Intelligent Adaptive Control of the SAPF Intended to Improve the Power Grid Energy Quality

Oualid Aissa
LPMRN Laboratory
Faculty of Sciences and Technology
University of Bordj Bou Arreridj
Bordj Bou Arreridj, Algeria
oualid.aissa@univ-bba.dz

Samir Moulahoum
LREA Laboratory
Faculty of Technology
University of Médéa
Médéa, Algeria
samir.moulahoum@gmail.com

ilhami Colak
Faculty of Engineering and Architecture
Nisantasi University
Istanbul, Turkey
ilhcol@gmail.com

***Abstract*—The increasing use of static converters in the industrial sector is the main cause of the power grid energy quality degradation. These kinds of converters are characterized by their absorption of non-sinusoidal currents and their functioning under a degraded power factor. The purpose of this paper is to improve the power grid quality supplying a polluting load via the three-phase shunt active power filter (SAPF). To do this, an advanced approach based on a combination of the adaptive technique and the fuzzy logic theory was applied to ensure an advanced control of the SAPF. The three current hysteresis comparators and the voltage regulator of the conventional filter control have been replaced respectively by three fuzzy adaptive hysteresis regulators and a fuzzy controller. The smart control law made up of these advanced regulators makes it possible to guarantee an operation of the filter with improved performances. The effectiveness of the developed control strategy for the studied SAPF was tested and evaluated under the MATLAB/Simulink software. The obtained results show that the DC bus voltage is maintained perfectly at its imposed reference; the source currents are presented by a sinusoidal form; the power factor is very close to the unity and the two-level DC/AC converter of the SAPF operates under a fixed switching frequency.**

Keywords—power grid, power quality, adaptive strategy, fuzzy logic controller, MATLAB/Simulink

I. Introduction

In recent years, the expansive use of nonlinear loads based on power electronics in different sectors has led to problems related to harmonic disturbances or distortions in power grid [1],[2]. This phenomenon affects all sectors: domestic, tertiary and industrial. The origin of disturbances in the electrical network comes from nonlinear loads which are static converters consuming non-sinusoidal currents and reactive power, despite the fact that the source is sinusoidal [1-3]. This situation will systematically lead to the electrical network pollution. It is therefore obvious that these disturbances have a negative impact on electrical equipment, namely: the strong overheating, the sudden shutdown and the total destruction of these devices [4],[5].

Several means have been adopted to clean up the power grid. These solutions are divided into two categories: traditional and modern [6],[7]. The traditional solution consists of passive filtering composed of inductors and capacitors placed between the polluting nonlinear load and the electrical network. The disadvantages of this solution are the high installation costs, the decrease in reliability, the need for a large space for the structure and the risk of resonance between the reactive elements and the impedance of the network [2],[4]. The modern solution, for its part, consists of active filtering which has recently appeared through the remarkable progress that has been made in the field of semiconductor components [2],[8]. The main function of active filters is to clean up the grid and keep the value of the total harmonic distortion rate (THD) in the accepted international standards. The active filters; the most commonly used and encountered in the industry are: parallel active filters, series active filters and the parallel-series combination [9]. For this reason, and with regard to the first variant of these filters, several research works have studied and developed control techniques ensuring good control of the shunt active power filters (SAPF) under different operating conditions. Current control by traditional hysteresis regulator is the most used for controlling the SAPF [7]. However, this technique suffers from the problem of not fixing the switching frequency [10-12]. Other new control laws have marked their presence in the literature where the authors of these research works have presented and discussed. We will cite by way of example: the predictive control [2],[3]; the control by artificial neural networks [8]; the adaptive control [13]; the command in sliding mode [14]; the fuzzy logic control [15]; the PSO technique [16] and the adaptive-fuzzy combined commands [5],[6],[10-12]. These advanced techniques have been developed to ensure the correct regulation of the DC bus voltage of the filtering device, the proper delivery of reference currents and the assurance of the SAPF operation with a fixed switching frequency. Recently, another variety of SAPF has appeared where the depollution device control is designed from multi-level inverters with the aim of considerably improving the quality of the input current and increasing the range of the SAPF operating power [1],[17-19].

In this paper, we presented the study and the simulation of an advanced control strategy of the three-phase SAPF, allowing the improvement of the energy quality of the power grid in the presence of nonlinear loads. This advanced control approach is based on a combination of adaptive technique and fuzzy logic theory. The three adaptive hysteresis regulators controlling the filter current and the standard PI-type DC bus regulator have been replaced respectively by three fuzzy adaptive hysteresis regulators and an intelligent PI controller. This new control law made up of these modern regulators makes it possible to guarantee an operation of the filter with improved performances. Maintaining the DC bus voltage with good stability, rapidity and accuracy is assured. The switching frequency of the switches of the two-level DC/AC converter is fixed. The source current THD meets the international standard of the IEEE, guaranteeing a network power factor very close to the unit. The proposed fuzzy-adaptive control for the SAPF mastery has proven its superiority compared to the conventional control (equipped with adaptive hysteresis regulators and conventional PI) thanks to the simulation results obtained via the MATLAB/Simulink software.

II. Architecture and Principle of the SAPF System

The active parallel filter is designed to compensate for all disturbances affecting the current such as the harmonics, the imbalances and the presence of reactive power [1]. In Fig. 1 appears the block diagram of a parallel active filter. The SAPF consists of a voltage inverter and an inductive filter at the output. Thus, the inductance placed at the output of the inverter gives the nature of current source to the active filter [2],[3]. This filtering device restores in the electrical network the harmonic currents (I_f) equal to those absorbed by the non-linear load (I_L) so that the current supplied by the network (I_s) is sinusoidal and in phase with the corresponding voltage [19],[20].

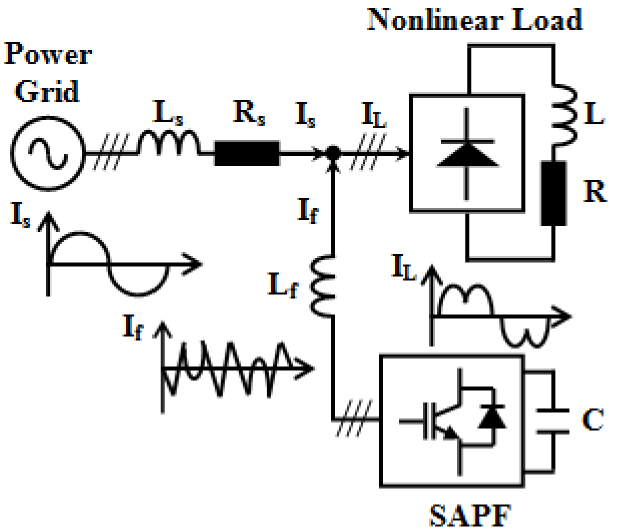

Fig. 1. Connection of the SAPF to the power grid in the presence of the nonlinear load.

III. Fuzzy Adaptive SAPF Control

The performance of this type of filter is certainly linked to the performance of the delivery of harmonic current references, but also depends on the control strategy of the voltage inverter [4]. Two strategies for controlling the active filter voltage inverter are commonly implemented, namely: The so-called direct control, the principle of which is based on the comparison of the reference current (I_f^*) with the real current (I_f) injected by the active filter; the so-called indirect control for which the reference current (I_f^*) is compared with the source current (I_s). In our research work we used the direct method. The pulses of the inverter are produced using the fuzzy adaptive hysteresis regulators whose the voltage located across the capacitor of the same converter is regulated intelligently by a fuzzy controller.

A. Filter Current Control by Adaptive Hysteresis Comparator

In order to obtain control signals which mastery the opening and closing of the inverter switches under a fixed switching frequency, adaptive hysteresis comparators were first used to replace the conventional hysteresis regulators. The current controller via adaptive hysteresis changes the hysteresis bandwidth (HB) according to the variation of instantaneous compensation current (dI_f/dt) and the voltage (V_{dc}) to minimize the influence of current distortion on the modulated waveform [6]. According to Fig. 2, the current (I_{fa}) tends to pass through the lower hysteresis band at point 1, where the switch S_1 is activated. The current increasing linearly (I_{fa}^+), touches the upper hysteresis band at point 2, where switch S_2 is activated. The current descending linearly (I_{fa}^-), touches the lower hysteresis band at point 3 [10],[11]. This operating cycle is repeated during the control of the filter current in order to ensure the task of improving the quality of energy.

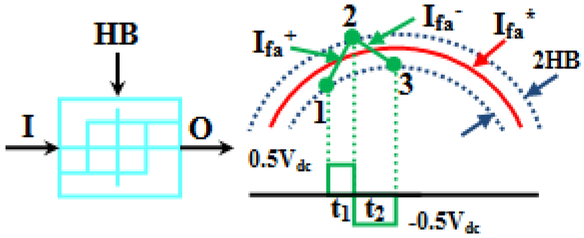

Fig. 2. Adaptive control of the filter current.

After mathematical development as indicated in [5], [10] and [11], the HB is identified as follows:

$$HB = \frac{V_{dc}}{8\, f_s\, L_f}\left[1 - \frac{4\, L_f^2}{V_{dc}^2}\left(\frac{V_s}{L_f} + \frac{dI_f^*}{dt}\right)^2\right] \qquad (1)$$

Based on (1), it is clearly that HB depending on the switching frequency (f_s), the filter inductance (L_f), the input voltage (V_s), the filter output voltage (V_{dc}) and the reference current of the filter (I_f^*).

B. Filter Current Control by Fuzzy Adaptive Hysteresis Comparator

The purpose of the fuzzy control is to manage a process according to a desired instruction, by acting on physical quantities. Its particularity is to reproduce the behavior of a human operator, rather than creating a mathematical model of the system [15]. The use of the adaptive hysteresis regulator intended to control the filter current causes the existence of switching losses generated during the application of a high switching frequency. To solve this problem, a fuzzy adaptive hysteresis regulator is proposed in this paper. The hysteresis band is calculated through the fuzzy logic theory with only two electrical quantities (V_s and dI_f^*/dt), to optimize the switching frequency and reduce the switching losses characterizing the depollution control device.

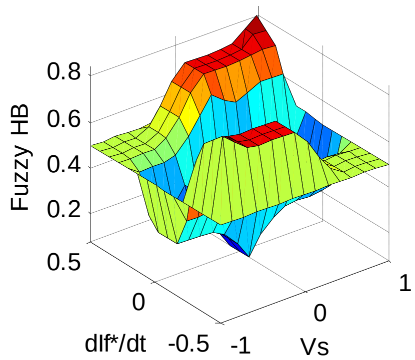

Fig. 3. Description of the (inputs/output) characterizing the fuzzy adaptive hysteresis comparator.

The proposed fuzzy hysteresis band is identified by two input variables and one output variable as described in Fig. 3 [11]. It receives the supply voltage (V_s), the slope of the reference filter current (dI_f^*/dt) and fuzzifies these inputs by five fuzzy subsets of triangular shapes each. The output of the studied controller consists of the fuzzy hysteresis band (Fuzzy HB), fuzzified by five fuzzy subsets of triangular shapes. A list of 25 fuzzy rules has been designed and presented in Table I in order to ensure adequate functioning of the developed regulator [11].

TABLE I. FUZZY RULES CHARACTERIZING THE FUZZY ADAPTIVE HB

Vs		NS	NM	Z	PM	PB
d If*/dt	NS	PVS	PS	PS	PM	PM
	NM	PS	PS	PS	PM	PM
	Z	PB	PB	PVB	PB	PB
	PM	PM	PM	PS	PS	PS
	PB	PM	PM	PS	PS	PVS

N: Negative, Z: Zero, P: Positive, S: Small, M: Medium, B: Big, V: Very.

C. Intelligent DC bus voltage regulation

A fuzzy controller has been integrated into the SAPF control to provide an improved regulation of the DC bus voltage involved in the delivery of control signals of the filter inverter. The fuzzy controller used in this case is of the Mamdani type with two input variables and one output variable as described in Fig. 4 [10],[15].

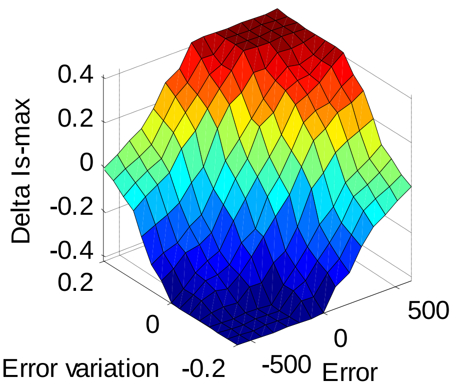

Fig. 4. Description of the (inputs/output) characterizing the intelligent PI controller.

It receives the error of the DC bus voltage (e), the variation of this error (Ve) and fuzzifies these inputs by seven sub-fuzzy sets of triangular shapes each.

$$e(n) = V_{dc}^*(n) - V_{dc}(n) \tag{2}$$

$$Ve(n) = e(n) - e(n-1) \tag{3}$$

The output of the developed fuzzy controller presents the delta maximum reference current ($\Delta I_{s\text{-max}}$). For its part, this output is also fuzzified by seven fuzzy subsets of triangular shapes. For defuzzification we used the center of gravity method. In order to link the state of each set of possible inputs to the appropriate output, a list of fuzzy rules is also necessary. For this studied control structure, an inference system is used with 49 fuzzy rules as shown in Table II [10].

The DC bus voltage (V_{dc}) is detected and compared to a reference voltage (V_{dc}^*), the result of this comparison is applied to this fuzzy controller to obtain the amplitude of the three source reference currents ($I_{s\text{-max}}$), as indicated in (4).

$$I_{s-\max}(n) = I_{s-\max}(n-1) + \Delta I_{s-\max}(n) \tag{4}$$

Then, this amplitude will be multiplied by three sinusoidal signals of amplitude equal to unity, delivered by the phase-locked loop (PLL) to obtain the three instantaneous source reference currents (I_{sa}^*, I_{sb}^* and I_{sc}^*). The difference between the three line currents (I_{La}, I_{Lb} and I_{Lc}) and those of the source references delivers the three desired filter currents. The difference calculated between these reference currents (I_{fa}^*, I_{fb}^* and I_{fc}^*) and the currents supplied by the inverter (I_{fa}, I_{fb} and I_{fc}) must be controlled by fuzzy adaptive hysteresis regulators in order to set the control orders of the DC/AC converter constituting the SAPF. The block diagram of the intelligent adaptive control governing the SAPF in the presence of a polluting nonlinear load is illustrated in Fig. 5.

TABLE II. FUZZY RULES CHARACTERIZING THE INTELLIGENT PI CONTROLLER

Error		NB	NM	NS	Z	PS	PM	PB
Error variation	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

N: Negative, Z: Zero, P: Positive, S: Small, M: Medium, B: Big.

IV. SIMULATION RESULTS WITH DISCUSSIONS

The behavior of the SAPF system studied in both static and dynamic states was examined by simulation using MATLAB/Simulink software, where the necessary parameters adopted for this task are given as follows: Three-phase voltage source (V_s): 70V; Switching frequency (f_s): 20kHz; Desired output voltage (V_{dc}^*): 300V; DC link capacitor (C): 2200μF; Input resistance (R_s): 0.1Ω; Input inductance (L_s): 0.15mH; Filter inductance (L_f): 0.66mH; Nonlinear load resistance (R): 6.7Ω; Nonlinear load inductance (L): 20mH.

For adaptive control of the SAPF and after activation of it, we can notice that the DC bus voltage has reached its imposed reference value of 300V with recording of a slight overshoot of 5V which will disappear quickly after 0.2 seconds as shown in Fig. 6a. Two robustness tests were carried out at the time t_1 = 0.3 sec and t_2 = 0.6 sec characterized by load variations to evaluate the efficiency of the voltage regulator used in this command. The classical PI regulator used has proven its capacity to reject disturbances caused on the DC bus with recording of a voltage drop of around 19V for a period of 0.15 sec on the one hand and a voltage increase of 19V for a period of 0.15 sec on the other hand.

The use of the fuzzy controller instead of the classical PI regulator made it possible to control the DC bus voltage in a very satisfactory manner compared to the results obtained during the control of the SAPF by the classical PI regulator. The superiority of the intelligent controller compared to the conventional PI regulator lies in the rapid conservation of the DC bus voltage at its reference value without recording of overshoot as shown in Fig. 6b. On the same figure, we can observe the appearance of a voltage drop followed by a voltage increase of 2V for a very short time (0.012 sec) due to the variation of the load.

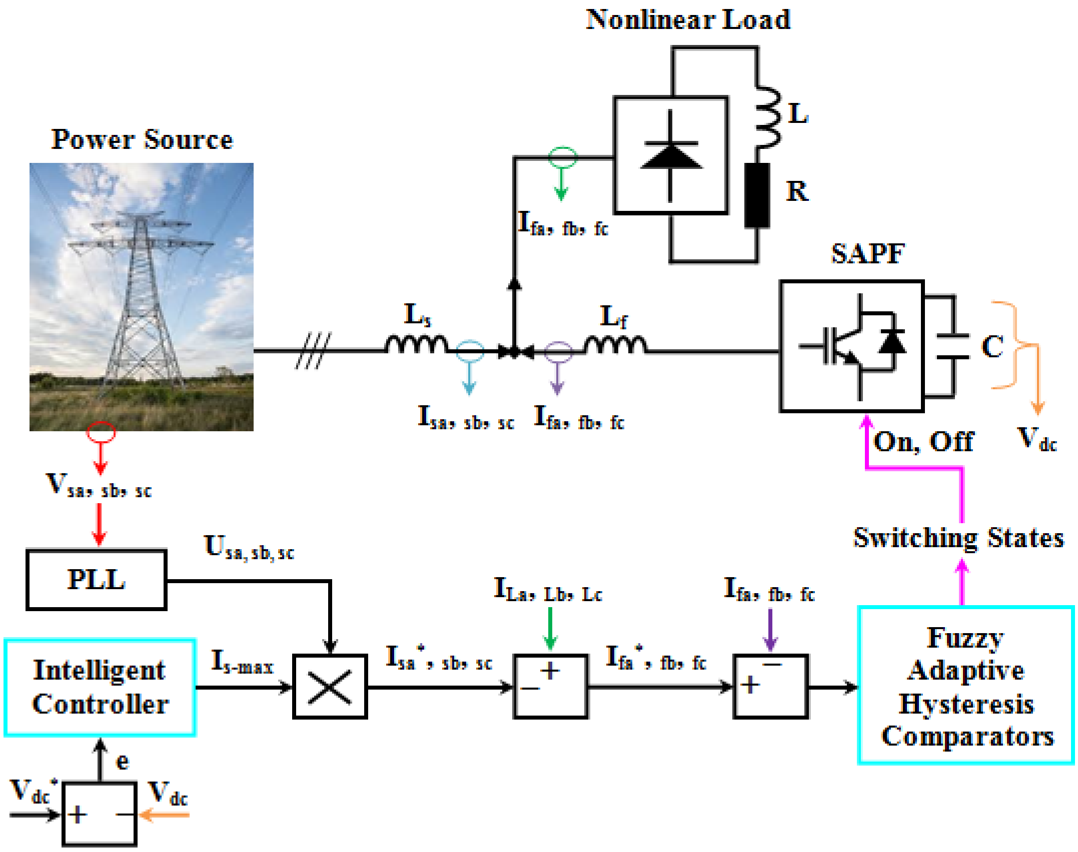

Fig. 5. Illustrative block diagram of the SAPF based on the fuzzy adaptive control law.

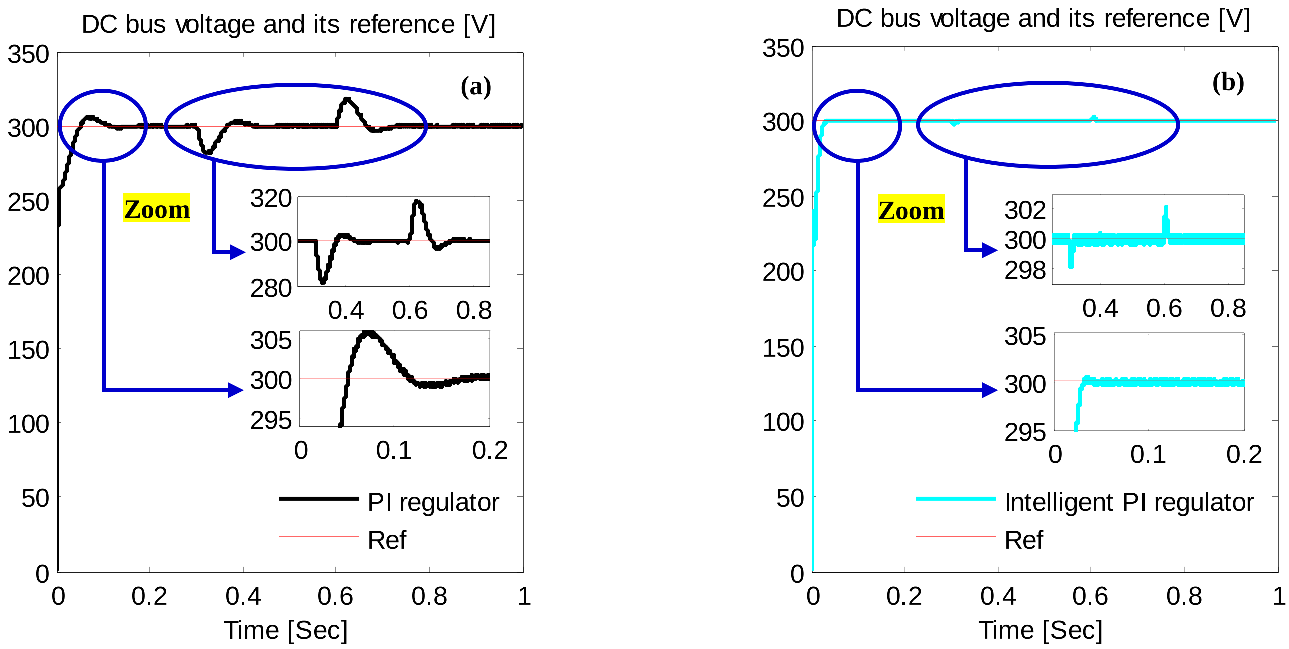

Fig. 6. Simulation result of DC bus voltage with its reference and Zoom: (a) Adaptive control of SAPF (adaptive hysteresis comparators + classical PI regulator); (b) Intelligent adaptive control of the SAPF (fuzzy adaptive hysteresis comparators + fuzzy regulator).

Thanks to the intervention of the SAPF, the source current of phase (a) became sinusoidal. Furthermore, this same current reacted correctly to the variations caused at times t_1 = 3 sec and t_2 = 0.6 sec on the load as illustrated in Fig. 7. Also, the filter current and the load current relating to the phase (a) illustrated in Fig. 8 and Fig. 9 respectively, respond correctly to the same robustness tests carried out.

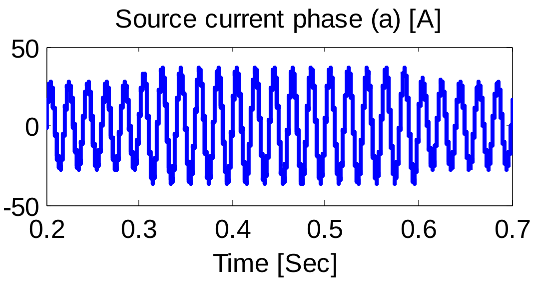

Fig. 7. Simulation result of the source current for intelligent adaptive control of the SAPF.

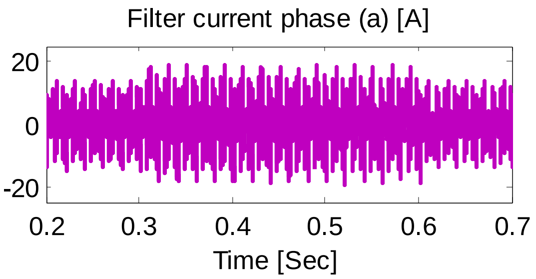

Fig. 8. Simulation result of the filter current for intelligent adaptive control of the SAPF.

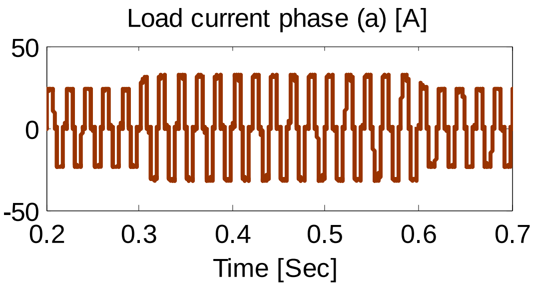

Fig. 9. Simulation result of the load current for intelligent adaptive control of the SAPF.

Fig. 10 represents the shape of the source voltage and current as well as the harmonic spectrum relative to the source current of the phase (a). We notice that the source voltage is sinusoidal and the input current is distorted. The THD rate of this source current is 26.08%. This will cause an operation of the system under a degraded power factor of the electrical network rated at 0.9602.

The input current and the source voltage for the phase (a) present a zero phase shift between them. The recorded THD of the source currents are equal to 3.91% and 1.93% in the case of the application of the adaptive control and the intelligent adaptive control of the SAPF respectively (Fig. 11 and Fig. 12). Both THD values obtained meet the international IEEE standard and ensure operation of the system under a power factor very close to unity, valued respectively at 0.9988 and 0.9998.

The superiority of the intelligent adaptive technique of the SAPF was confirmed by these results compared to the adaptive control method. In addition, the use of fuzzy adaptive hysteresis regulators has made it possible to intelligently set the switching frequency, thus presenting another advantage for the control of the studied filter.

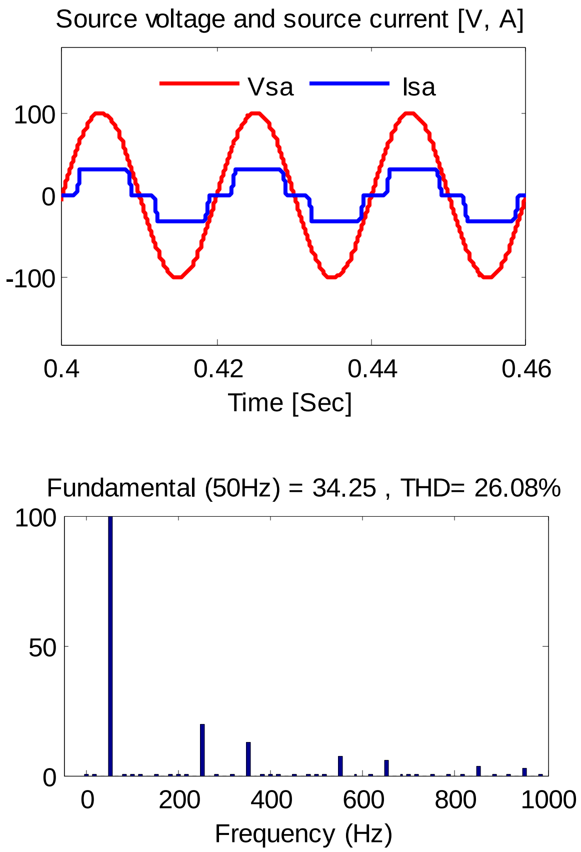

Fig. 10. Simulation results of the source voltage and current with its THD value in the absence of the SAPF.

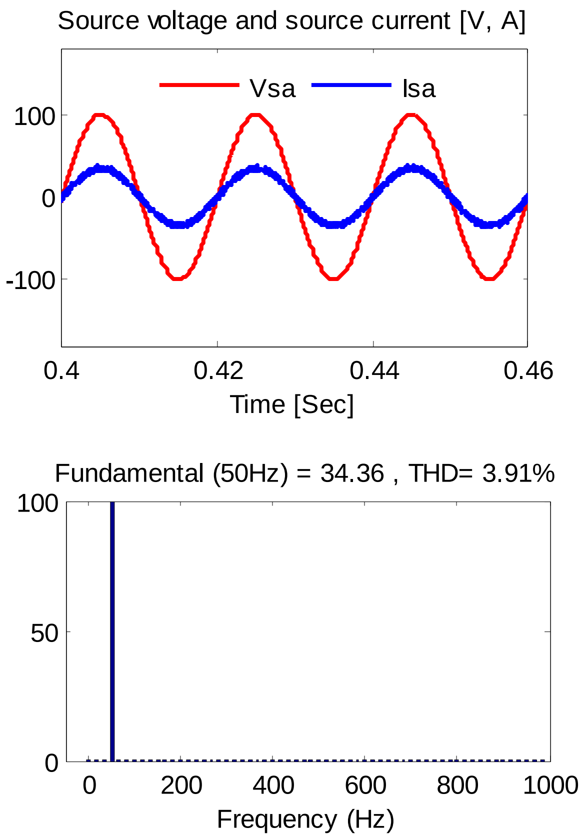

Fig. 11. Simulation results of the source voltage and current with its THD value for the adaptive SAPF control.

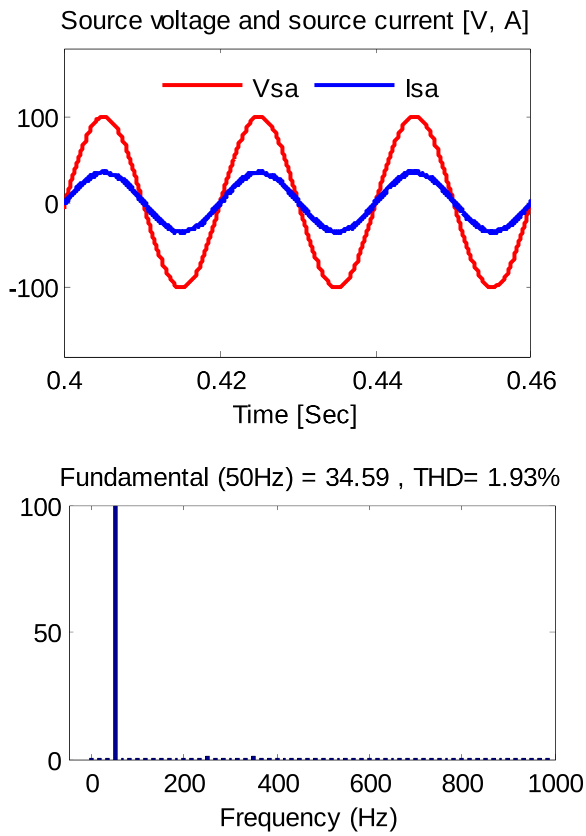

Fig. 12. Simulation results of the source voltage and current with its THD value for the intelligent adaptive SAPF control.

V. CONCLUSION

The research work presented in this paper consists of the study and simulation of the SAPF based on the fuzzy adaptive control, intended to compensate the disturbances generated by the nonlinear loads. A fuzzy controller was used in place of the classical PI regulator to regulate the DC bus voltage of the filter on one side and to participate in the supply of reference source currents on the other side. In addition, to fix the switching frequency of the studied filtering system, thus operating with low switching losses, the fuzzy adaptive hysteresis comparators have been used to perform this task. The proposed control of the SAPF has been verified by digital simulation using MATLAB/Simulink software. The obtained results showed that the quality of the controlled DC bus voltage and the source current are better than those obtained when applying the control strategy with adaptive hysteresis regulators and with the classical PI controller. In addition, the studied SAPF operates under a power factor very close to the unit as well as with a fixed switching frequency and optimized in terms of switching losses.

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