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Comparative study of two structures of shunt active filter suppressing particular harmonics

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Abstract. This paper deals with the study of shunt active filters used for suppressing particular harmonics generated by nonlinear loads in utility distribution power systems. Both structures of shunt active filter, voltage source active filter (VSAF) and current source active filter (CSAF), are considered. The analytical study of specific harmonics identification in a given spectrum is first presented. For simulation as well as experimentation the nonlinear load is a conventional three phase thyristor rectifier and harmonics 5 and 7 are selected to be eliminated by active filter. The whole system consisting of the ac power supply network, the SCR rectifier and the shunt active filter (VSAF/CSAF) is then simulated. The simulation results are discussed and the efficiency of the two kinds of active filter are compared. Finally, for the first structure, VSAF, the simulation results are confirmed by experimental test realized by means of a fully digital control active power filter developed in our laboratory.

PACS. 84.30.Jc Power electronics; power supply circuits – 84.30.Vn Filters – 84.70.+p High-current and high-voltage technology: power systems; power transmission lines and cables (including superconducting cables)

1 Introduction

Harmonics in power systems which are generated by nonlinear loads, such as thyristor rectifiers or cycloconverters, have become a serious problem for the utility distribution system. Passive filters have been generally used. Parallel active filters or mixed passive and active filters are the most recently used solutions of harmonic elimination [1,5,7]. Meanwhile, significant progress in fast switching devices such as IGBT and GTO thyristors, has spurred interest in the study of active power filter for harmonic compensation, but economic reasons still seem to be an obstacle against the general utilization of such filters. In fact, the VA power of parallel active filter without reactive power compensation is about 33% of that of non-linear load in the case where this one is a conventional rectifier. This VA power attains the maximum rate of 52% if reactive power compensation is also aimed [4]. At present, the active filter rating could be highly reduced when the suppression of only one or two special harmonics is effected by the active filter. For instance, it will be about 20% when the 5$^{\text{th}}$ harmonic is only compensated, 14% for the 7$^{\text{th}}$ harmonic compensation, *etc.* [9,10].

In this paper, the power circuit elements of the two structures are first described and compared to each other. Then we present an analytical method for identification of one harmonic among all of the harmonics of a given spectrum. The reduction of the filter VA power when suppressing particular harmonics is demonstrated. The filtering performance of each structure is tested by means of simulation study. Finally a small rate laboratory prototype of voltage source active filter with DSP controller is presented and the experimental results are discussed.

2 Description of two shunt active filter topologies

2.1 Voltage source structure (VSAF)

Figure 1a shows the voltage source structure of a shunt active filter which uses a dc capacitor, C, as an energy storage source. The inductance, L_f, through which the inverter is connected to the power supply network, ensures firstly the controllability of the active filter currents and secondly acts as a first order passive filter [4].

The voltage level across the terminals of capacitor C is fixed so that to ensure the controllability of the active filter current during the rectifier commutation [10]. At a given dc voltage, the capacitor C is chosen in order to meet low dc voltage ripples. The inductance L_f is selected in order to provide a sufficient attenuation of the high switching current harmonics generated by the inverter. In fact, the attenuation of high order harmonics goes with increasing L_f. However increasing L_f may deteriorate the

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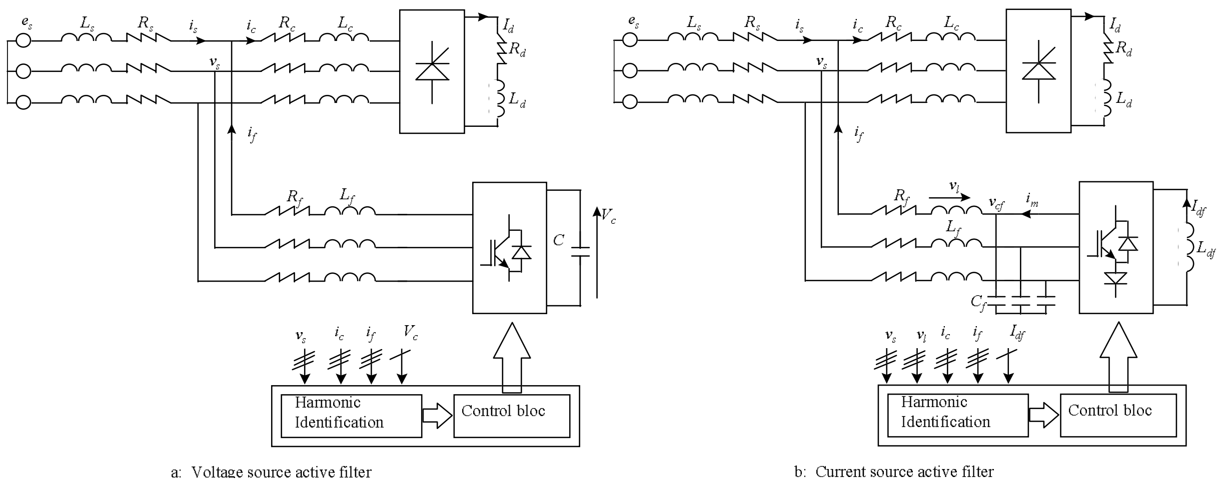

Fig. 1. The two structures of shunt active filter: (a) voltage source active filter (VSAF), (b) current source active filter (CSAF).

active filter efficiency if the dc voltage V_c is not increased proportionally.

2.2 Current source structure (CSAF)

In Figure 1b, a current source active filter made up of a current source inverter using an inductance, L_{df}, as a dc current source is given. In this case, the inverter is connected to the ac mains through a second order low pass filter formed by C_f and L_f. The harmonics near to the filter's resonance frequency are amplified. In order to prevent this phenomenon an additional resistance has to be added or an appropriate current control takes into account the derivative of the instantaneous active filter current should be adopted. Despite its resonance damping capacity, the first method is not retained because of caused additional losses [8,11]. Besides, the voltage of the blocked switch is equal line to line capacitor voltage. In this way, the capacitor C_f acts as a snubber for the semiconductor devices and suppresses their switching spike voltages.

The dc current, I_{df}, in the inductance must be higher than the peak value of the harmonic current of the nonlinear load. The inductance L_{df} is chosen in order to meet a feeble dc current ripple. The values of L_f and C_f are determined considering two constraints: 1) to achieve proper attenuation of high frequency harmonics, 2) to provide a sufficient band-pass for the active filter. To satisfy the first constraint, the resonance frequency of the output filter, $\omega_0 = \frac{1}{\sqrt{L_f C_f}}$ must be much lower than the inverter switching frequency. To meet the second target, this frequency must be higher than that of the highest harmonic to be compensated by the active filter. At the chosen resonance frequency, since the capacitor acts as a snubber for the switching devices, increasing L_f will result in decreasing C_f and consequently reduces the semiconductor protection. On the other hand, L_f, must be chosen to be higher than the internal inductance of the ac mains in order to ensure the independence of active filter with regard to the power supply network. Thus, a compromise has to be made in order to obtain the optimum filter design.

2.3 Comparison of power circuit of the two structures

The power circuit design of shunt active filter in both structures, VSAF and CSAF, involves selecting the parameters of the dc energy storage element, the elements of the passive filter and the choice of the proper semiconductor devices for each circuit topology.

2.3.1 dc energy storage element

In CSAF structure, the inverter is fed by a dc inductance which plays an essential role as an energy storage element. In the case of VSAF structure a dc capacitor is used. As has been already mentioned in Sections 2.1 and 2.2, the value of the capacitor, C, or the inductance, L_{df}, is based on the allowable voltage or current ripple during operating cycle of the active filter [11]. However increasing these parameters increases the cost of the active filter. In low and average power applications, a capacitive energy storage element is more efficient and costs less than an inductive energy storage element. On the contrary, in the case of high power applications, superconductor coils are the most reliable energy storage elements. Further, these elements have a large inductance value resulting in dc current ripple elimination.

It can be deduced that for a selective harmonic suppression which requires a reduced VA power, VSAF is more suitable than CSAF with regard to dc element.

2.3.2 The decoupling output passive filter

The VSAF is connected to the power supply network via a first order low-pass filter formed by a simple inductance, L_f. In order to provide a sufficient attenuation of the high switching ripples caused by the inverter, this inductance should be increased. Increasing L_f deteriorates the filtering efficiency of VSAF if the inverter dc voltage is not increased simultaneously. So, in order to improve high frequency harmonics attenuation, a third order filter should

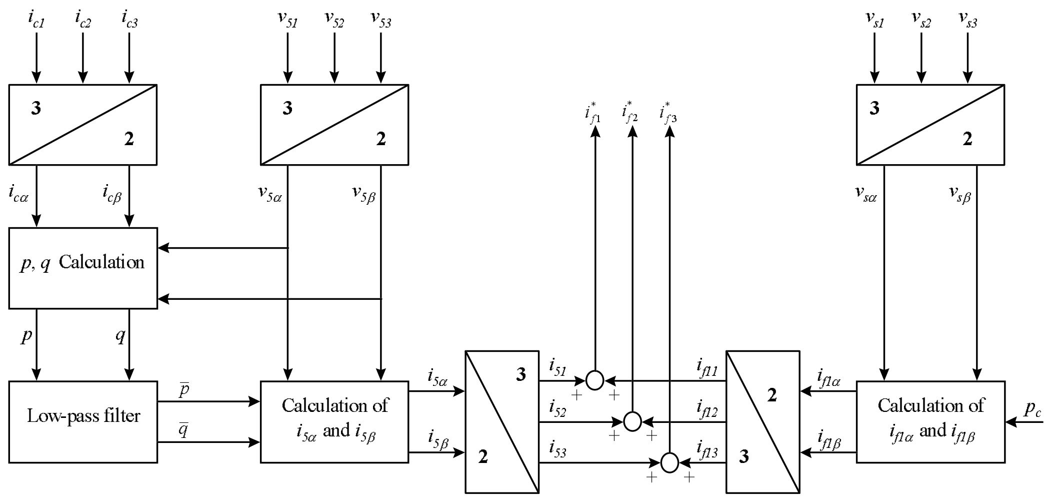

Fig. 2. Reference current calculation scheme.

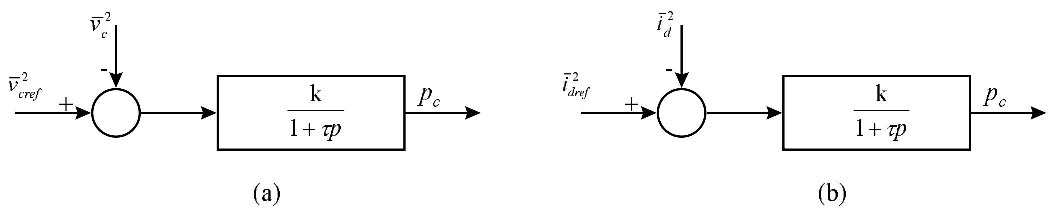

Fig. 3. Scheme of DC power control: (a) case of VSAF, (b) case of CSAF.

be employed. In this case, because of the resonance between the passive elements of the output filter and the high order of the system, the active filter control becomes more complicated.

The optimized output filter, through which the CSAF is connected to the power supply network, is a second order low-pass filter realized by means of a capacitor C_f and inductance L_f. This filter gives a good compromise between a sufficient band-pass and a proper attenuation of switching harmonics.

From the forgoing discussions, it can be concluded that CSAF offers a better compromise between control complication and filtering capability of high frequency harmonics than VSAF.

2.3.3 Semiconductor devices

In case of VSAF structure, the voltage which must be supported by the switching device is unipolar and limited by the dc voltage level. The peak value of the current which is bidirectional is imposed by the active filter current. Thus the appropriate semiconductor device may be an IGBT with an antiparallel diode and must be protected against overcurrent. On the contrary, for the CSAF structure, the current is unidirectional and limited by the dc current, I_{df}, while the voltage is bipolar and its peak value corresponds to that of the line voltage. So the suitable semiconductor device, in this case, may be a GTO with reverse voltage blocking capability or an IGBT transistor with series diode and must be protected against overvoltage. So VSAF can be preferred to CSAF from this point of view.

3 Control of the active filter

The control of the active filter is composed of two parts: the reference current computation and the generation of control signals for the inverter semiconductor devices. These parts can be analogical, digital or mixed. The reference current computation is the same whatever the power circuit configuration, VSAF or CSAF. On the contrary the generation of control signals is highly dependent on the kind of inverter.

3.1 Reference current computation

For identifying harmonic currents in general, the method of instantaneous real and imaginary powers is used [2]. If one wants to suppress only one harmonic (for example 5$^{\text{th}}$ harmonic), the reference current computation should be realized as illustrated in Figure 2.

First the instantaneous phase voltages v_{s1}, v_{s2}, v_{s3} and some arbitrary 5$^{\text{th}}$ harmonic voltages v_{51}, v_{52}, v_{53} as well as the load currents i_{c1}, i_{c2}, i_{c3} are transformed into $\alpha{-}\beta$ orthogonal coordinates according to the Concordia transformation:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{s1} \\ v_{s2} \\ v_{s3} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{5\alpha} \\ v_{5\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{51} \\ v_{52} \\ v_{53} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix}. \quad (3)$$

Note that the instantaneous supply voltages v_{s1}, v_{s2}, v_{s3} and load currents i_{c1}, i_{c2}, i_{c3} are measured where the 5$^{\text{th}}$ harmonic voltages v_{51}, v_{52}, v_{53} can be generated by the control system.

Then the instantaneous real and imaginary powers are calculated by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_{5\alpha} & v_{5\beta} \\ -v_{5\beta} & v_{5\alpha} \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix}. \quad (4)$$

In the case of six pulse rectifier considered here as the non-linear load, the 5$^{\text{th}}$ harmonic currents constitute a three phase negative sequence system which can be expressed as follows:

$$\begin{cases} i_{51} &= \sqrt{2} I_5 \sin(5\omega t + 5\phi_5) \\ i_{52} &= \sqrt{2} I_5 \sin(5\omega t + \frac{2\pi}{3} + \phi_5) \\ i_{53} &= \sqrt{2} I_5 \sin(5\omega t - \frac{2\pi}{3} + \phi_5) \end{cases} \quad (5)$$

where I_5 is the r.m.s value and ϕ_5 is the phase displacement with respect to the fundamental supply voltage. Consequently, the harmonic voltages v_{51}, v_{52} and v_{53} must be also a three phase negative sequence system as given by (6):

$$\begin{cases} v_{51} &= \sqrt{2} V_5 \sin(5\omega t + \varphi_5) \\ v_{52} &= \sqrt{2} V_5 \sin(5\omega t + \frac{2\pi}{3} + \varphi_5) \\ v_{53} &= \sqrt{2} V_5 \sin(5\omega t - \frac{2\pi}{3} + \varphi_5) \end{cases} \quad (6)$$

Thus, the instantaneous real end imaginary powers given by (4) can be separated into continuous powers noted by $\overline{p}$ and $\overline{q}$, and alternating powers noted by $\tilde{p}$ and $\tilde{q}$:

$$\begin{cases} p = \overline{p} + \tilde{p} \\ q = \overline{q} + \tilde{q} \end{cases} \quad (7)$$

where the 5$^{\text{th}}$ harmonic of load current corresponds to the dc parts of p and q and the other harmonics and also the fundamental component compose the ac parts.

The next step in the reference current computation is the extraction of the continuous parts $\overline{p}$ and $\overline{q}$ from p and q by using a low-pass filter as shown in Figure 2.

In this case, $\overline{p}$ and $\overline{q}$ are:

$$\begin{cases} \overline{p} &= 3V_5 I_5 \cos(\varphi_5 - \phi_5) \\ \overline{q} &= 3V_5 I_5 \sin(\varphi_5 - \phi_5). \end{cases} \quad (8)$$

Ones the continuous powers are separated from the alternating powers, the 5$^{\text{th}}$ harmonic current components in $\alpha{-}\beta$ coordinates can be expressed by:

$$\begin{bmatrix} i_{5\alpha} \\ i_{5\beta} \end{bmatrix} = \begin{bmatrix} v_{5\alpha} & v_{5\beta} \\ -v_{5\beta} & v_{5\alpha} \end{bmatrix}^{-1} \begin{bmatrix} \overline{p} \\ \overline{q} \end{bmatrix}. \quad (9)$$

And then the harmonic current references can be calculated by:

$$\begin{bmatrix} i_{51} \\ i_{52} \\ i_{53} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{3}{2} \end{bmatrix} \begin{bmatrix} i_{5\alpha} \\ i_{5\beta} \end{bmatrix} \quad (10)$$

which results in:

$$\begin{bmatrix} i_{51} \\ i_{52} \\ i_{53} \end{bmatrix} = \sqrt{2} I_5 \begin{bmatrix} \sin(5\omega t + \phi_5) \\ \sin(5\omega t + \frac{2\pi}{3} + \phi_5) \\ \sin(5\omega t - \frac{2\pi}{3} + \phi_5) \end{bmatrix}. \quad (11)$$

These calculations show that in harmonic current identification, only the frequency of the voltages v_{51}, v_{52}, v_{53} is fundamentally important and their amplitude and phase displacement have no effect.

On the other hand, in order to keep constant the dc voltage in the case of VSAF, or the dc current in the case of CSAF, the active filter has to be supplied in some active power, noted p_c, from the power supply network. The fundamental active current which corresponds to this power can be determined by (12):

$$\begin{bmatrix} i_{f11} \\ i_{f12} \\ i_{f13} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{3}{2} \end{bmatrix} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ -v_{s\beta} & v_{s\alpha} \end{bmatrix}^{-1} \begin{bmatrix} -p_c \\ 0 \end{bmatrix}. \quad (12)$$

The fundamental active power, p_c, is determined by the dc link voltage control of the capacitor of VSAF or the dc current control of the inductance of CSAF through the schemes given in Figure 3. In fact, the controller can be a simple proportional since in steady state operation of the non-linear load only a small active power (p_c) is drained from active filter [10]. During load transient operation, active filter exchanges some active power with the mains which causes dc link voltage (VSAF) or current (CSAF) variation. In this case, a proportional-integral controller can be preferred. In both cases, a low-pass first order filter is added in order to remove the voltage or current ripples of the measured dc voltage (V_c) or current (I_{df}). Finally the active filter reference current is given by:

$$\begin{cases} i^*_{f1} = i_{51} + i_{f11} \\ i^*_{f2} = i_{52} + i_{f12} \\ i^*_{f3} = i_{53} + i_{f13}. \end{cases} \quad (13)$$

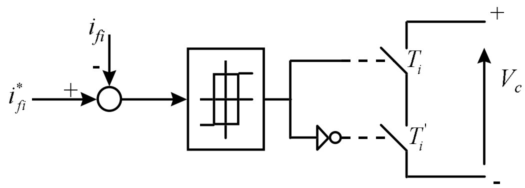

Fig. 4. Switching control of VSAF.

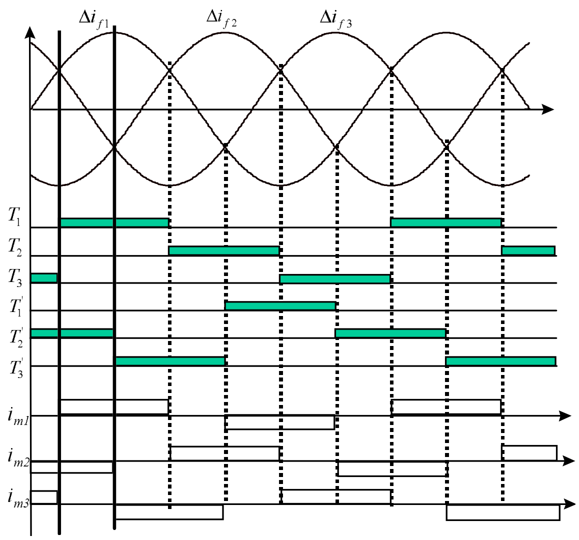

Fig. 5. The principle of the current control of CSAF.

For other harmonic current compensation (for example the 7th harmonic), a voltage with the same frequency and in the same order as harmonic current should be generated and the calculations (1) to (4) and (7) to (10) be repeated.

3.2 Current control of the VSAF

Figure 4 shows the current control scheme for each phase of the active filter. The power switches, the IGBT in our case, are switched so that the output current i_{fi} is limited within a hysteresis band enveloping the reference current i^*_{fi}. That is, the T_i is turned on (T_i' is turned off) when i_{fi} is equal to the lower limit and turned off (T_i' is turned on) when it equals the higher limit. Therefore, the output current i_{fi} is forced to follow the reference current i^*_{fi} and the power circuit of active filter can be considered as a kind of controlled three phase current source.

3.3 Current control of the CSAF

3.3.1 Current control

In fact, for the CSAF (Fig. 1b), in order to damp the oscillations caused by the resonance in decoupling passive filter $L_f - C_f$, the term, ξv_1, corresponding to the active filter current derivative is added to the reference current given by (13). So, the active filter reference current becomes:

$$\begin{cases} i^{**}_{f1} = i^*_{f1} - \xi v_{l1} \\ i^{**}_{f2} = i^*_{f2} - \xi v_{l2} \\ i^{**}_{f3} = i^*_{f3} - \xi v_{l3} \end{cases} \tag{14}$$

The analysis bellow shows how this additional term, ξv_l, permits to damp the resonance oscillations.
From Figure 1b, the following relations may be obtained:

$$\begin{cases} L_f \dfrac{di_f}{dt} = \nu_{cf} - v_s \\ C_f \dfrac{dv_{cf}}{dt} = i_m - i_f \end{cases} \tag{15}$$

which results in:

$$L_f C_f \frac{d^2 i_f}{d^2 t} = i_m - i_f - C_f \frac{dv_s}{dt} \cdot \tag{16}$$

Besides, if the active filter's control operates perfectly, the output inverter current i_m has to be equal to i^*_m approximately given by:

$$i^*_m \approx i^{**}_f + C_f \frac{d\nu_s}{dt} \cdot \tag{17}$$

The second term of the right-hand side of (17) corresponds to the fundamental current of the capacitor. From relations (14, 16) and (17) we obtain:

$$L_f C_f \frac{d^2 i_f}{d^2 t} = i^*_f - \xi v_1 - i_f. \tag{18}$$

The voltage, v_l, can be expressed as follows:

$$v_l = L_f \frac{di_f}{dt} \cdot \tag{19}$$

And then (18) becomes:

$$L_f C_f \frac{d^2 i_f}{d^2 t} + \xi L_f \frac{di_f}{dt} + i_f = i^*_f. \tag{20}$$

By use of Laplace transformation, the following transfer function can be deduced:

$$\frac{i_f(p)}{i^*_f(p)} = \frac{1}{L_f C_f s^2 + \xi L_f s + 1} \cdot \tag{21}$$

From this relation it appears clearly that the parameter ξ acts as a damping factor in active filter transfer function.

3.3.2 Switching control technique

The current source active filter which operates between a dc current source and an ac voltage source requires a special control. At any time only two semiconductor devices among six can be in on state, one from each half-bridge. Thus, considering this constraint, it is difficult to apply

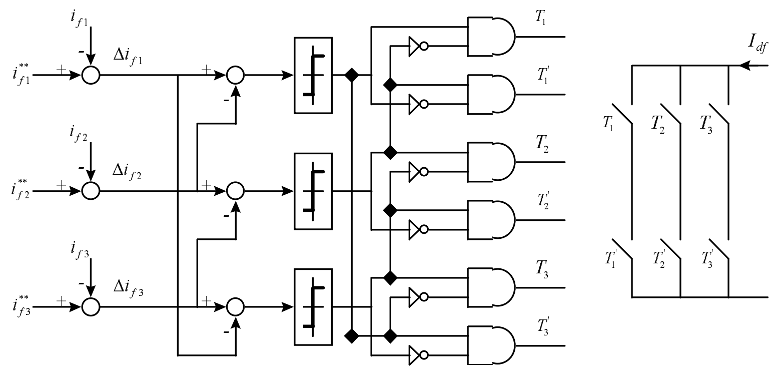

Fig. 6. Switching control of CSAF.

ordinary hysteresis switching control used in the voltage source active filter described above.

Some switching control techniques which consider these constraints are available in the literature [3,6]. Almost all require numerical implementation or complicated analogical circuits. In this paper, a new hysteresis control which is based on the correction of the two out of three larger errors of the real active filter current with respect to its reference is proposed. This principle is illustrated in Figure 5. The errors Δi_{f1}, Δi_{f2} and Δi_{f3} between the active filter currents i_{f1}, i_{f2}, i_{f3} and their references i_{f1}^{**}, i_{f2}^{**}, i_{f3}^{**} are first compared to each other. And then, as long as Δi_{f1} is the largest error with the positive polarity and Δi_{f2} is the largest with negative polarity, the current in phase 1, i_{m1} is made equal to I_{df}, whilst i_{m2} is equal to $-I_{df}$ and i_{m3} null. Thus the semiconductor devices T_1 and T_2' are kept in on state when T_2, T_3, T_1' and T_3' are blocked. The active filter current in phase 1, i_{f1}, increases and that in phase 2, i_{f2}, decreases resulting in decreasing the errors Δi_{f1} and Δi_{f2} respectively. This state does not change until the error in phase 3, Δi_{f3}, becomes larger than Δi_{f1} or lower than Δi_{f2}. The circuit realization of this switching method is given in Figure 6.

4 Active filter design and numerical simulation

4.1 Active filter design

The major advantage of a particular current harmonic filtering is the VA power reduction of active power filter. In the case of a six pulse rectifier feeding a highly inductive load, the harmonic ranks are:

$$k = 6n \pm 1 \quad n = 1,\ 2,\ 3,\ldots \tag{22}$$

and the magnitudes:

$$I_k = \frac{I_1}{k}, \tag{23}$$

where I_1 is the magnitude of the fundamental component. Thus the r.m.s value of the k^{th} harmonic can be expressed, in terms of the average dc current I_d, as:

$$(I_k)_{rms} = \frac{1}{k}\frac{\sqrt{6}}{\pi}I_d. \tag{24}$$

Consequently the corresponding VA power is:

$$S_k = \sqrt{3}U_1(I_k)_{rms} = \sqrt{3}U_1\left(\frac{1}{k}\frac{\sqrt{6}}{\pi}I_d\right). \tag{25}$$

Finally, the ratio of this VA power to the total nonlinear load VA power is:

$$\frac{S_k}{s_{load}} = \frac{\sqrt{3}U_1\left(\frac{1}{k}\frac{\sqrt{6}}{\pi}I_d\right)}{\sqrt{3}U_1\left(\frac{\sqrt{6}}{\pi}I_d\right)} = \frac{1}{k}\cdot \tag{26}$$

This shows that to suppress the k^{th} current harmonic, the active filter VA power is $\frac{1}{k}$ times of the nonlinear load. For instance, in the case of the elimination of the fifth harmonic, the active filter power is 20% of that of the nonlinear load.

If more than one harmonic is selected to be filtered, 5^{th} and 7^{th} for example, the total r.m.s current can be calculated as follows:

$$(I_{5.7})_{rms} = \sqrt{\left(\frac{1}{5}\right)^2 + \left(\frac{1}{7}\right)^2}\left(\frac{\sqrt{6}}{\pi}I_d\right) = 0.245\left(\frac{\sqrt{6}}{\pi}I_d\right) \tag{27}$$

and consequently: $\frac{S_{5.7}}{S_n} = 24.5\%$.

In Table 1, the VA power of an active filter for the elimination of 5^{th} harmonic, 5^{th} and 7^{th} harmonics and all harmonics generated by a three phase rectifier are compared.

4.2 Numerical simulation

4.2.1 Nonlinear load parameters

In the following simulations, the nonlinear load power is set at 400 kVA. The input ac voltage is 220 V. So the

Table 1. Comparison of the VA power of a shunt active filter in case of total and selective harmonic filtering.

	S_{filter}/S_{load} (%)	$S_{filter}/S_{filter(all)}$ (%)
Suppression of all harmonics	31	100
Suppression of harmonic 5	20	64
Suppression of harmonics 5 and 7	24.5	79

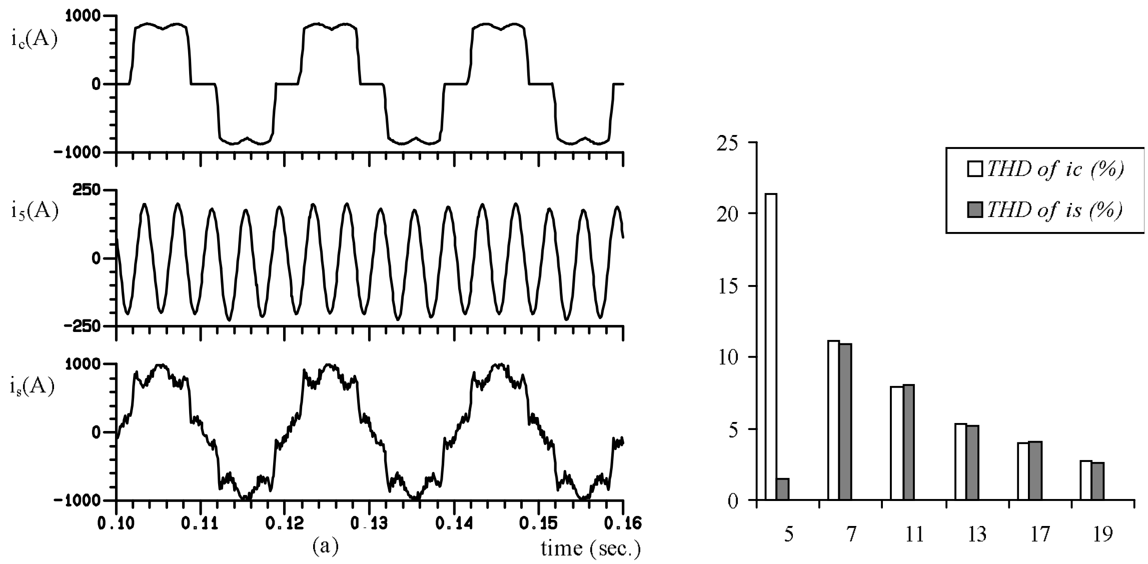

Fig. 7. Simulation results for 5th harmonic elimination with VSAF.

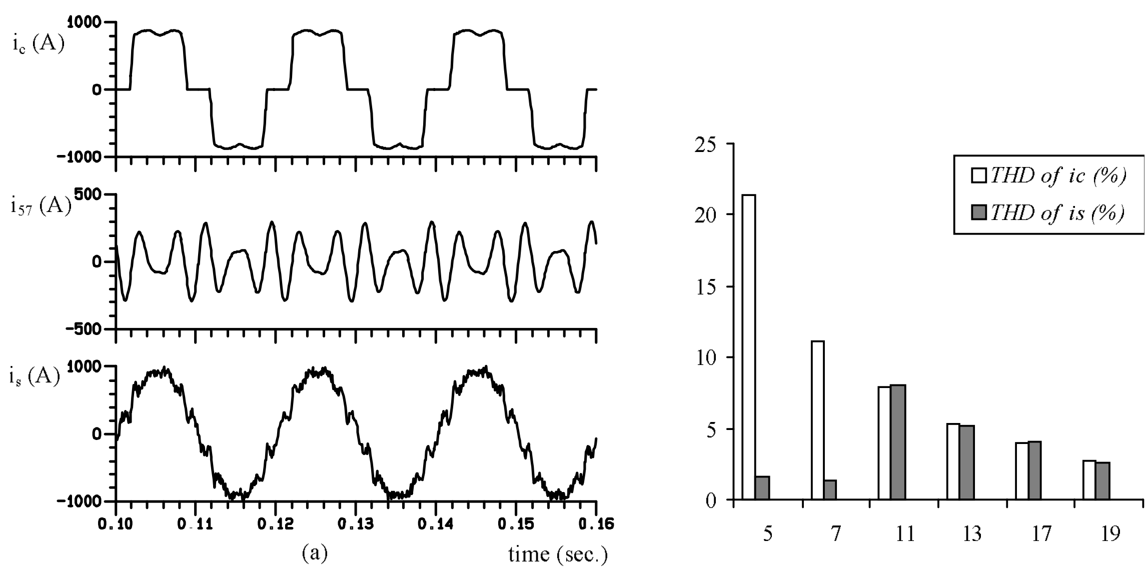

Fig. 8. Simulation results for 5th and 7th harmonic elimination with VSAF.

maximum average dc voltage, when the firing angle equals 0°, is given by:

$$U_d = \frac{3\sqrt{6}}{\pi} 220 = 515 \text{ V}$$

and according to $I_d = \dfrac{S_n}{U_d}$, the average dc current can reach 777 A.

The previous values of U_d and I_d involve a resistance R_d of 0.66 Ω. In order to obtain smooth dc current, the time constant of dc load $T_d = \dfrac{L_d}{R_d}$, must be larger than the dc voltage period ($\dfrac{20 \text{ ms}}{6} = 3.33$ ms) which implies that $L_d > 5$ mH.

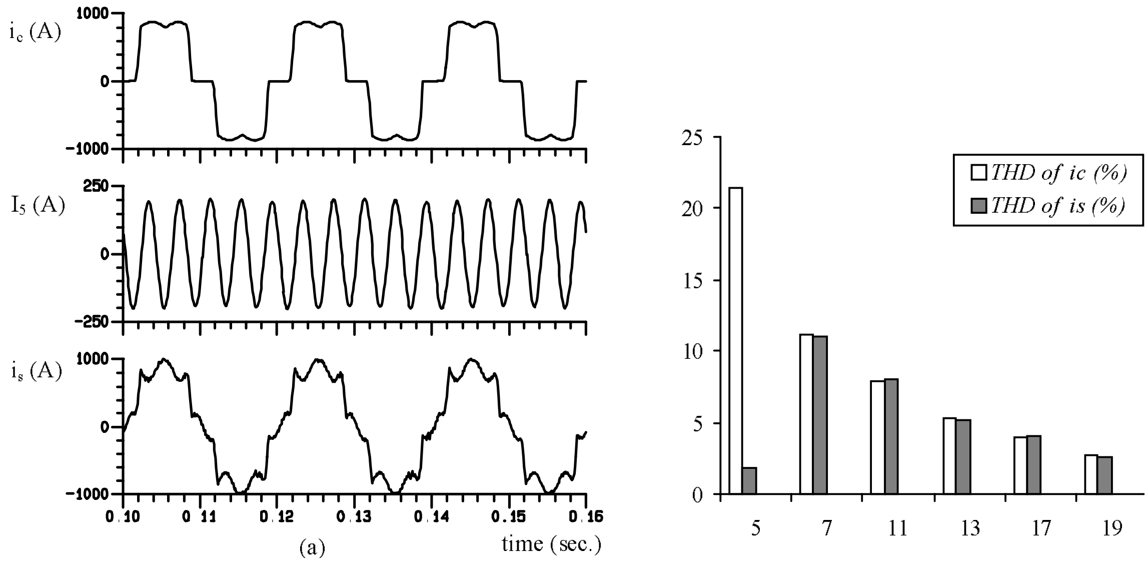

Fig. 9. Simulation results for 5$^{\text{th}}$ harmonic elimination with CSAF.

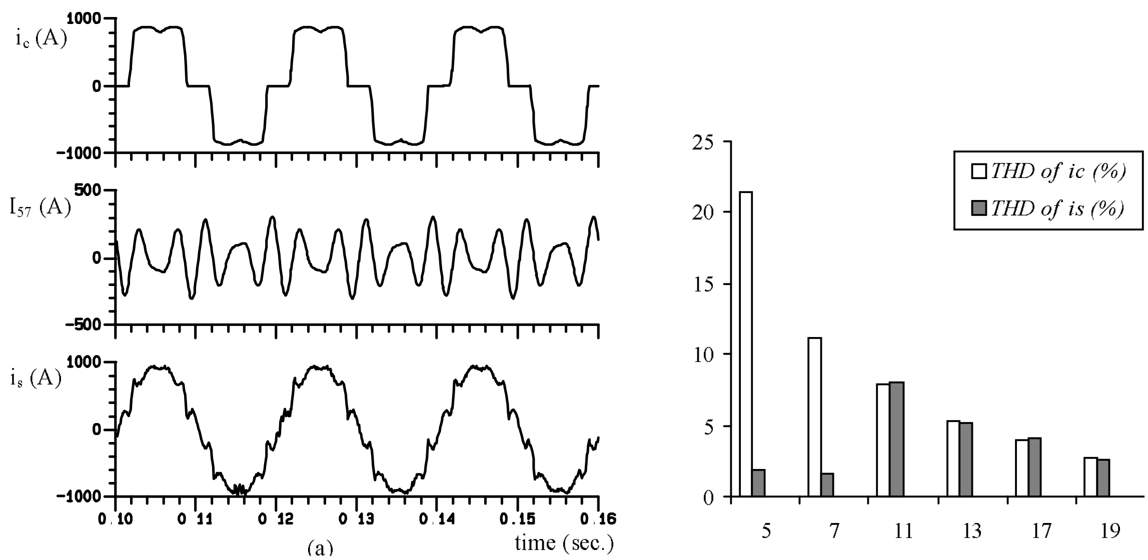

Fig. 10. Simulation results for 5$^{\text{th}}$ and 7$^{\text{th}}$ harmonic elimination with CSAF.

On the other hand, the nominal short-circuit impedance of the ac mains is $Z_n = \dfrac{3V_n^2}{D_n} = 0.363\ \Omega$. In fact the ac mains internal reactance is generally chosen to fall between 1% and 10% of the nominal short-circuit impedance. In our case the inductance L_s is set at 30 μH (*i.e.* 4.3% of Z_n).

4.2.2 Active filter parameters

For the VSAF structure, the dc voltage is fixed at 700 V, the capacitor C is set at 3.3 mF and the inductance L_f at 110 μH. The hysteresis band width is chosen ± 30 A.

For CSAF, the dc current level, I_{df}, is fixed at 350 A, since the peak value of the harmonic current is about 300 A. The inductance L_{df} is set at 40 mH. At the chosen resonance frequency, 1000 Hz, the optimized values of L_f and C_f deduced from simulation, are 150 μH and 150 μF respectively. These parameters are chosen based on the design criteria discussed in Sections 2.1 and 2.2.

4.2.3 Simulation results

The primary purpose of the active filter is the elimination of the 5$^{\text{th}}$ harmonic of the load current. The elimination of the 5$^{\text{th}}$ and the 7$^{\text{th}}$ harmonics simultaneously is subsequently realized by the active filter.

Figures 7a and 8a give the simulated waveforms of load, reference and source current obtained by voltage source active filter. Figures 7b and 8b compare the harmonic content of the load and source current, showing that

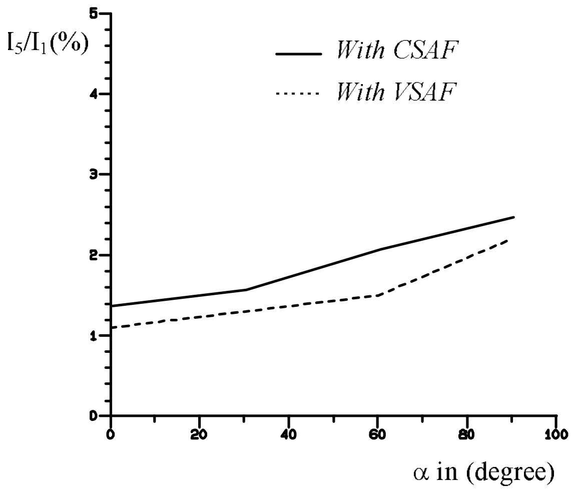

Fig. 11. Evolution of the 5^{th} harmonic filtering *versus* firing angle α.

the 5^{th} and 7^{th} harmonics are highly reduced. When only the 5^{th} harmonic is considered it is decreased from 21.4% to 1.4%. Meanwhile when both 5^{th} and 7^{th} harmonics are simultaneously filtered their rates are reduced from 21.1% and 11.5% to 1.6% and 1.4% respectively.

The simulation results obtained by current source active filter realized in the same conditions as VSAF are reported in Figures 9 and 10. The waveforms of source, reference and load current are given in Figure 9a where harmonic 5 is considered lonely and in Figure 10a where the two harmonics 5 and 7 are simultaneously filtered. It is evident, from Figures 9b and 10b, that the corresponding harmonics have been considerably reduced from 21.0% to 1.8% in the first case, and from 21.0% and 11.1% to 1.9% and 1.6% in the second case.

4.3 Filtering performance comparison of the two structures

Comparisons are made under the same operating conditions, *i.e.* both structures of active filter operate at the same average switching frequency which is about 3.3 kHz. The simulation results presented above show that both structures reduce highly selected harmonics. A slightly better efficiency of the voltage source with respect to current source is noticeable. Otherwise, high frequency harmonics due to inverter switchings are better filtered in the current source structure thanks to its decoupling second order passive filter. From Figure 11, it appears that the 5^{th} harmonic evolution, when the thyristor firing angle α is increased, is roughly the same in both cases. The superiority of the VSAF to eliminate 5^{th} harmonic can be recognized for any value of α.

Finally, Table 2 summarizes the principle comparison points:

- dc energy: A large difference between two structures can be noticed. However, for CSAF, the dc current I_{df} fixed at 350 A is imposed in order to suppress all harmonic currents. This means that it can be highly reduced in particular harmonic suppression, to 300 A for 5^{th} and 7^{th} harmonics and until 200 A for 5^{th} harmonic filtering. Whilst for VSAF, the voltage V_c is chosen in relation with mains line to line voltage and cannot be reduced in specific harmonic compensation.
- Switch's voltage and current peak: For the studied case, slightly the same values are obtained.
- Switch's protection: VSAF is obviously favored with respect to CSAF.
- Inverter control: VSAF with a simple inductance as decoupling filter is easily controllable. Otherwise, CSAF control is less complicated than VSAF when this one is connected to the mains through a third order filter.

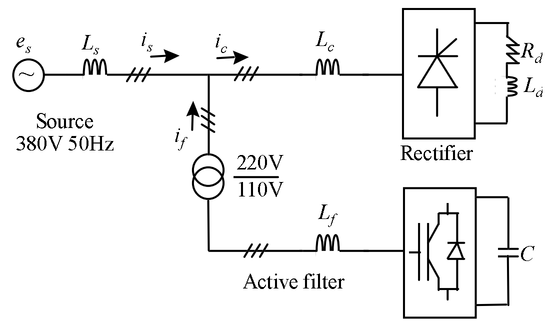

Fig. 12. Diagram of the experimental prototype.

Finally, regarding the technological facilities, VSAF realization is less complicated than CSAF.

5 Experimental device

A prototype consisting of a 20 kVA thyristor rectifier as the nonlinear load and a 10 kVA IGBT voltage-source active filter is developed in our laboratory (Fig. 12). The parameters of this model are deduced from the initial simulations. The same line voltage is chosen whilst the simulation current is divided by 80. The following values are then used:

Line voltage:	380 V
Resistance R_d:	48 Ω
Inductance L_d:	40 mH
Inductance L_c:	1 mH
dc side voltage V_c:	400 V
Capacitor C:	3.3 mF
Inductance L_f:	2.2 mH
Hysteresis band width:	±1.8 A.

Both analogical and numerical controls using DSP circuits are applicable to this model. According to the numerical simulation, different tests have been realized on the experimental model. Figures 13a and 14a show the current waveforms for different operation modes. Figure 13a presents the active elimination of the 5^{th} harmonic of the load current while Figure 14a shows the same but for the elimination of the 5^{th} and 7^{th} harmonics simultaneously. Corresponding spectrums are given in Figures 13b and 14b. In Figure 13, the 5^{th} harmonic in the load current is

Table 2. Principle comparison points between the two structures.

	CSAF	VSAF
dc energy*	$(1/2)L_{df}I_{df}^2 = 2450$ J	$(1/2)CV_c^2 = 808.9$ J
Switch's voltage peak*	700 V (depends on I_{df} and C_f)	700 V (given by V_c)
Switch's current peak*	350 V (given by I_{df})	300 A (depends on V_c and L_f)
Switch's protection	complex (against over voltage)	simple (against over current)
Control	relatively complicated	simple with first order decoupling filter (complicated with third order output filter)

* Values for the studied case.

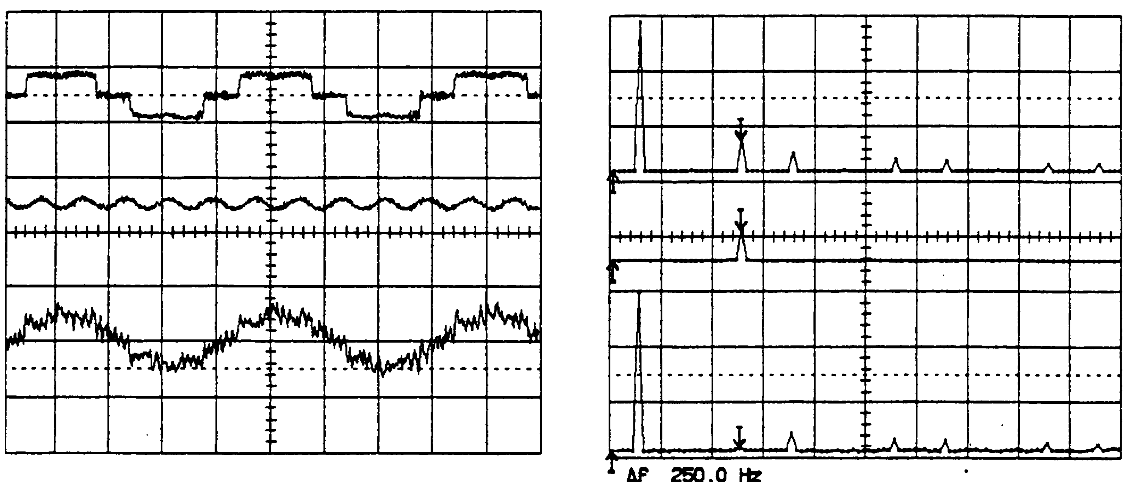

Fig. 13. Experimental results of elimination of the 5th harmonic, current: 25 A/div, time: 10 ms/div (from top to bottom: load current, active filter current, source current).

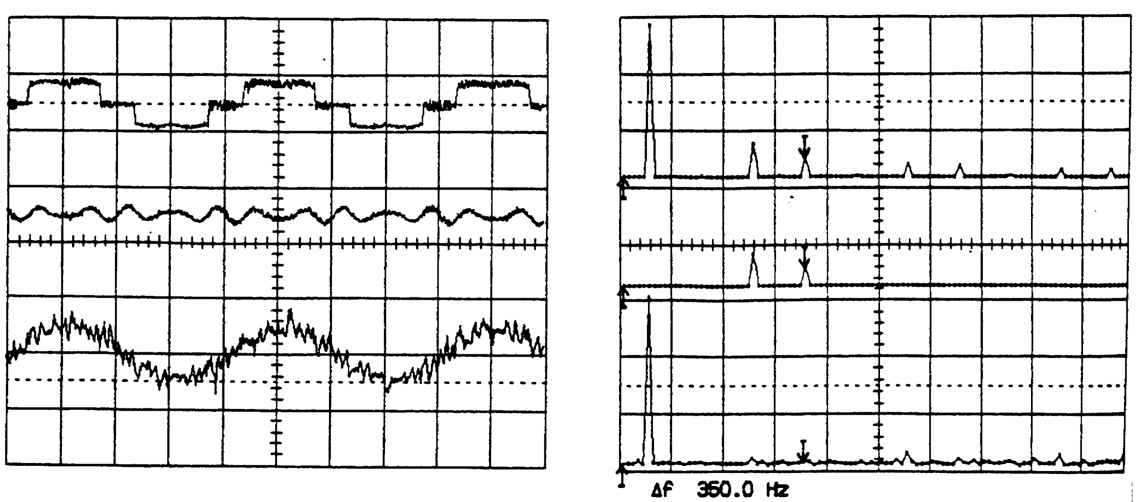

Fig. 14. Experimental results of elimination of the 5th and 7th harmonic, current: 25 A/div, time: 10 ms/div (from top to bottom: load current, active filter current, source current).

decreased from 21.16% to 1.38% while in Figure 14 the 5^{th} and 7^{th} harmonics are decreased from 21.06% and 12.30% to 3.04% and 1.90%. It is shown that the corresponding harmonics have been considerably reduced in both cases and the experimental results confirm almost exactly those of the simulation. Nevertheless it can be noticed that in comparison with the second case the 5^{th} harmonic is slightly better filtered in the first experimentation. This fact is presumably due to the non-linearity of the inverter and its control.

6 Conclusion

In this paper, a shunt active filter used to compensate the particular current harmonics generated by a conventional rectifier bridge has been presented. The efficiency of the two kinds of shunt active filter, the VSAF and the CSAF has been demonstrated by means of simulation results: the magnitude of the harmonic currents selected to be eliminated is divided by about ten. The comparison between the two structures of the shunt active filter shows some advantages of VSAF over CSAF. Besides, the economic reasons remain at present in favor of using the VSAF. Nevertheless, in high power applications CASF may be more efficient than VSAF when the possibility of using superconductor coil is taken into account. This device offers a large energy storage capacity with lower losses which results in an easy dc current control. Further, a smooth dc current will circulate in this element because of its large inductance which suppresses low frequency ripples caused by harmonic current generated by the active filter.

Satisfying simulation and experimental results have been obtained with limited operating frequency and low power circuit design. In fact, the rating of the active filter is reduced to 60% (if one compensates only 5^{th} harmonic) of that of the active filter when all harmonics are compensated. This gain in active filter power should be seriously examined in the future. Active filtering of particular harmonics should be considered as an economical solution and exploited whenever justified by the application. This argument could be reinforced when considering the advantages of active filtering over the passive compensation.

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