Combination of Fuzzy Logic with Direct Power Control Technique for Shunt Active Filter Control

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Abstract **-** Generally, the efficiency and performance of the shunt active filter (SAF), in particular the reduction of the total harmonic distortion (THD) of the source current and the improvement of the power factor, are related to the control strategy adopted. The use of voltage sensorless control techniques, mainly direct power control (DPC), has provided several advantages such as reducing the number of sensors and eliminating identification and modulation techniques. Nevertheless, the use of such techniques generates current ripples in the SAF, which are caused by an uncontrollable switching frequency in the presence of hysteresis controllers. This can limit the filtering and compensation performance of the SAF and thus affect the quality of the electrical power. To avoid such a problem, the switching table of the DPC technique is replaced by a fuzzy inferences system, so that the input variables are represented by membership functions. Also, a stable exchange of active power between the SAF and the power grid can be achieved by adopting an effective system for controlling the direct voltage of the SAF. For this purpose, DC voltage regulation is carried out with a fuzzy regulator. The effectiveness of the proposed control techniques is shown at the end of this article by a numerical simulation using Matlab/Simulink.

Keywords **-** Shunt Active Filter (SAF), direct power control, fuzzy set theory, fuzzy switching table, fuzzy logic controller.

I. INTRODUCTION

The proliferation of electrical equipment using static converters has led in recent years to a significant increase in the level of harmonic pollution of electrical networks [1, 2].

This electrical equipment is considered as non-linear loads emitting harmonic currents whose frequencies are integer multiples of the fundamental frequency, or sometimes at any frequency [3]. The flow of these harmonic currents through the impedances of the power grid can cause harmonic voltages at the connecting points and thus affect consumers supplied from the same power grid [4]. The most important effect is thermal, which results in heating, resulting in premature fatigue of the line material. Harmonic currents also generate additional joule losses in transformer windings, accentuated by the skin effect, as well as hysteresis and eddy current losses in magnetic circuits [5, 6].

To provide consumers with good quality electrical energy, even under the most disturbed operating conditions, active power filters are proposed as advanced solutions for the harmonic mitigation of power grids [7, 8].

Active power filters are an effective means of compensating for currents or voltages harmonics generated by non-linear loads [9]. They compensate the disturbances due to a non-linear load by reinjecting the harmonics and the load reactive current into the network in phase-opposite mode so that the power grid only supplies a sinusoidal current in phase with the voltage.

The performance of the power active filter, and in particular the reduction of the THD of the source current and the improvement of the power factor, are related to the performance of the generation of harmonic current references, but also depend on the control strategy adopted. Several control strategies have been proposed in the literature [10, 11]. Although their principles differ, the main objective of these techniques is to obtain an almost unity power factor and a sinusoidal current.

Direct Power Control (DPC) is based on instant control of active and reactive power. In this type of control, the current control loops and modulation technique are eliminated, and the states of the converter switches are selected from a switching table based on instantaneous errors between the estimated active and reactive powers and their reference values. The major disadvantage of DPC technique is the presence of current ripples [12, 13]. To this end, it is proposed to use an intelligent method for generating the switching times of the inverter, and to select the position of the voltage vector, replacing the traditional switching table by a fuzzy inferences system. In order to further improve the filtering performance of the SAF, the DC voltage control system is performed by a fuzzy logic controller.

The numerical simulation results given at the end of this article show the effectiveness of the proposed solution.

II. SHUNT ACTIVE FILTER (SAF)

Fig. 1. illustrates the structure and principle of an SAF based on a voltage source inverter.

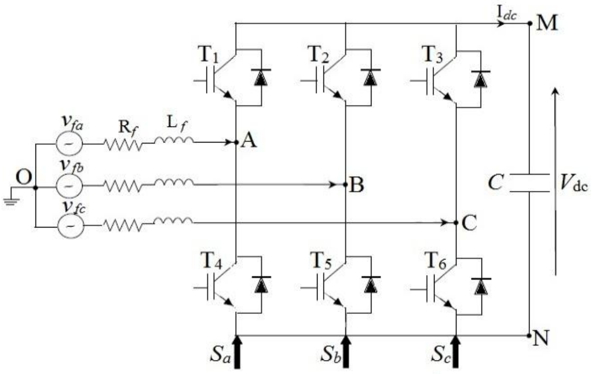


Fig. 1. Active filter with voltage source structure.

The operating principle of the SAF on the AC side is given by:

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \begin{bmatrix} V_{fa} \\ V_{fb} \\ V_{fc} \end{bmatrix} - \begin{bmatrix} R_f & 0 & 0 \\ 0 & R_f & 0 \\ 0 & 0 & R_f \end{bmatrix} . \begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix} - \begin{bmatrix} L_f & 0 & 0 \\ 0 & L_f & 0 \\ 0 & 0 & L_f \end{bmatrix} . \frac{d}{dt} \begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix} - \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} . V_{NO} \quad (1)$$

V_{fa}, V_{fb}, V_{fc} are the AC voltages SAF and V_{AN}, V_{BN}, V_{CN} represent the input voltages of the converter.

The compound voltages V_{AN}, V_{BN}, V_{CN} are created at the switch terminals by the commands S_a, S_b, S_c applied to the converter and are transformed at the phase level into V_{AO}, V_{BO} and V_{CO} [14].

The phase currents on the AC side I_{fa}, I_{fb}, I_{fc} are caused by the voltage drops across the network impedances ($V_{fa} - V_{AO}$), ($V_{fb} - V_{BO}$) et ($V_{fc} - V_{CO}$), then these currents will be cut through the switches commutation to provide the direct current I_{dc}.

$$I_{dc} = S_a I_{fa} + S_b I_{fb} + S_c I_{fc} \quad (2)$$

On the DC side, the current is given by:

$$I_{dc} = C \frac{dV_{dc}}{dt} \quad (3)$$

This implies:

$$V_{dc} = \frac{1}{C} \int I_{dc} . dt \quad (4)$$

III. DIRECT POWER CONTROL TECHNIQUE DPC

The principle of the DPC technique is illustrated in Fig. 2. It consists in selecting a control vector according to a switching table, whose inputs are the errors (Sp, Sq) between the reference and measurement values of the instantaneous powers [15]. The active power reference is obtained by regulating the DC voltage. While to ensure a unit power factor, a reactive power control is performed at zero [16].

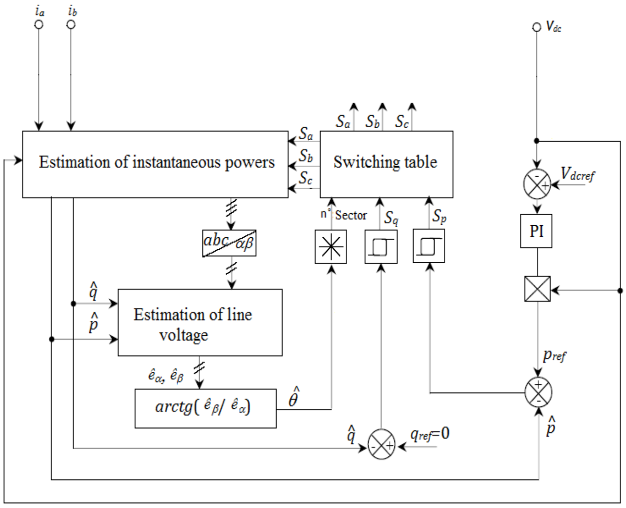


Fig. 2. General configuration of the DPC strategy.

The estimation of instantaneous active and reactive powers is carried out by:

$$\hat{p} = L\left(\frac{di_a}{dt} i_a + \frac{di_b}{dt} i_b + \frac{di_c}{dt} i_c\right) + V_{dc}\left(S_a i_a + S_b i_b + S_c i_c\right) \quad (5)$$

$$\hat{q} = \frac{1}{\sqrt{3}} \left\{ \begin{array}{l} 3L\left(\frac{di_a}{dt} i_c - \frac{di_c}{dt} i_a\right) \\ -V_{dc}\left(S_a\left(i_b - i_c\right) + S_b\left(i_c - i_a\right) + S_c\left(i_a - i_b\right)\right) \end{array} \right\} \quad (6)$$

IV. CONVENTIONAL SWITCHING TABLE

The synthesis of the switching table is based on the signs of the derivatives of the active and reactive powers in each sector. The variation in reactive power is positive for three vectors, negative for three vectors, and zero for V_0, V_7. The sign of the variation in active power is positive for four vectors, negative for two or three vectors [17].
Thus, the switching table is given by Table 1.

Table 1 Conventional switching table

S_p	S_q	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_5	V_6	V_1	V_2	V_3	V_4
0	1	V_1	V_2	V_3	V_4	V_5	V_6
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5

V. FUZZY DIRECT POWER CONTROL F-DPC

In conventional DPC, the system does not differentiate between very small and relatively large errors of active and reactive powers. This can cause a slightly slow response during a step change in active or reactive power. Thus, fuzzy set theory is used to take into account all the variations of active and reactive powers.

The proposed fuzzy inference system is designed to have three input variables Δp, Δq and θ as well as an output variable V_i, as shown in Fig. 3.

The active power error Δp is defined by:

$$\Delta p = p_{ref} - \hat{p} \tag{7}$$

The reactive power error Δq is given by:

$$\theta = \tan^{-1}\left(\frac{\hat{e}_\beta}{\hat{e}_\alpha}\right) \tag{8}$$

The position of the voltage vector θ is:

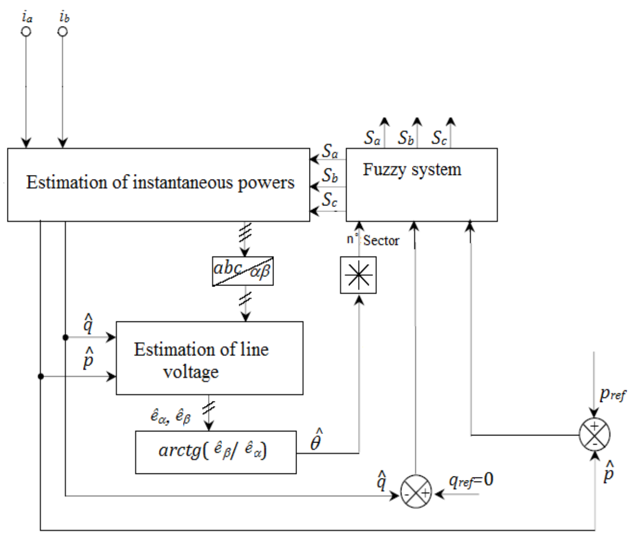


Fig. 3. General configuration of the Fuzzy DPC technique

The three input variables are divided into fuzzy sub-sets, where the number of fuzzy sub-sets is chosen to have maximum control with minimum inference rules. The discourse universe of the active power error is divided into two linguistic variables with triangular and trapezoidal membership functions, where N and P denote respectively the negative and positive values of the active power error, as shown in Fig. 4. The discourse universe of reactive power error is divided into three linguistic variables with triangular and trapezoidal membership functions, where N, Z, and P denote the negative, zero, and positive values of the reactive power error, respectively, as shown in Fig. 5.

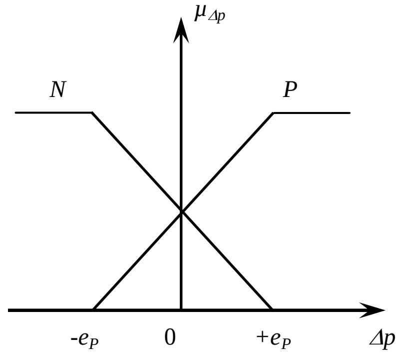


Fig.4. Membership functions for the active power error Δp

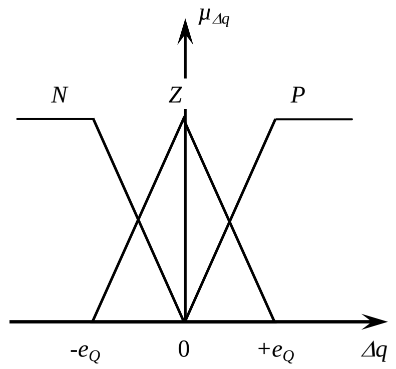


Fig. 5. Membership functions for the reactive power error Δq

For greater accuracy, the discourse universe of the position of the voltage vector θ is divided into six fuzzy sets θ_1 to θ_6, as shown in Fig. 6.

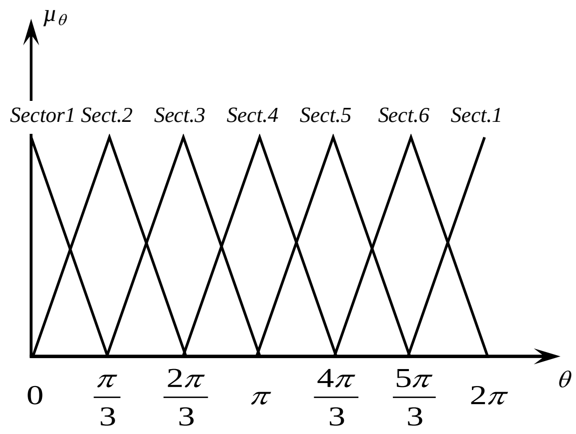


Fig.6. Membership functions for the position of the voltage vector θ

The control variables are the switching states of the active filter. For a six-pulse inverter, seven switching states are possible.

The switching states are tightened, so there is no need to represent them with fuzzy membership functions. For the voltage vectors V_i $(i=0÷6)$, the distribution in membership functions is given in Fig. 7.

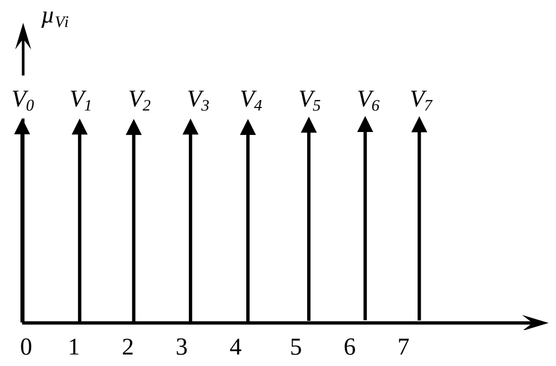


Fig. 7. Membership functions for the control variable.

Each control rule can be described using the state variables Δp, Δq and θ and the control variable n which characterizes the switching states of the inverter. The i^{th} rule R_i can be written as follows:

R_i: if Δp is A_i, Δq is B_i and θ is C_i so n is N_i

With: A_i, B_i, C_i and N_i are the membership functions of the variables.

Table 2. Fuzzy switching table.

Δp	Δq	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
P	*P*	V_3	V_4	V_5	V_6	V_1	V_2
	Z	V_7	V_0	V_7	V_0	V_7	V_0
	N	V_5	V_6	V_1	V_2	V_3	V_4
N	*P*	V_1	V_2	V_3	V_4	V_5	V_6
	Z	V_0	V_7	V_0	V_7	V_0	V_7
	N	V_6	V_1	V_2	V_3	V_4	V_5

To perform a precise control action, the controller was designed using Mamdani's inference method, based on the min-max decision. The weighting factor (α_i) for the i^{th} rule can be given by:

$$\alpha_i = \min\left(\mu_{Ai}(\Delta p), \mu_{Bi}(\Delta q), \mu_{Ci}(\theta)\right) \tag{10}$$

The Membership factor μ_N of the output n is given by:

$$\mu_N(n) = \max_{i=1}^{36}\left(\mu'_{Ni}(n)\right) \tag{11}$$

In this case, the outputs are crisp; the maximum criterion is used for defuzzification. By this method, we can write :

$$\mu_{Nout}(n) = \max_{i=1}^{7}\left(\mu_{Nout}(n)\right) \tag{12}$$

VI. FUZZY LOGIC CONTROL OF DC VOLTAGE

The principle diagram of the fuzzy DC voltage control is given in Fig. 8.

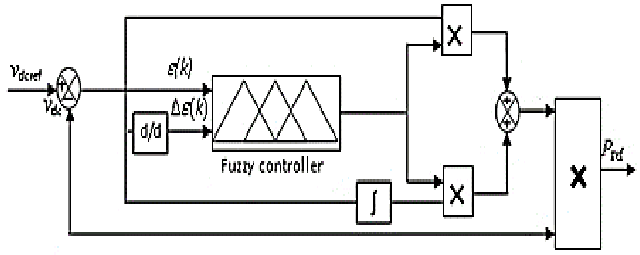


Fig. 8. Fuzzy control of DC voltage.

The new DC voltage control structure preserves the same model when using a *PI* regulator. This is an association of the fuzzy controller output with the proportional and integer actions of the control signal.

The fuzzy regulator uses two inputs: the first input is the error between the measured value and the reference value of the *DC* voltage. The second represents the variation of this error. These two signals are represented as follows:

$$\varepsilon(k) = v_{dcref}(k) - v_{dc}(k) \tag{13}$$

$$\Delta\varepsilon(k) = \varepsilon(k) - \varepsilon(k-1) \tag{14}$$

The membership functions representing the input and output variables are given in Fig. 9.

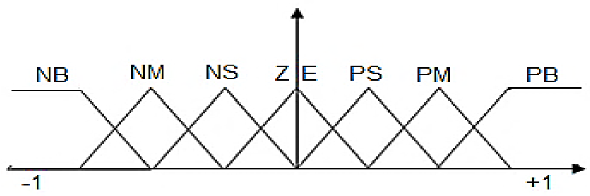


Fig. 9. Input and output variable membership functions.

VII. RESULTS AND INTERPRETATION

To test the performance of the proposed control techniques, a simulation was performed under the MATLAB\SIMULINK environment and using the Fuzzy Logic Toolbox.

The simulation is carried out in two steps:

1. The efficiency of the fuzzy DPC controlled SAF is tested for reactive power compensation and harmonic elimination. The power grid feeds an inductive linear load, then the load is eliminated between 0.06 s and 0.12 s. Finally, a non-linear load will be connected between 0.12 s and 0.2 s.

2. The proposed control system for the DC voltage V_{dc} is tested, in terms of setpoint monitoring, by performing a step disturbance at the DC voltage reference value at t=0.1s from 700V to 750V.

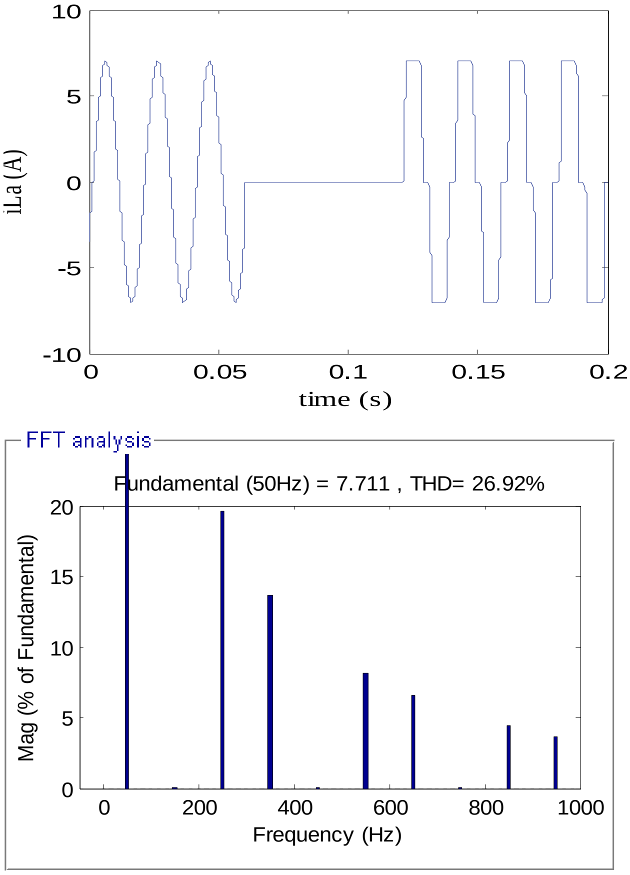
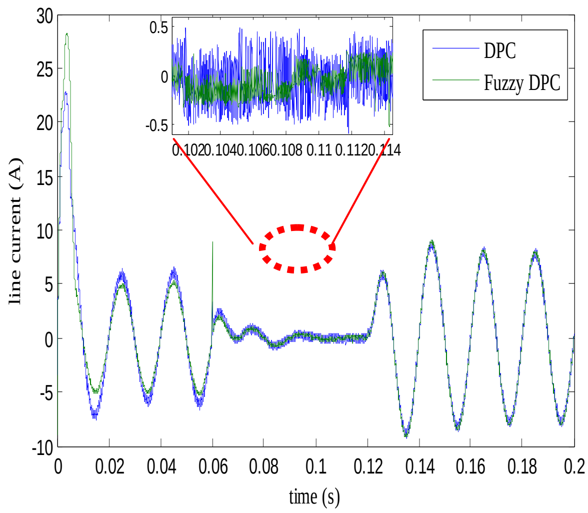


Fig. 10. Current absorbed by the non-linear load i_{La} [A] and the harmonic spectrum of the current i_{La}.

The waveforms of the load current and the line current with their spectral representations are illustrated in Fig. 10 and Fig. 11 respectively. It can be seen that the proposed technique is a control strategy that combines reactive power compensation with harmonic mitigation. The THD of the line current is significantly reduced from 26.92% to 1.45%..



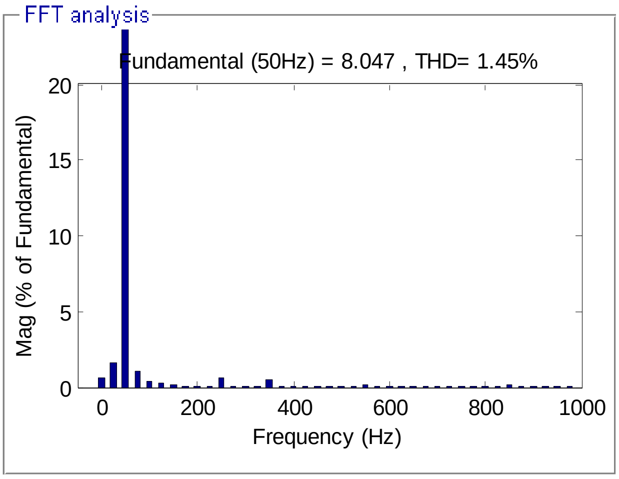


Fig. 11. Waveform of the line current and the harmonic spectrum of the current i_s.

The Fig. 12 to Fig.14 clearly illustrate the main advantage of combining the DPC technique based on fuzzy logic control. This advantage is the considerable reduction of current ripples. These figures show us that the control technique used acquires a dual role for the SAF: Reactive power compensation in fundamental regime, and the attenuation of dominant harmonics by pushing them towards higher frequencies.

Fig. 12 shows that fuzzy DPC has a positive influence on the performance of the DC voltage control system. In this figure, the overshoot disappears completely and the response time is reduced. From Fig. 13 and Fig. 14 show that the DPC provides a certain speed and stability to the system response

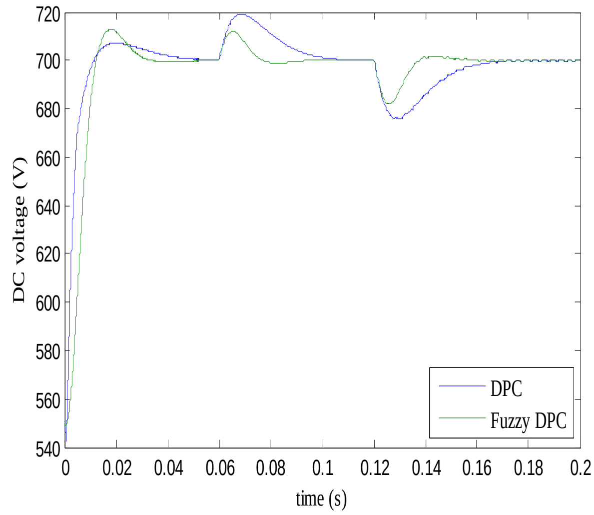


Fig. 12. Waveform of the *DC* voltage V_{dc}(V).

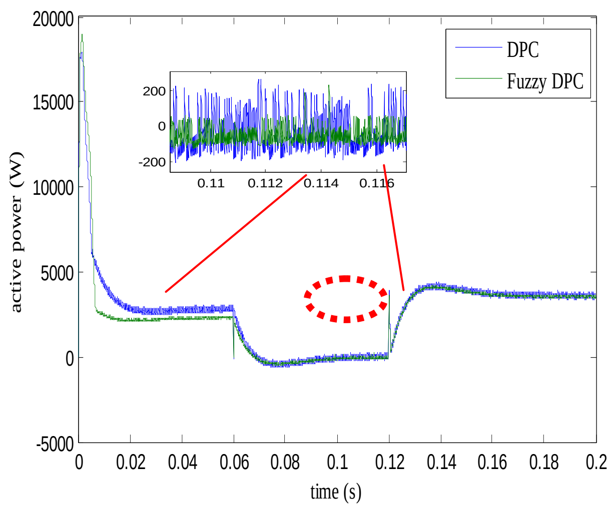


Fig. 13. Waveforms of the instantaneous active power of the line (*W*).

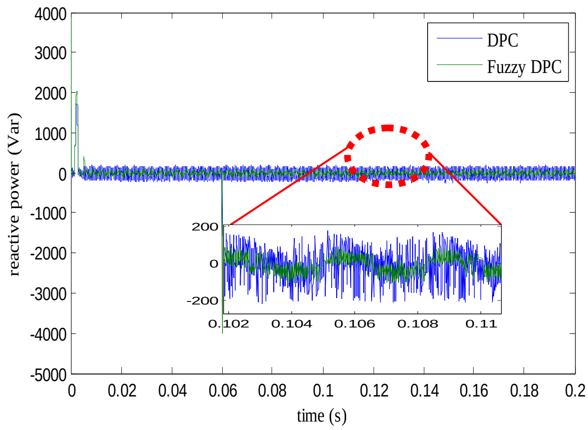


Fig. 14. Waveforms of the instantaneous reactive power of the line (*Var*).

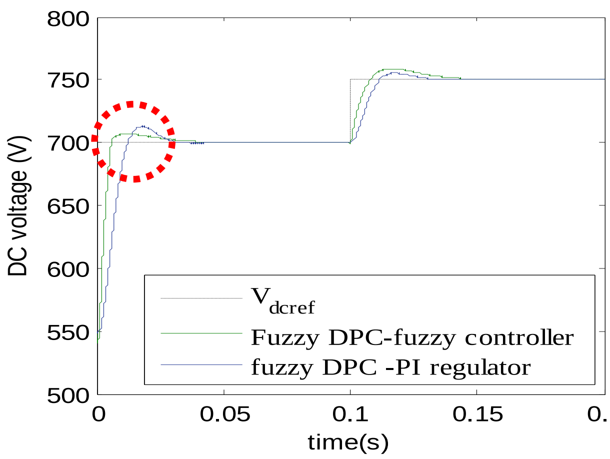


Fig. 15. Waveform of the *DC* voltage V_{dc} (*V*).

The step variation of the DC voltage is given in Fig. 15, (from 700 to 750 volts). Fig. 15, Fig. 16 and Fig. 18 show, respectively, that when the DC voltage reaches its new reference value, the active power increases and consequently the line current increases. In the case of the fuzzy controller, the increase in active power is limited, which prevents the system from being subjected to dangerous over-currents. To obtain a unit power factor on the AC side, the reactive power reference value is set to 0.

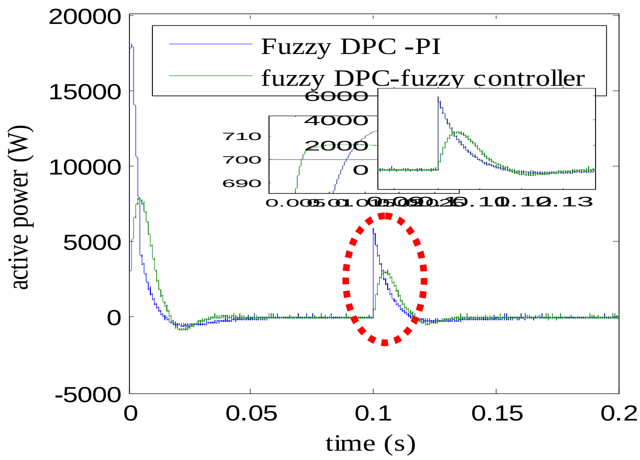


Fig. 16. Waveforms of the instantaneous active power of the line (*W*).

Fig. 17 shows that the reactive power is almost zero. Fig. 18 also shows that the current is almost sinusoidal.

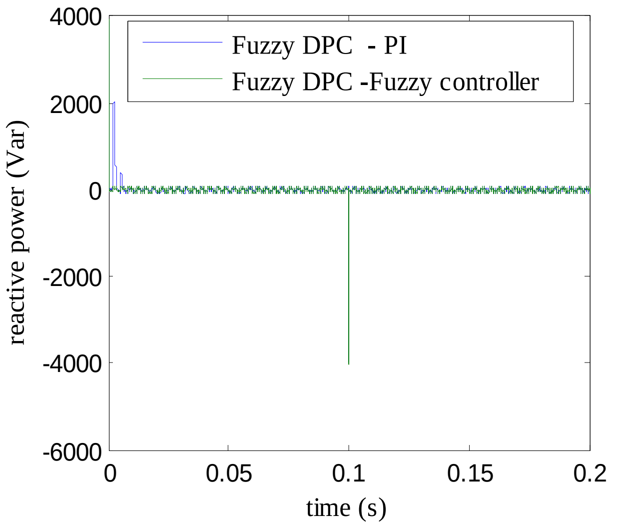
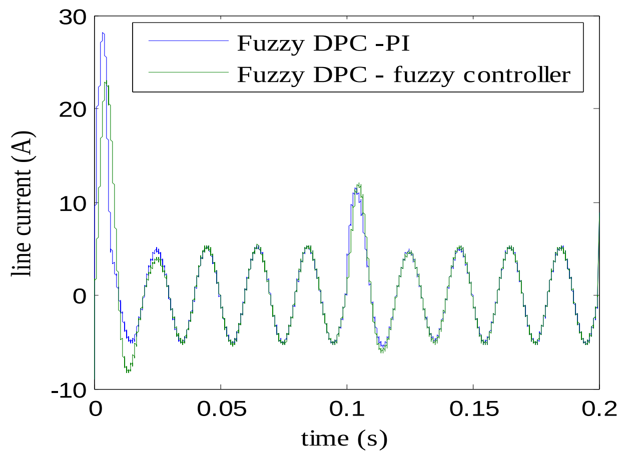


Fig. 17. Waveforms of the instantaneous reactive power of the line (*Var*).



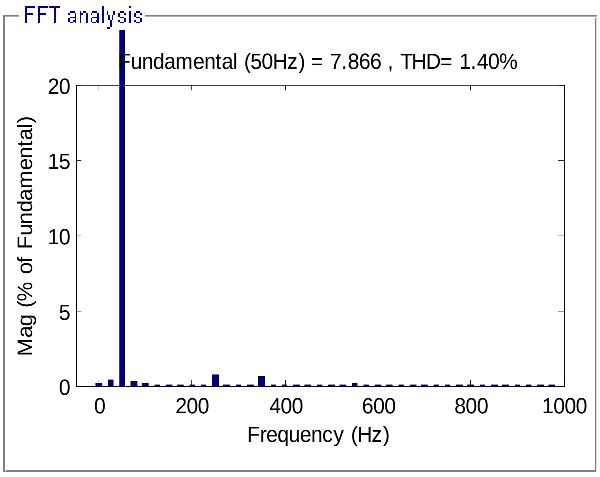


Fig. 18. Waveform of the line current and the harmonic spectrum of the current i_s.

VIII. CONCLUSION

In this article, we have been able to show the contribution of fuzzy logic to the control performance of an active parallel power filter, with which the DPC technique is associated. All the simulation results confirmed the supremacy of fuzzy DPC over conventional DPC in reducing waveforms of the different magnitudes of the system under study. Also the introduction of fuzzy logic into the DC voltage control system has contributed to improving the performance of the system's response (overshoot and response time), as well as the power factor and THD of the line current.

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