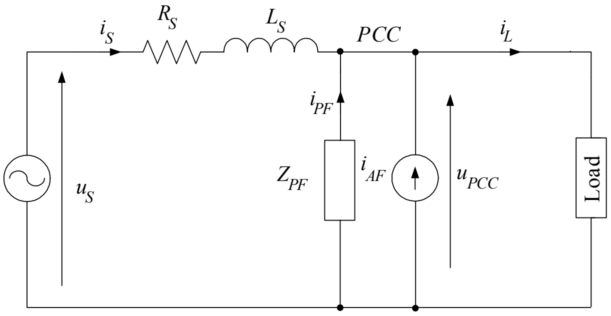


Fig. 3. Compensation with an AFPPF

As the AF shares the compensation objectives with the passive filters, its reference current is proposed as

$$i_{AFref} = i_L - i_{Sref} - i_{PF} = i_L - i_{Sref} - i_{Lh_{PF}}^{lim} + \frac{u_{PCC1}}{Z_{FPh_{PF}}^{1}}\,, \quad (6)$$

being:

$$i_{Lh_{PF}}^{lim} = \begin{cases} i_{Lh_{PF}} & \text{if } I_{Lh_{PF}} \le I_{PFh_{PF}}^{lim} \\ \dfrac{i_{Lh_{PF}}}{I_{Lh_{PF}}} \cdot I_{PFh_{PF}}^{lim} & \text{if } I_{Lh_{PF}} > I_{PFh_{PF}}^{lim} \end{cases}, \quad (7)$$

where $I_{Lh_{PF}}$ is the RMS tuned harmonic load current and $I_{PFh_{PF}}^{lim}$ is the limited RMS tuned current in the passive filter. This novel control strategy improves the operation of the equipment, preventing overload due to increased tuned harmonic components in the load current and allowing dynamic changes in fundamental reactive power. The rating of the active equipment is reduced thanks to the collaboration of the passive part. The features and disadvantages of this topology under different conditions are displayed in Table II.

D. Active Filter in series to Passive Filters (AFSPF)

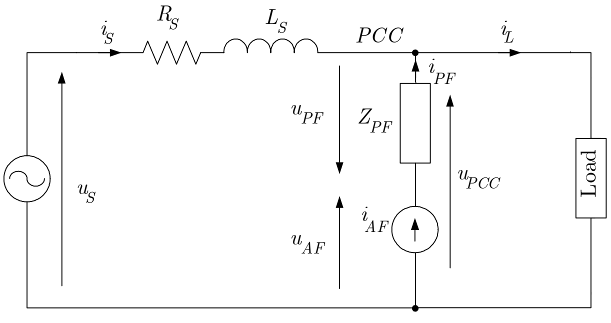


Fig. 4. Compensation with an AFSPF

An AFSPF consists of an active filter connected in series to one or more parallel passive filters, as it is shown in Fig. 4. The displacement power factor and tuned harmonic currents are compensated in a passive manner, so under normal conditions the voltage across the active filter u_{AF} for fundamental or tuned frequencies is zero (see Table I). The active filter only operates at other harmonic orders and helping passive filters under abnormal situations.

TABLE I. – Active filter behaviour for different harmonic orders under normal or abnormal conditions

Harmonic order	Normal conditions	Abnormal situations which need compensation
$h = 1$	$u_{AF1} = 0$	- Changes in Q_1 - Unbalance
$h = h_{PF}$	$u_{AFh_{PF}} = 0$	- $\Delta u_{PCCh_{PF}}$ - $\Delta i_{Lh_{PF}}$ - Mistuning
$h \neq h_{PF}$, $h \neq 1$	$u_{AFh} = u_{PCCh} + i_{Lh} \cdot Z_{PF}^{h}$	- Series resonance - Parallel resonance

However if the compensation of fundamental reactive power has been looked for in the design of passive filters, they will exhibit a small bandwidth, offering a high impedance for not-tuned frequencies. In these situations it would be required a great harmonic voltage generation by the active filter, resulting a large rating equipment. That is the reason why this topology is usually used to operate as a Dominant Harmonic Filter (DHF) [4] paying only attention to fundamental and tuned harmonic compensation, reducing the apparent power of the active component.

A novel control strategy is proposed for the DHF, which calculates the reference source current as:

$$i_{AFref} = i_{PFref} = (i_{L1} - i_{L1d}^{+}) + i_{Lh_{PF}}^{lim}\,, \quad (8)$$

where i_{L1d}^{+} is the positive-sequence fundamental load current and $i_{Lh_{PF}}^{lim}$ has been defined in equation (7).

E. Comparison of compensation capabilities

The compensation capabilities of these four topologies have been analyzed taking into account these different conditions:

1) *Ideal mains: u_S sinusoidal and balanced*
2) *Series resonance*
3) *Parallel resonance*
4) *Tuned harmonics on utility voltage, u_S*
5) *Increase of tuned harmonics on load current, i_L*
6) *Mistuning*
7) *Dynamic compensation of Q_1*
8) *Unbalance*
9) *Compensation of non-dominant harmonics*

The results of this comparative evaluation using the control strategies explained in the previous sections are summarized in Table II.

TABLE II. – Compensation capabilities of the compared topologies under different conditions

Conditions	PPF	PAF	HF: AFPPF	HF: AFSPF
Ideal mains	☑	☑	☑	☑
Series resonance	☒	-	☒	☑
Parallel resonance	☒	-	☑	☑
Tuned harmonics in u_S	☒	☑	☒	☑
Increase of tuned harmonics in i_L	☒	☑	☑	☑
Mistuning	☒	-	☒	☑
Dynamic compensation of Q_1	☒	☑	☑	☑
Unbalance	☒	☑	☑	☑
Compensation of non-dominant harmonics	☒	☑	☑	☒

(☑: YES; ☒: NO; -: Without sense)

3. Simulation analysis

In order to demonstrate the conclusions obtained in the theoretical analysis and get numerical results for comparison purposes, computer simulations have been performed using Simulink and Matlab.

The system chosen for simulation is shown in figure 5. It is a three-phase four-wire system, 50 Hz. The supply impedance has been selected so that the Short Circuit Ratio SCR < 20, getting an unfavourable value that increases distortion at the PCC and possibilities of series and parallel resonances. The non-linear load is a controlled rectifier with resistive load. The parameters of the system are displayed in Table III, where the basis values of voltage and apparent power are also indicated.

TABLE III. – Parameters of the simulation system

U_B^{L-L}	$S_B^{3\phi}$	R_S	L_S	SCR	R_L
400 V	350 kVA	25 mΩ (5,47%)	82 μH $X_S^1 = 5,63\%$	13,3	0,82 Ω

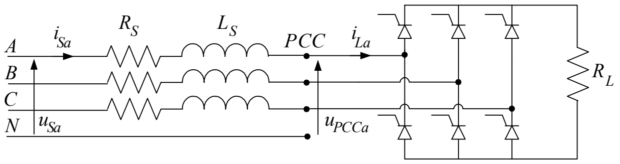


Fig. 5. Three-phase four-wire system with the non-linear load used in computer simulations.

The compensation objectives are:

1) meet IEEE-519 recommended harmonic levels in source current and voltage at the PCC,
2) attain unity displacement power factor from a limit value of 0,87 and
3) get balanced source currents.

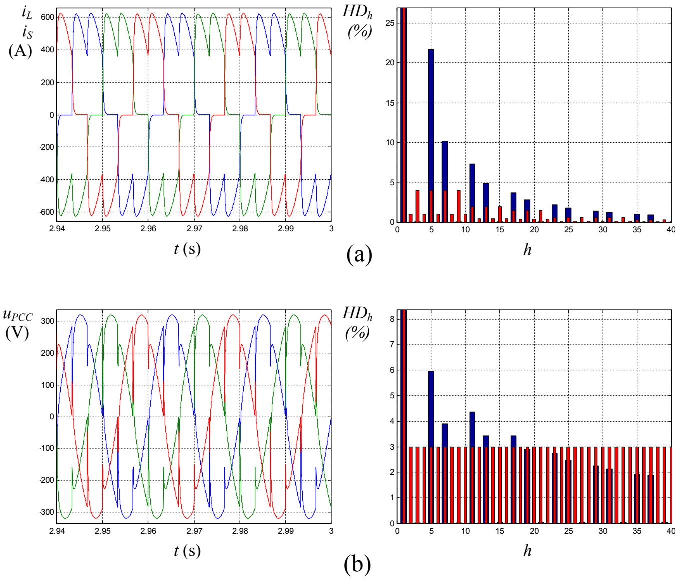
Varying the firing angle of the controlled rectifier, the unfavourable displacement power factor (0,87) corresponds to $\alpha = 30^{o}$, which at the same time, produces the highest current slopes. The waveforms and spectra of the load current and the voltage at the PCC when the mains are ideal are shown in Fig. 6. Following Standard IEEE-519 the individual harmonic distortion HD_h in current and voltage are calculated as

$$HD_{h,I_L} = \frac{I_h}{I_L}100\%; \quad HD_{h,Un} = \frac{U_h}{U_n}100\% \;, (9)$$

where I_L is 480,5 A and U_n is 230 V for this simulation case.

Some values of the HD_h are over the IEEE-519 limits (drawn in red in the frequency spectra), so unacceptable values of *THD* result in the source current and voltage at the PCC (26,20% and 13,23% respectively, both greater than 5%). The four power filter topologies are applied to this system trying to comply with the compensation objectives.

As the dominant harmonics of this type of loads are 5th and 7th orders, two parallel passive filters tuned to those frequencies form the passive components of passive and hybrid topologies. The main parameters for each filter are summarized on Table IV, where *QF* is the quality factor and Q_1 the fundamental reactive power.



(a)

(b)

Fig. 6. Waveform and frequency spectrum for phase *A* in blue (in red EEE-519 HD_h limits) with α=30º: (a) load current, (b) voltage at PCC.

TABLE IV. – Passive Filters components and properties

	C_{PF}	L_{PF}	R_{PF}	QF_{PF}	Q_1
PF_5	1,9 mF	0,216 mH	5,2 mΩ	64,6	78644 VAr
PF_7	1,3 mF	0,154 mH	5,2 mΩ	66,2	57315 VAr

The active component for active and hybrid topologies is a NPC voltage source PWM inverter operating at 10 kHz, which uses dead-beat as duty-cycle modulation technique. The active filter parameters are indicated in Table V, depending on the topology.

TABLE V. – Active Filter parameters

L_{AF}	$C_1 = C_2 = C$	U_{dc}	Topology
0,3 mH (R_{int} = 0,05 Ω)	3 mF	1000 V	PAF AFPPF
0,3 mH (R_{int} = 0,05 Ω)	3 mF	600 V	AFSPF

The power filter topologies schemes are shown in Fig. 7. The simulation conditions that have been performed are indicated in the following sections.

A. Ideal mains: u_S sinusoidal and balanced

This is the reference case, where balanced and perfectly sinusoidal voltage without harmonic content is applied to the load. U_n = 230 V, 50 Hz.

B. Resonance

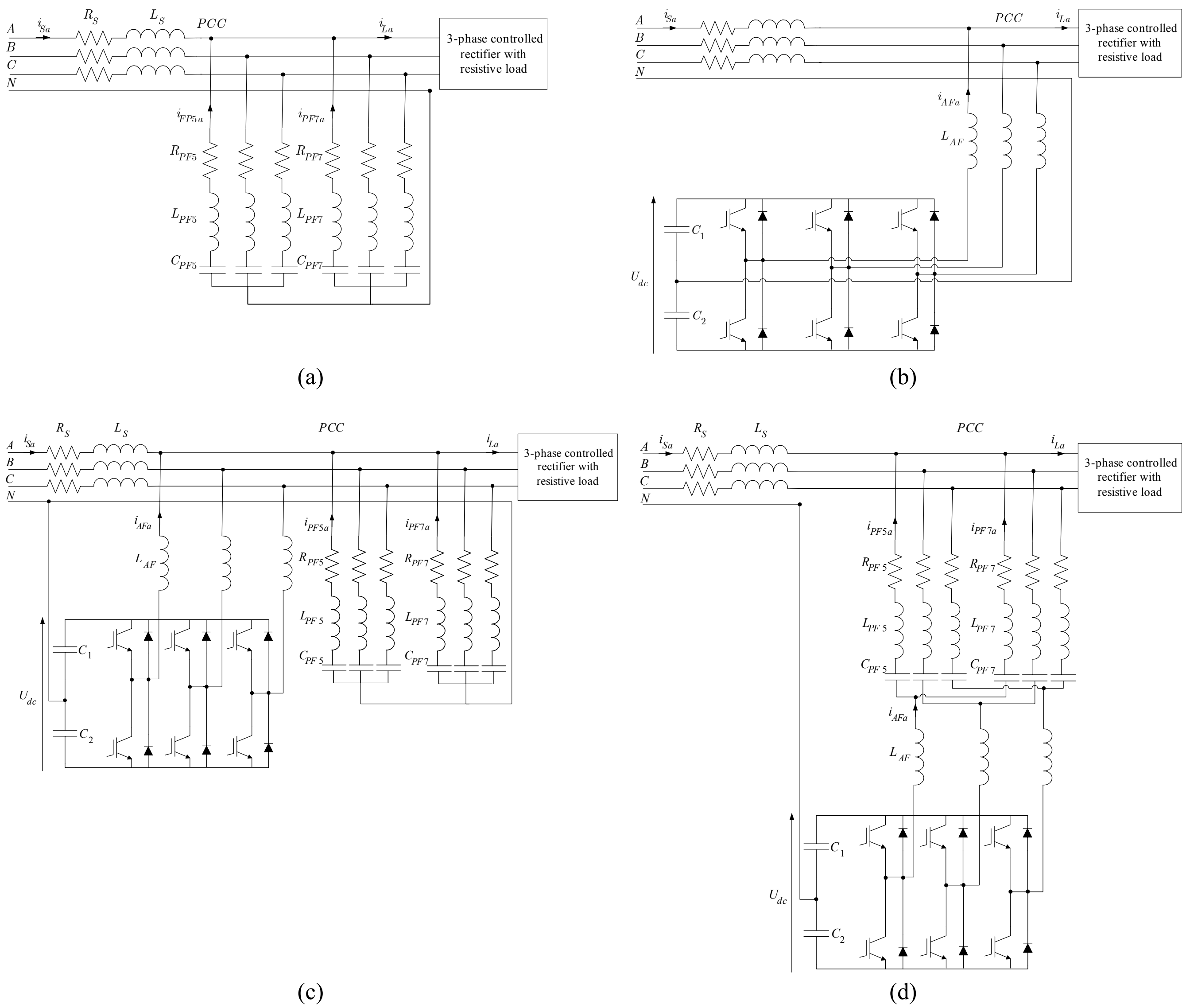
The impedance curves of the systems are presented in Fig. 8. The series resonance curve is in blue, while the parallel resonance curve is in red. In green the equivalent impedance of the two parallel passive filters is represented. Finally in magenta the source impedance curve is drawn.

1) Series resonance

Analyzing the series resonance curve, the minimum values, which correspond to the series resonance frequencies are obtained for orders 4,1 and 6,3. A 3% of 4th harmonic is superimposed to the source voltage in order to produce the phenomenon of series resonance between passive filters and the source impedance.

2) Parallel resonance

The maximum values in the parallel resonance curve are the parallel resonance frequencies of the system. These points corresponds to the orders 4 and 6,2. A 10% of sixth harmonic component is added to the load current for illustrating the effect of parallel resonance between passive filters and the source impedance.



(a) (b)

(c) (d)

Fig. 6. Power filter topologies used in simulation: (a) PF, (b) PAF, (c) AFPPF, (d) AFSPF.

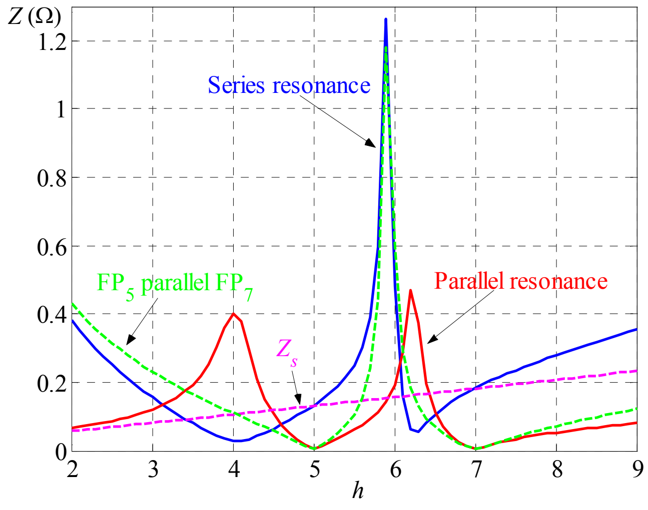


Fig. 7. Impedance curves of the system

C. Overload

Passive filters act as sinks to the tuned harmonic currents, so they can be overloaded due to tuned harmonics in the utility voltage or increase of tuned harmonic load currents.

1) Tuned harmonics in u_S

The effect of overload in the fifth passive filter due to fifth harmonic in the source voltage is studied adding a 3% of this harmonic component to the utility voltage.

2) Increase of tuned harmonics in i_L

Overload due to increase of tuned harmonics in the load current is analyzed adding a 20% of the seventh harmonic in the load current.

D. Mistuning

L_{FP} and C_{FP} component tolerances as well as source frequency variations cause mistuning in passive filters, increasing the filter impedances at tuned frequencies, resulting worse filtering capabilities (see the passive filters impedance at 5th and 7th harmonics under tuning or mistuning conditions in Fig. 8).

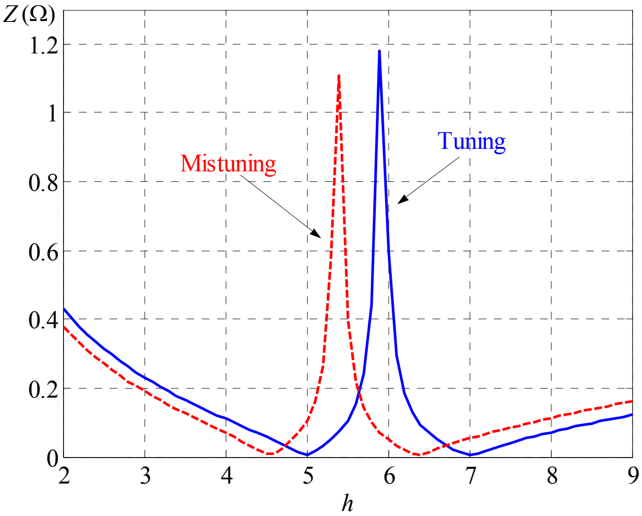


Fig. 8. Impedance curves with tuned and mistuned filters

An increase of 10% in capacitance and inductance of both passive filters is carried out for studying this effect.

E. Dynamic compensation of displacement power factor

If passive filters have been designed for the greatest displacement power factor, the unfavourable situation from the fundamental reactive compensation point of view occurs when this power is zero. In the simulation system this happens when the firing angle of the rectifier is $\alpha = 0^o$.

F. Unbalance

In order to study the capability of the topologies for suppressing unbalance, the amplitude of the supply voltage in each phase has been intentionally changed to the values $U_{Sa} = U_n$, $U_{Sb} = 1{,}10 \cdot U_n$ and $U_{Sc} = 0{,}85 \cdot U_n$, resulting the following unbalance ratios: $U_S^- / U_S^+ = U_S^0 / U_S^+ = 7{,}39\%$.

4. Simulation results

Simulation results for all these conditions are summarized in Table VI, where the *THD* in source current and the inverter rating of the active filter S_{invAF} are indicated. The worst results for each topology are signalled with bold typing and grey background.

TABLE VI. – Simulation results summary (basis power of the system $S_B^{3\phi} = 350$ kVA)

		PF$_5$ parallel PF$_7$	PAF	AF parallel (PF$_5$ parallel PF$_7$)	AF series (PF$_5$ parallel FP$_7$)
Ideal mains	*THD* i_S	10,57%	9,8%	9,06%	12,53%
	S_{invAF}	-	**370,71 kVA**	107,94 kVA	76,36 kVA
Series resonance (3% u_{S4})	*THD* i_S	17,30%	-	NO	12,72%
	S_{invAF}	-			76,42 kVA
Parallel resonance (10% i_{L6})	*THD* i_S	14,30%	-	11,49%	**16,10%**
	S_{invAF}	-		128,02 kVA	75,88 kVA
Tuned harmonics in u_S (3% u_{S5})	*THD* i_S	**37,07%**	-	NO	12,83%
	S_{invAF}	-			84,16 kVA
Increments of tuned harmonics in i_L ($\Delta i_{L7} = 20\%$)	*THD* i_S	10,83%	-	**11,56%**	12,78%
	S_{invAF}	-		108 kVA	79,14 kVA
Mistuning (+10% L_{FP}, +10% C_{FP})	*THD* i_S	20,93%	-	NO	12,40%
	S_{invAF}	-			**113,98 kVA**
Dynamic compensation of Q_1 ($\alpha = 0^o$)	*THD* i_S	NO	6,69%	7,16%	10,14%
	S_{invAF}		186,57 kVA	**281,6 kVA**	91,48 kVA
Unbalance $U_S^- / U_S^+ = U_S^0 / U_S^+ = 7{,}39\%$	*THD* i_{SA}	NO	**11,14%**	9,10%	13,38%
	S_{invAF}		336,24 kVA	129,14 kVA	92,3 kVA

From Table VI the following can be concluded:

- Topologies formed by passive filters working alone should not be used because they suffer from resonance, overload and mistuning problems. Besides, their fundamental reactive power compensation is fixed and they can not correct unbalance. Paying attention to the numerical results displayed in Table VI, it can be observed that supply voltage distortion at tuned or series resonance frequencies make a worse influence in passive filtering characteristics than load current distortion changes.
- PAF topologies offer good compensation capabilities under every analyzed simulation conditions. However, the rating of the equipment results too much large (the apparent power of the inverter can be even greater than the maximum power demanded by the load, as it is shown for the case of ideal mains in Table VI).
- AFPPF hybrid topologies only operate suitably if the source voltage is not distorted. Mistuning, overload due to tuned harmonics in the utility voltage and series resonance can not be avoided, although the active filter try to help the passive equipments. The rating of the active part is lower comparing with PAF filters installed alone, but their use is not advised due to the incapability to solve the mentioned problems.
- Finally, AFSPF hybrid topologies are only effective if they operate as dominant harmonic filters, although they can not compensate all the harmonics present in the load current. The rating of the active equipment is strongly reduced. Under the worst conditions, the apparent power of the required inverter is less than a third part of the basis power of the system. In case of less exigent conditions the rating of the inverter is less than a fifth part of the maximum load power.

After this exhaustive analysis, the question is: Which is the most suitable topology? The advantages of PAF and AFSPF over the topologies left have been already argued, but the selection between them depends on many characteristics of the system such as the number of wires (that influences in the possibility of unbalance) and the value of the source impedance (what produces stiff or non-stiff utilities). However, the main influence on the decision is due to the type of harmonic-producing load and the power it demands. Based on these characteristics the following criterions are concluded as factors that should be taken into account in the selection.

1) *Frequency spectrum of the load current*

- If the load current frequency spectrum presents few components over the IEEE-519 limits, the best solution is employing an AFSPF topology using passive filters tuned to that dominant frequencies. Besides, in case of fixed fundamental reactive power demanded by the load, for example with non-controlled rectifiers, advantages using AFSPF are greater because it is not needed any contribution to fundamental component compensation by the active equipment, so the rating of the inverter decreases more.
- However if the frequency spectrum of the load current does not show dominant harmonics, exhibiting many components whose HD_h is over the IEEE-519 limits, a PAF topology is the only effective solution.

2) *Load power levels*

- PAF filters require a large inverter rating with high current bandwidth, what makes them a not cost-effective solution for non-linear loads above 500 kVA.
- AFSPF filters suppose the only viable and cost-effective topology for higher power levels due to small rating of the active element. In case of loads with frequency spectrum not centred in few harmonic components, this solution can be used with another active or passive equipment which would be in charge of the non-dominant harmonics.

These criterions are summarized in a quantified manner in Table VII.

TABLE VII. – Criterions for the selection between PAF and AFSPF topologies depending on the characteristics of the harmonic-producing load

			PAF	AFSPF
$S_L > 500$ kVA			-	***
$S_L < 500$ kVA	Non-dominant spectrum in i_L	$Q_1 =$ cte	**	*
		$Q_1 \neq$ cte	***	-
	Dominant spectrum in i_L	$Q_1 =$ cte	*	***
		$Q_1 \neq$ cte	*	**

5. Conclusions

A comparison among four different parallel power filter topologies has been developed. Simulation results have been obtained for different conditions in order to conclude which the best topology is depending on the frequency spectrum and characteristics of the load. Besides, novel control strategies for hybrid filters have been demonstrated by simulation.

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