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A New Control Method of Hybrid Active Filter to Eliminate the 5th and 7th Harmonic Frequency Using Self-Tuning-Filter in the Feedforward Loop

Mohamed Abdusalam¹, Philippe Poure² and Shahrokh Saadate¹

Abstract – In this paper, we proposed a new control method for a three-phase hybrid active filter, based on a classical active filter topology connected in series with a passive filter. The non linear load is a diode rectifier feeding a (R, C) parallel load. The proposed method is based on two Self Tuning Filters placed in both feedback and feedforward loops dedicated to eliminate the 5th and 7th harmonic frequency. The feedforward loop consists in two branches, the first one to remove the 5th harmonic and the second one to remove the 7th harmonic frequency. The use of Self Tuning Filters simplifies the control scheme by reducing the number of extraction filters used in classical feedback and feedforward loops. More, in this case, no Phase Locked Loop is necessary for the feedforward loop. The effectiveness of the new proposed scheme has been verified by computer simulation and the results are compared with the classical control scheme.

Keywords: Active Hybrid Filter, Diode Rectifier, Feedback and Feedforward Control, Harmonics, Self-Tuning Filter (STF).

Nomenclature

STF	Self Tuning Filter
PLL	Phase Locked Loop
AC	Alternating Current
DC	Direct Current
n	Harmonic rank
ω_F	Fundamental pulsation
ω_n	STF tuning pulsation
THD	Total Harmonic Distortion
i_{Sa}, i_{Sb}, i_{Sc}	Three-phase supply currents
i_{La}, i_{Lb}, i_{Lc}	Three-phase load currents
$\tilde{i}_\alpha, \tilde{i}_\beta$	α - β harmonic components of the supply currents

I. Introduction

The passive filters, although their simplicity and low cost, present some disadvantages such as sensitivity to temperature changing, dependence of the filtering characteristic on the grid impedance and parallel resonances.

For these reasons, many applications have been proposed for active filters development [1]-[3]. On the other hand, the cost of active filters in industrial applications could be very high because of the large power converter rating. These cost considerations limit the use of active filters in the power systems.

In the recent years, various topologies of hybrid active filters with different control strategies have been

proposed in the literature as lower cost alternatives to active filtering for harmonic compensation. Nowadays, hybrid active filters could be considered as one of the best solutions for improving power quality [4]-[6]. Fig.1 shows the hybrid active filter topology studied in this paper [7]-[9]. The hybrid filter consists in a passive filter connected in series with an active filter without any transformer. The passive filter is a three-phase LC filter usually tuned at 7th harmonic.

Fig. 2 shows the classical control scheme. Here the feedback control is applied to the diode rectifier input harmonic currents, whereas the feedforward loop is applied to the most dominant 5th harmonic current component, to improve filtering characteristics of the hybrid filter [10]-[14].

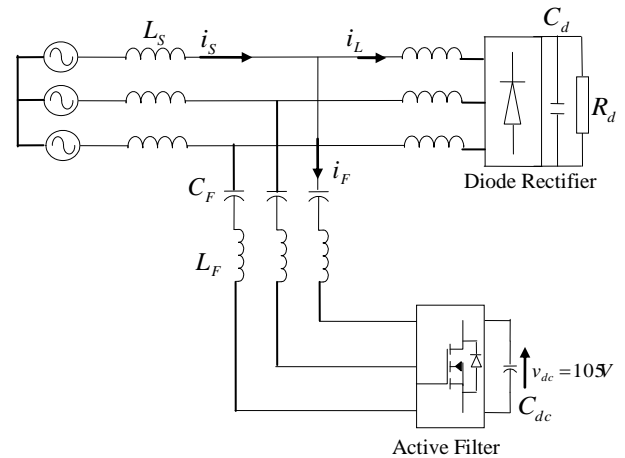


Fig. 1. Parallel hybrid filter configuration.

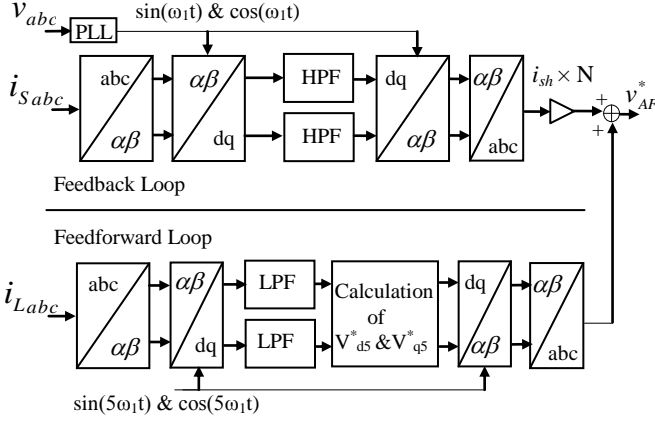


Fig. 2. Classical feedback and feedforward loops.

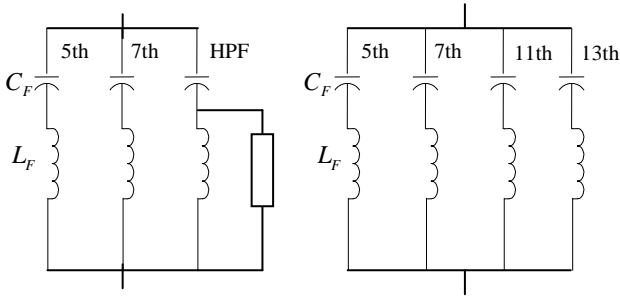


Fig. 3. Passive filter configurations.

In this paper, we present a new control scheme for the hybrid active filter topology (Fig. 1). The feedback control is either applied to the diode rectifier input harmonic currents, whereas the feedforward loop is applied to the most dominant 5th and 7th harmonic current components, to improve filtering characteristics of the hybrid filter. This means that the feedforward loop in this paper will replace the classical passive filter configuration tuned for 5th and/or 7th harmonic currents (figure 3).

More, this paper is aimed to improve filtering characteristics of the hybrid filter. Performances are increased and control scheme is simplified (no more PLL in the feedforward loop) by using STF in the feedback and feedforward loops of the new control scheme (block diagram presented in Fig. 2). The basic principle of the STF was first studied by Hong-Sook Song [15] and a modified version has been developed in our laboratory [16].

II. Modified Control Scheme

The classical control scheme is simplified by using STF in the feedback and feedforward loops. The bloc diagram of the STF tuned at the ω_n pulsation is depicted in figure 4.

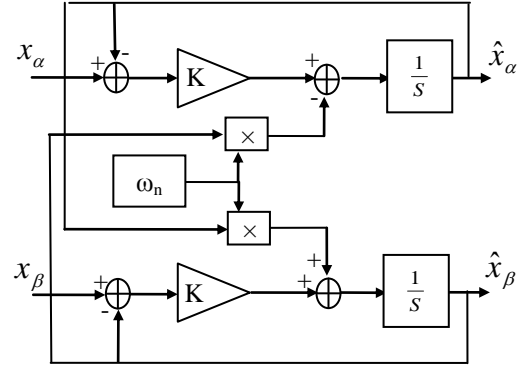


Fig. 4. Self Tuning Filter principle.

The STF is a high selectivity pass-band filter, tuned at the pulsation ω_n . It extracts the AC components at this pulsation directly from the measured load or source currents in the α - β axis. The general equation of this STF is:

$$H(s) = \frac{\hat{x}_{\alpha\beta}(s)}{x_{\alpha\beta}(s)} = K \frac{(s+K) + j \cdot \omega_n}{(s+K)^2 + j \cdot \omega_n^2} \quad (1)$$

where k is a constant value and $x_{\alpha\beta}(s)$ is the voltage or current component in the α - β axes at the input of the STF, defined by:

$$x_{\alpha\beta}(s) = x_\alpha(s) + j \cdot x_\beta(s) \quad (2)$$

$\hat{x}_{\alpha\beta}(s)$ is the filtered voltage or current component in the α - β axis at the output of the STF, defined by:

$$\hat{x}_{\alpha\beta}(s) = \hat{x}_\alpha(s) + j \cdot \hat{x}_\beta(s) \quad (3)$$

The equation (1) can be expressed by:

$$H(s) = \frac{\hat{x}_\alpha(s) + j \cdot \hat{x}_\beta(s)}{x_\alpha(s) + j \cdot x_\beta(s)} = K \frac{(s+K) + j \cdot \omega_n}{(s+K)^2 + j \cdot \omega_n^2} \quad (4)$$

Consequently, $\hat{x}_\alpha(s)$ and $\hat{x}_\beta(s)$ can be expressed as:

$$\hat{x}_\alpha(s) = \frac{(s+K) \cdot K}{(s+K)^2 + \omega_n^2} x_\alpha(s) - \frac{\omega_n \cdot K}{(s+K)^2 + \omega_n^2} x_\beta(s) \quad (5)$$

$$\hat{x}_\beta(s) = \frac{(s+K) \cdot K}{(s+K)^2 + \omega_n^2} x_\beta(s) + \frac{\omega_n \cdot K}{(s+K)^2 + \omega_n^2} x_\alpha(s) \quad (6)$$

Finally, the expressions of $\hat{x}_\alpha(s)$ and $\hat{x}_\beta(s)$ become:

$$\hat{x}_\alpha(s) = \frac{K}{s} [x_\alpha(s) - \hat{x}_\alpha(s)] - \frac{\omega_n}{s} \hat{x}_\beta(s) \quad (7)$$

$$\hat{x}_\beta(s) = \frac{K}{s} [x_\beta(s) - \hat{x}_\beta(s)] + \frac{\omega_n}{s} \hat{x}_\alpha(s) \quad (8)$$

where $\omega_n = \varepsilon \cdot n \cdot \omega_F$ with $\varepsilon = \pm 1$, depending on the harmonic order (direct or reverse). For the fundamental pulsation ($n = 1$), we have: $\omega_1 = \omega_F$. By this method we can tune this STF at any harmonic frequency.

The use of STF effectively modifies the block diagram of the classical control scheme presented in the literature. When using a STF in the feedforward loop, only classical α - β direct and inverse transformations in the stationary frame are needed. Consequently, neither PLL nor d-q transformation are necessary to compute the feedforward voltage references as shown in Fig. 5. By this way, calculations are greatly reduced for the feedforward loop.

III. Control of the Active Filter

Fig.5. shows the resulting new simplified scheme diagram for the control of the hybrid active filter. This scheme replaces the classical control presented in Fig.2.

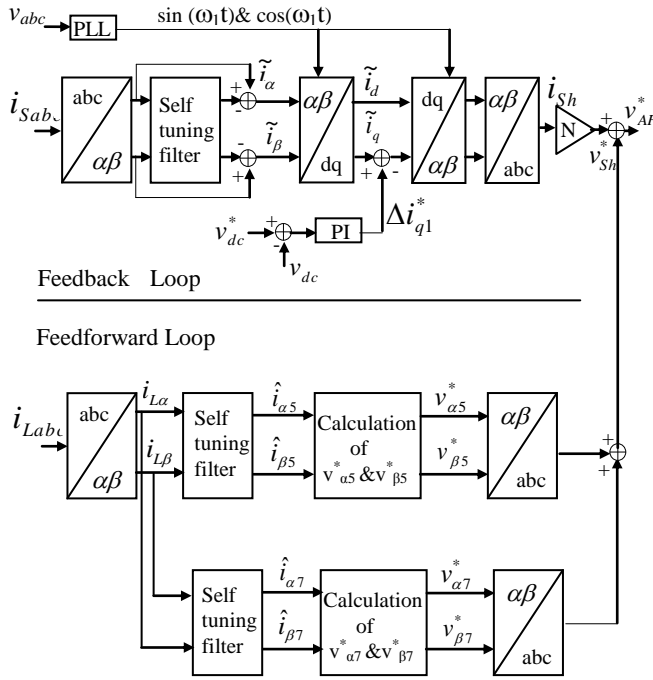


Fig. 5. New control scheme for the hybrid active filter.

For the feedback loop, the use of a PLL for $\sin(\omega_1 t)$ and $\cos(\omega_1 t)$ computation remains still necessary. The

computation of d-q current components is effectively necessary in this control loop for v_{dc} regulation.

According to Fig.5, the three phase supply currents, i_{Sa} , i_{Sb} and i_{Sc} are measured for the feedback loop and transformed into α - β reference frame:

$$\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (9)$$

Then, a STF extracts the fundamental AC components directly from the source current in the α - β axis. The extraction of the harmonic components is achieved by subtracting the STF input signals from the corresponding outputs (see Fig. 5). The resulting signals are the AC components, \tilde{i}_α and \tilde{i}_β , which correspond to the harmonic components of i_{Sa} , i_{Sb} and i_{Sc} in the stationary α - β reference frame.

Then, after computation based on d-q transformation, we obtain the three-phase harmonic reference currents i_{Sha} , i_{Shb} and i_{Shc} . Each harmonic current i_{Sh} is multiplied by a resistor N (Ω) in order to produce the three AC voltage references of the feedback loop, given by:

$$v_{Sh}^* = i_{Sh} \times N \quad (10)$$

The feedforward control greatly differs from the classical one presented in Fig.2. Here, we tuned this loop for the 5th and 7th harmonic frequency using the STF, which allows to extract directly and simultaneously \hat{i}_α and \hat{i}_β components for the 5th and 7th harmonics.

The three phase load currents, i_{La} , i_{Lb} and i_{Lc} , are measured and transformed into α - β reference frame by:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (11)$$

For the 5th harmonic, we tuned the STF by changing ω_n to ω_5 in the equations (7) and (8) in order to compute the DC components $\hat{i}_{\alpha 5}$ and $\hat{i}_{\beta 5}$ at the output of the self tuning filter, as follows:

$$\hat{i}_{\alpha 5} = \left(\frac{K}{s} [i_{L\alpha}(s) - \hat{i}_{\alpha 5}(s)] - \frac{\omega_5}{s} \cdot \hat{i}_{\beta 5}(s) \right) \quad (12)$$

$$\hat{i}_{\beta 5} = \left(\frac{K}{s} [i_{L\beta}(s) - \hat{i}_{\beta 5}(s)] + \frac{\omega_5}{s} \cdot \hat{i}_{\alpha 5}(s) \right) \quad (13)$$

where $\omega_5 (= -5\omega_f)$ is the 5th harmonic pulsation and the minus sign is due to the negative sequence.

The output signals of the STF tuned at the 5th harmonic called the components $\hat{i}_{\alpha 5}$ and $\hat{i}_{\beta 5}$, which corresponds to the 5th harmonic current. To calculate the feedforward voltage references for this harmonic, we note:

$$v_{\alpha\beta 5} = v_{\alpha 5} + j \cdot v_{\beta 5} \quad (14)$$

The complex impedance of the passive filter is given by:

$$Z_F = R_F + j\omega_5 L_F + \frac{1}{j\omega_5 C_F} \quad (15)$$

and the voltage is expressed by:

$$v_{\alpha\beta 5} = Z_F \times i_{\alpha\beta 5} \quad (16)$$

with:

$$i_{\alpha\beta 5} = i_{\alpha 5} + j \cdot i_{\beta 5} \quad (17)$$

Consequently, the voltage references at 5th harmonic are expressed by:

$$\begin{bmatrix} v_{\alpha 5}^* \\ v_{\beta 5}^* \end{bmatrix} = \begin{bmatrix} R_F & -\omega_5 L_F + \frac{1}{\omega_5 C_F} \\ \omega_5 L_F - \frac{1}{\omega_5 C_F} & R_F \end{bmatrix} \begin{bmatrix} \hat{i}_{\alpha 5} \\ \hat{i}_{\beta 5} \end{bmatrix} \quad (18)$$

When applying the α - β inverse transformation (19), we obtain the three-phase feedforward voltage references at the 5th harmonic.

$$\begin{bmatrix} v_{\alpha 5}^* \\ v_{\beta 5}^* \\ v_{c 5}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{\alpha 5}^* \\ v_{\beta 5}^* \end{bmatrix} \quad (19)$$

For the 7th harmonic, we realize the same operation as explained for the 5th harmonic, by changing ω_n to ω_7 in equations (7) and (8) to compute the DC components $\hat{i}_{\alpha 7}$ and $\hat{i}_{\beta 7}$ at the output of the STF, as follows:

$$\hat{i}_{\alpha 7} = \left(\frac{K}{s} [i_{L\alpha}(s) - \hat{i}_{\alpha 7}(s)] - \frac{\omega_7}{s} \cdot \hat{i}_{\beta 7}(s) \right) \quad (20)$$

$$\hat{i}_{\beta 7} = \left(\frac{K}{s} [i_{L\beta}(s) - \hat{i}_{\beta 7}(s)] + \frac{\omega_7}{s} \cdot \hat{i}_{\alpha 7}(s) \right) \quad (21)$$

where $\omega_7 (= 7\omega_f)$ is the 7th-harmonic pulsation.

The voltage references obtained at the 7th harmonic frequency are added to the voltage references at the 5th harmonic frequency to generate the three-phase feedforward voltage references. These references are added to the output voltage references established by the feedback loop to define the total voltage references for the active filter.

Finally, each voltage reference of the active filter is compared with a triangular waveform (10 KHz) to generate the switching signals for the six MOSFETs.

IV. DC Bus Voltage Control

A controller is required to regulate the DC bus voltage v_{dc} and to compensate the system losses. The measured DC bus voltage v_{dc} is compared with its reference value v_{dc}^* . The resulting error is applied to a Proportional Integral (PI) regulator. The proportional and integral gains are set to $0.4 \Omega^{-1}$ and $20 \Omega^{-1}S^{-1}$ respectively. Moreover the active filter can build up and regulate the capacitor voltage without any external power supply, the electrical quantity to be controlled in the dc-voltage feedback loop is Δiq [6], [8].

V. Simulation Results

The efficiency of the proposed control scheme has been examined by computer simulation performed using MATLAB and associated toolboxes “Simulink” and “Power System Blockset”. The parameters of the system are given in Table I [8], [9].

TABLE I
SIMULATION PARAMETERS

Capacitor : C_F	58.2 μF
Inductor : L_F	1 mH
Inductor : L_S	0.15 mH
DC bus voltage	105 V
Capacitor : C_d	1500 μF
Resistor : R_d	21 Ω
Capacitor : C_{dc}	1500 μF
System frequency	60 Hz
System voltage	480 V

Table II shows THD values for different choices of the resistor value N for the feedback loop of the active filter. The optimal value of 15 Ω provides the best filtering characteristics.

TABLE II
FEEDBACK RESISTOR (N) AND THD (%)

Feedback gain (N)	THD
10	2.5
15	1.6
20	2.1

Fig. 6.a and Fig. 6.b show the performances of the STF for different values of the parameter K when the STF is respectively tuned at fifth and seventh frequency. We have chosen a value of K equal to 20 in both cases to guarantee satisfactory filter selectivity and dynamic. One can notice that no delay is introduced by the STF at the tuning frequency.

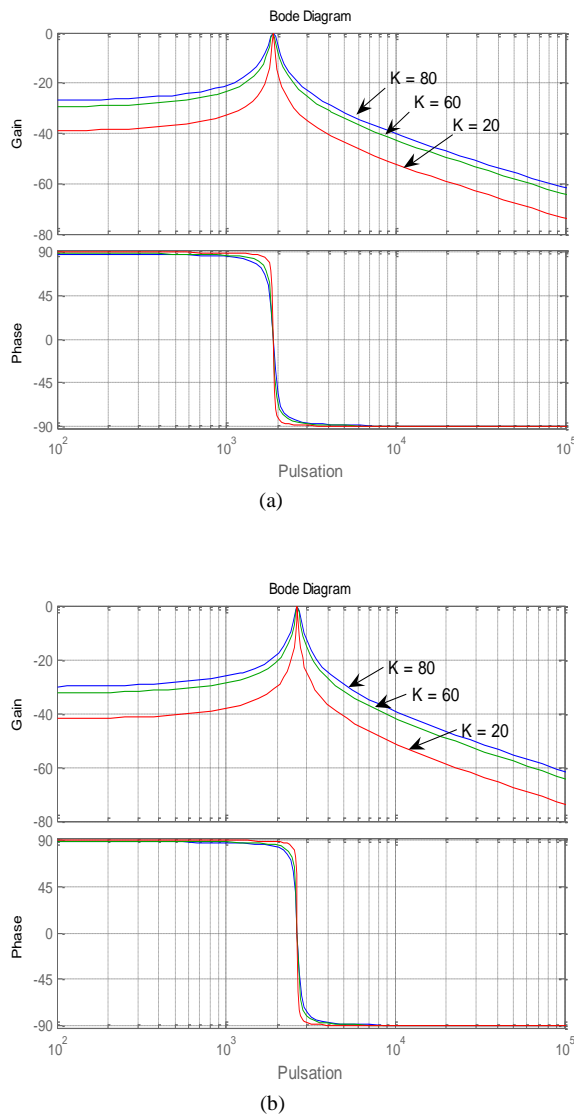


Fig.6. Performance of the STF with different values of the gain (K) versus the pulsation in rad/s.

(a) STF tuned at 5th frequency, (b) STF tuned at 7th frequency

Fig. 7 and Fig. 8 show respectively simulation results for the classical control scheme depicted in Fig.2 and

the new control scheme detailed in Fig.5. The new feedforward control has the capability of compensating the fifth and seventh harmonic successfully.

The major aims of this paper were to improve the performances of the classical feedback and feedforward control scheme presented in Fig.2 and to validate the efficiency of the proposed new control. For these reasons, some comparisons are performed between simulation results of the classical scheme and our simplified scheme.

As presented in Table III, the THD of the non-linear load current i_L is equal to 27.8% because of the large amount of the 5th harmonic while it is equal to 1.6 % for the source current i_S in case of the control scheme presented in figure 5.

The THD is equal to 4.8% for the source current i_S in case of the classical control scheme. The results we obtained demonstrated an improvement of the THD values by using the new control scheme examined in this paper. The v_{AF} waveform is not sinusoidal because of the large amount of switching-ripple voltage.

The high pass filter absorbs the voltage of the network at the fundamental frequency. Consequently, the dc voltage of the inverter v_{dc} can be reduced as low as 105V for both control schemes. This enables the hybrid filter to use low-voltage low-cost MOSFETs.

Table III summarises load and source current THD values and the harmonic-to fundamental current ratio (%) in the two control cases. It demonstrates the effectiveness of the new control scheme by using STF in the feedback and feedforward loops.

TABLE III

THD AND HARMONIC TO FUNDAMENTAL CURRENT RATIO (%) FOR LOAD AND SOURCE CURRENTS

	5 th	7 th	11 th	13 th	17 th	19 th	THD (%)
i_L	25.2	7.5	4.5	3.2	1.47	1.34	27.06
i_S (Fig.7)	1.5	0.4	3.1	2.4	1.3	1.2	4.8
i_S (Fig.8)	0.24	0.9	0.8	0.7	0.6	0.6	1.6

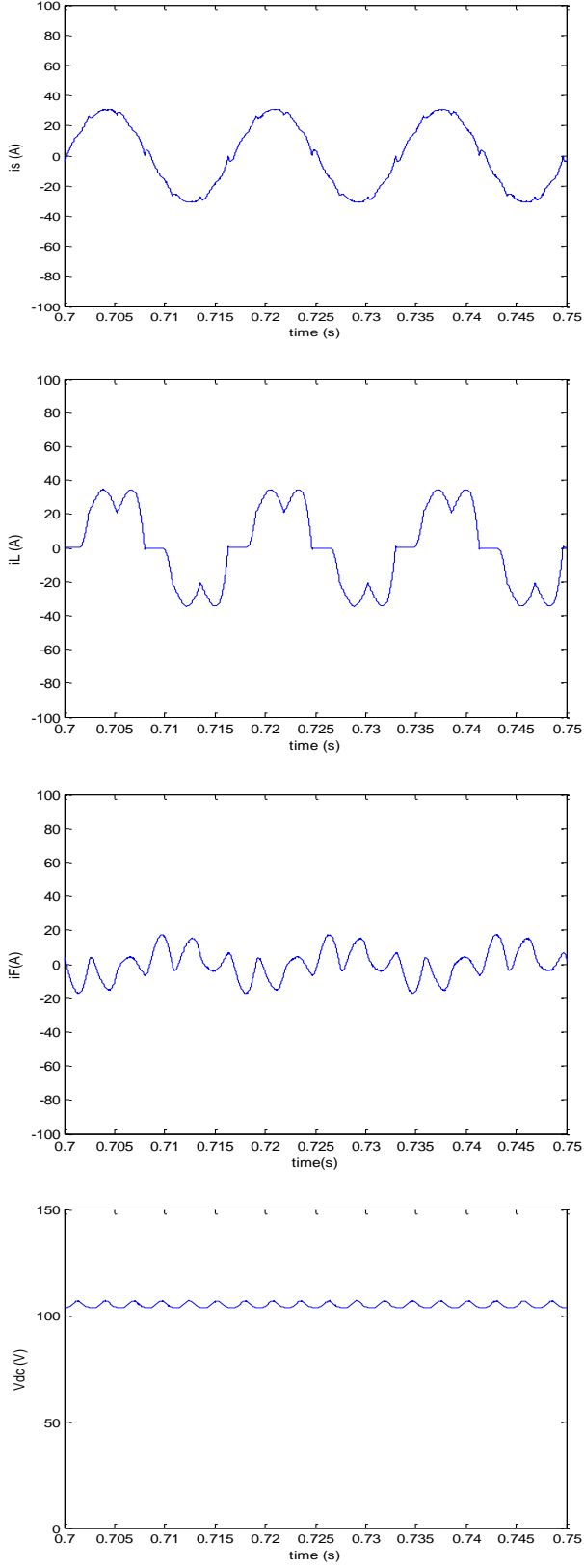


Fig. 7. Simulation results for the classical control scheme (phase a).
From top to bottom: Source current i_s (A), Load current i_L (A),
Injected current i_F (A) and DC-Bus voltage V_{dc} (V).

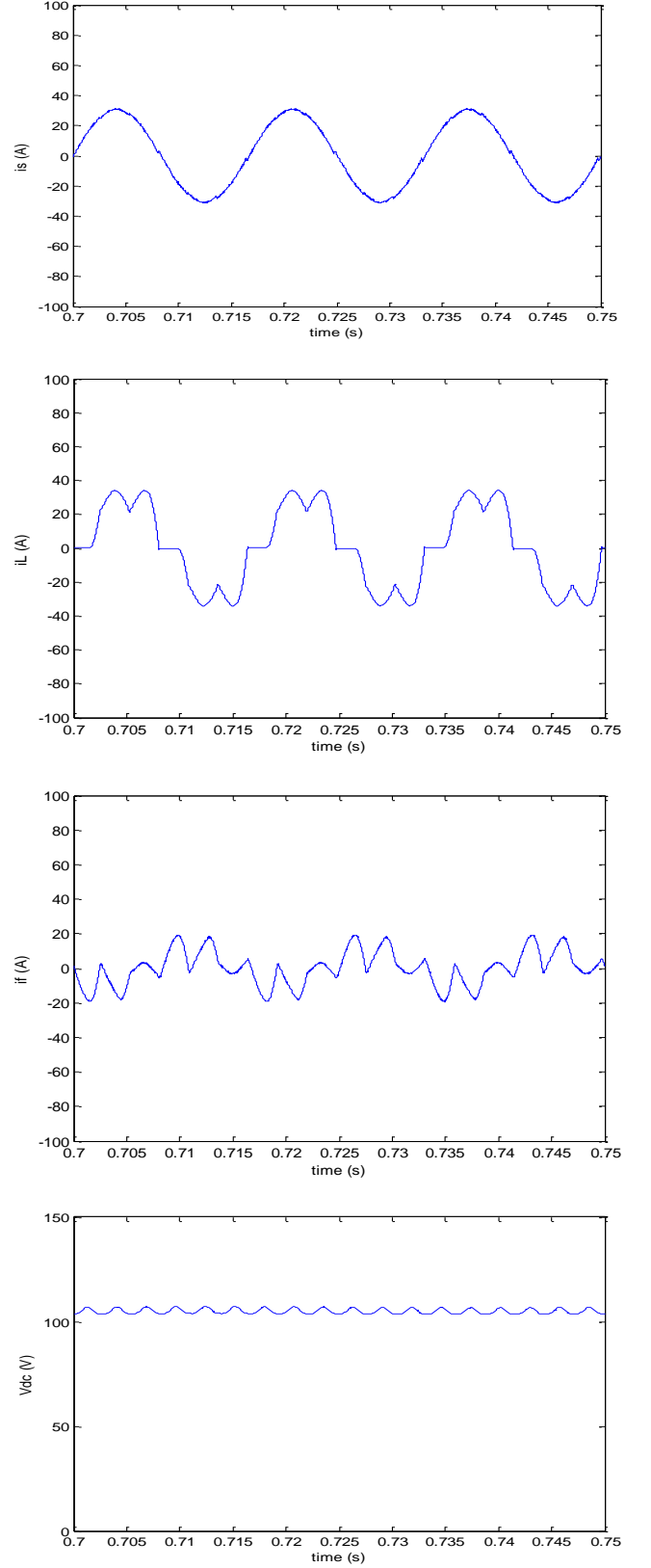


Fig. 8. Simulation results for the new control scheme (phase a).
From top to bottom: Source current i_s (A), Load current i_L (A),
Injected current i_F (A) and DC-Bus voltage V_{dc} (V).

VI. Conclusion

This paper validates by computer simulations the efficiency of a new control method to suppress the harmonic currents produced by nonlinear loads. Self tuning filters have been introduced instead of high pass and low pass filters in the feedback and feedforward loops respectively. The new feedforward loop improved the filtering performances of the active filter and achieved high quality filtering. Simulation results demonstrate the major advantages of using STF in the control system. Moreover, we can tune this STF at any frequency by using the same method as the one used for the 5th and 7th harmonic. By this way, complementary feedforward control can be added for other harmonics without major complexity of the global control.

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Shahrokh SAADATE was born in Teheran/IRAN on May 6th, 1958, received his engineer degree in 1982, his Master of research in 1982, his PHD thesis in 1986 and his "Habilitation à diriger des recherches" in 1995 from INPL-ENSEM Nancy, FRANCE. Currently, he is Professor in Electrical Engineering in the University Henri Poincaré - Nancy I, France, GREEN laboratory. His main research domains are power electronics and systems, power quality and wind energy conversion.