Samira DAHMANI[1], Abdelhafid SEMMAH[1], Mohamed KADEM[1], Patrice WIRA[2]

Djillali Liabes University of Sidi Bel Abes, Algeria (1), Haute Alsace University of Mulhouse, France (2)

doi:10.15199/48.2019.07.13

Genetic algorithm optimization of a SAPF based on the fuzzy-DPC concept

***Abstract**. This article presents a study on the use of the concept of direct power control (DPC) based on intelligent techniques in the control of a shunt active power filter (SAPF). In order to improve harmonic mitigation and reactive power compensation capabilities, the conventional switching table is replaced by a fuzzy inference system to generate the switching sequences of the shunt active power filter. To ensure an active power exchange stable and efficient, the DC voltage of the SAPF in controlled using an integrated proportional controller (PI) optimized by a heuristic optimization technique based on genetic algorithms (GA). The combination of two intelligent techniques in this proposed control strategy makes it possible to* reduce ripples in different variables *of the SAPF, to maintain the direct voltage at their reference value and to improve the THD of the grid current. The numerical simulation results obtained under Matlab / Simulink confirm the importance of the SAPF's proposed control technique.*

Streszczenie.** W artykule opisano wykorzystanie metody DPC (direct power control) do poprawy parametrów bocznikowego filtru aktywnego SAPF. Konwencjonalna tabela przełączeń jest zastąpiona przez system logiki rozmytej. Do optymalizacji filtru wykorzystano też algorytm genetyczny.* ***Optymalizacja aktywnego filtru bocznikowego SAPF z wykorzystaniem algorytmu genetycznego i logiki rozmytej

Keywords: Shunt active power filter, direct power control, fuzzy inference system, genetic algorithm.
Słowa kluczowe: aktywny filtr bocznikowy SAPF, logika rozmyta, algorytm genetyczny

Introduction

Harmonic distortion is generated by non-linear loads connected to the grid that absorb non-sinusoidal currents [1]. These current harmonics will successively generate harmonic voltages at the different grid connection points [2]. Many solutions for cleaning up electricity networks have already been proposed in the literature [3, 4].

Active power filters (APF) are to date the most appropriate advanced pollution control solutions [5, 6], APF has several advantages such as the elimination of harmonic currents, reactive energy compensation, rebalancing of non-linear load currents [7].

The principle of parallel active filters was introduced by [8]. The principle is based on the injection of harmonic currents or voltages opposite to those generated by the nonlinear load so as to have a current or voltage resulting quasi-sinusoidal. The performance of the active filter depends on the control strategy adopted. Several control strategies have been proposed in the literature [9].

The DPC concept is equivalent to direct torque control (DTC) one for electrical machines [6]. The principle is based on the selection of a voltage vector using a switching table, direct self-control, or space vector modulation [10]. Among these DPC techniques, the strategy of voltage vector selection using a switching table is widely studied and marketed. This is due to its concept which is simple to implement.

The selection of the voltage vector is based on the active power error, reactive power and therefore the position of the voltage vector. The most disadvantages in conventional DPC are: the system doesn't differentiate between very small and relatively large errors of the active and reactive powers which can affect the stability of the system response, the occurrence of ripples at different SAPF quantities, additionally the utilization of conventional analysis methods to select the parameters of the PI controller need determining a transfer function including the controller and the system to be controlled. This needs the adoption of simplifying assumptions which will take us away from studying the important behavior of the system. Iteratively, it is identified that the PI parameters strongly have an effect on the THD of the system input current [11].

To remedy this, a new direct power control for the SAPF is proposed in this article, based on the use of fuzzy logic, replacing the conventional switching table with a fuzzy inference system, for the generation of the inverter switching times, and on the other hand, it is necessary to select the PI controller parameters in an optimal way to control the DC voltage, thus using a heuristic optimization technique based on genetic algorithms (GA).

Shunt active power filter

Fig. 1 illustrates the structure and principle of an SAPF based on voltage source converter.It consists of a bridge of six power transistors with anti-parallel diodes.

Let us consider the voltages on the AC side of the active filter V_{fa}, V_{fb}, V_{fc} and the input voltages of the converter V_{AN}, V_{BN}, V_{CN}.

S_a, S_b, S_c represent the logical control variables

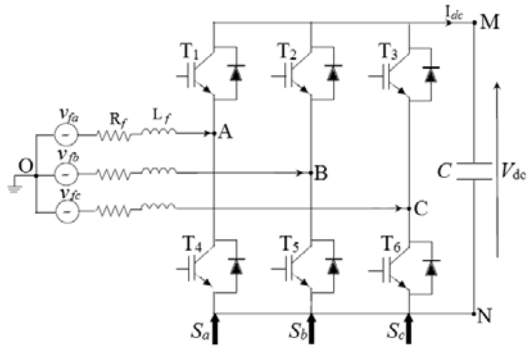

Fig.1. Structure of the SAPF based on voltage source converter

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

$$V_{AN} = V_{AO} + V_{ON} = V_{fa} - R_f I_{fa} - L_f \frac{dI_{fa}}{dt} - V_{NO} \quad (1)$$

$$V_{BN} = V_{BO} + V_{ON} = V_{fb} - R_f I_{fb} - L_f \frac{dI_{fb}}{dt} - V_{NO} \quad (2)$$

$$V_{CN} = V_{CO} + V_{ON} = V_{fc} - R_f I_{fc} - L_f \frac{dI_{fc}}{dt} - V_{NO} \quad (3)$$

The phase-to-phase 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 into phase voltages V_{AO}, V_{BO} and V_{CO} [10].
On the DC side, the current is given by:

$$I_{dc} = C\,\frac{dV_{dc}}{dt} \tag{4}$$

This implies:

$$V_{dc} = \frac{1}{C}\int I_{dc}\,.dt \tag{5}$$

Conventional Direct Power Control

The principle of the DPC strategy is based on a selection of a control vector according to a switching table based on the digitized errors S_p and S_q of the instantaneous active and reactive powers, as well as on the angular position of the estimated voltage vector. The digitized errors are provided by two hysteresis regulators. According to the position of the voltage vector, the (α -β) plane is divided into many sectors where one must associate at each sector a switching time of the inverter. Reference value of the active power is obtained by using a proportional-integrator controller for the DC voltage. In order to ensure a unitary power factor, reference value of the reactive power is set at zero (Fig.2).

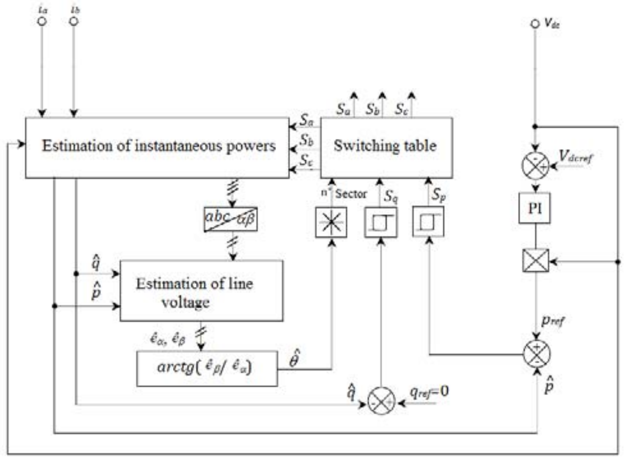

Fig.2. General configuration of the DPC strategy

The key points for implementing DPC strategy is a correct and fast estimation of instantaneous active and reactive powers. [9-11].

Table 1. Conventionnal 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

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

$$\hat{p} = L\left(\frac{di_a}{dt}+\frac{di_b}{dt}+\frac{di_c}{dt}\right)+V_{dc}\left(S_a i_a + S_b i_b + S_c i_c\right) \tag{6}$$

$$\hat{q}=\frac{1}{\sqrt{3}}\left(\frac{di_a}{dt}i_c-\frac{di_c}{dt}i_a\right)+V_{dc}\left(S_a(i_b-i_c)+S_b(i_c-i_a)+S_c(i_a-i_b)\right) \tag{7}$$

The line voltage can be estimated using the following equation:

$$\begin{bmatrix}\hat{e}_\alpha\\ \hat{e}_\beta\end{bmatrix}=\frac{1}{i_\alpha^2+i_\beta^2}\begin{bmatrix}i_\alpha & -i_\beta\\ i_\beta & i_\alpha\end{bmatrix}\begin{bmatrix}\hat{p}\\ \hat{q}\end{bmatrix} \tag{8}$$

Knowledge of the estimated voltage sector is necessary to determine optimal switching states. Let us consider that the α-β plant is divided into 6 sectors.

The outputs hysteresis regulators, given by the boolean variables S_p and S_q, indicate higher or lower limits of powers errors according to the below logic:

$$\begin{cases} p_{ref}-\hat{p}>h_p & \Rightarrow \quad S_p=1\\ p_{ref}-\hat{p}>-h_p & \Rightarrow \quad S_p=0\\ q_{ref}-\hat{q}>h_q & \Rightarrow \quad S_q=1\\ q_{ref}-\hat{q}>-h_q & \Rightarrow \quad S_q=0\end{cases} \tag{9}$$

Where: h_p, h_q – the variations of the hysteresis regulators.

Neglecting line voltage variations [9, 10], dynamics of active and reactive powers can be given as follows:

$$\frac{dp}{dt}=\frac{1}{L}\left(e_\alpha^2+e_\beta^2\right)-\frac{1}{L}\left(e_\alpha.u_{c\alpha}+e_\beta.u_{c\beta}\right) \tag{10}$$

$$\frac{dq}{dt}=\frac{1}{L}\left(e_\alpha.u_{c\beta}-e_\beta.u_{c\alpha}\right) \tag{11}$$

Fuzzy direct power control

The switching table (Table 1) will be replaced by the fuzzy inference system shown in Fig. 3.

The proposed fuzzy controller is designed to have three fuzzy state variables Δp, Δq, θ, and one control variable V_i. The first variable Δp, the active power error, defined by:

$$\Delta p = p_{ref}-\hat{p} \tag{12}$$

The second variable Δq, the reactive power error, given by:

$$\Delta q = q_{ref}-\hat{q} \tag{13}$$

The third fuzzy state variable is the position of the voltage vector θ given by:

$$\theta = tan^{-1}\left(\frac{v_{S\beta}}{v_{S\alpha}}\right) \tag{14}$$

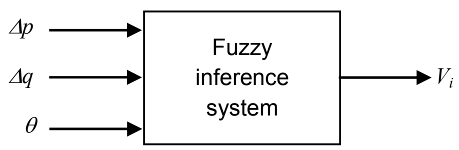

Fig.3. Input and output variables of a fuzzy switching table

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.

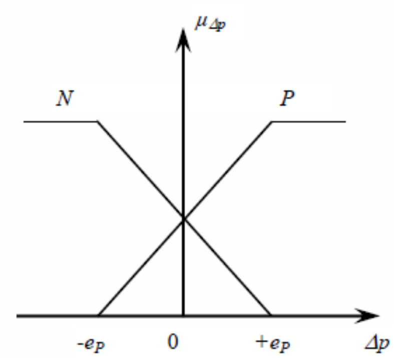

Fig.4. Membership functions for the active power error Δp

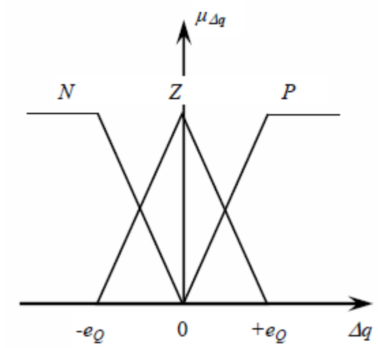

Fig.5. Membership functions for the reactive power error Δq

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. Association

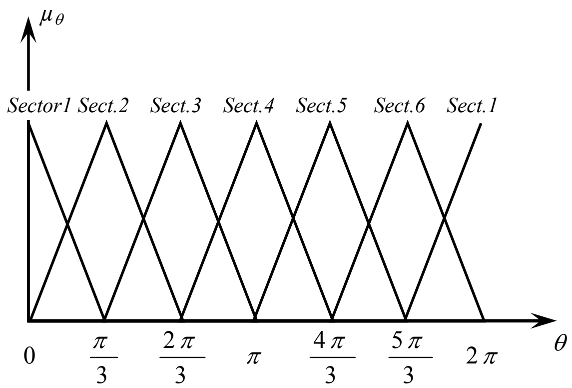

Fig.6. Membership functions for the position of the voltage vector θ

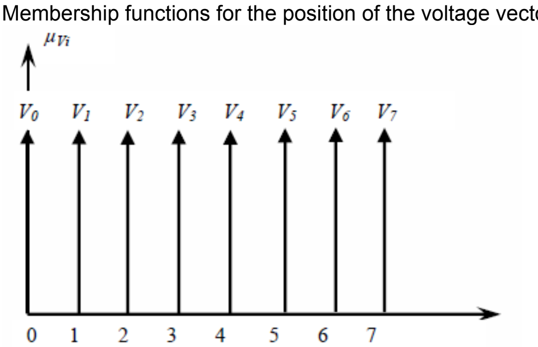

Fig.7. Membership functions for the control variable

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 $(i=0\div6)$, the distribution in membership functions is given in Fig. 7.

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 then n is N_i

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:

$$\alpha_i = min\left(\mu_{Ai}(\Delta p), \mu_{Bi}(\Delta q), \mu_{Ci}(\theta)\right) \quad (15)$$

The degree of belonging μ_N of the output n is given by:

$$\mu_N(n) = \max_{i=1}^{36}\left(\mu'_{Ni}(n)\right) \quad (16)$$

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

$$\mu_{Nout}(n) = \max_{i=1}^{7}\left(\mu_{Nout}(n)\right) \quad (17)$$

PI regulator optimized by genetic algorithm (PI_GA)

The active power reference is generated by a reliable control system based on DC voltage control by a PI corrector optimized by a genetic algorithm [12].

The PI_GA controller principle is illustrated in Fig.8. The PI_GA controller receives at its input a signal represented by the error between the set-point input and the measured one. It provides at its output the control signal with which the system will be controlled.

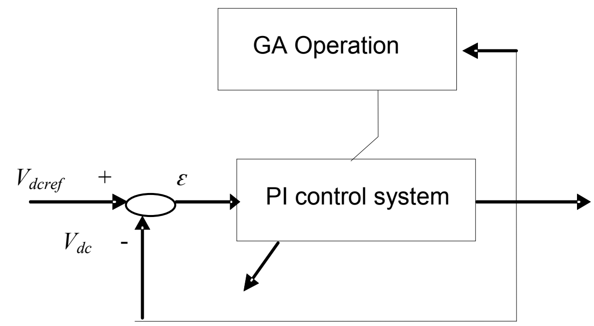

Fig.8. Structure of a regulator based on the principle of the genetic algorithm

A genetic algorithm typically works through a simple cycle [13]:

A- Evaluation

The evaluation function is a function that depends on 2 parameters (individual genotype), $X=[x_1\ x_2]$ which are the proportional gain and the integral time constant. The f_{val} evaluation is the same for each generation and for each individual.

The evaluation function must be even higher the criteria, which corresponds to efficient regulation. To do this, we use the evaluation function defined by the following expression:

$$f_{val} = \frac{1}{1 + a.y_{os} + bT_s + c.IEA + d.ISE} \quad (18)$$

where a, b, c and d are weighting coefficients. These coefficients are set before the optimization process in order to take more or less into account each performance criterion [12].

ISE: is the Integral of Squared Error

$$I_1 = \int_0^{\omega} \varepsilon^2(t)dt \quad (19)$$

IAE: is the Integral of Absolute Error between a reference set point V_{dcref} and the voltage V_{dc}:

$$I_2 = \int_0^{\omega} |\varepsilon(t)|dt \quad (20)$$

T_s: Stabilization time of the transitional regime.

y_{os}: overshoot rate.

B- Initial population

The initial population is composed of N binary coded individuals. Each individual (chromosome) is a vector of two parameters [14], representing respectively the integral time constant and the integral gain, and enters the cross mutation selection loop. The size of the population is constant over successive generations

C- Selection

We select breeding groups based on their evaluation by the f_{val} function.

D- Crossover

The crossover takes place in 2 stages:

Selection of C pairs of breeders who will become parents,

Crossover of parents and formation of 2 children per couple.

Each couple generates 2 children by the simple crossover method. We choose a crossover point for both parents, and we form 2 children by exchanging part of the chromosomes.

E- Mutation

We perform a mutation on individuals. This mutation consists in changing a given bit for each individual. We change the 0 to 1 and vice versa for the mutation point that varies from one individual to another and is randomly selected.

The best chromosomes will represent the parameters of the optimized PI controller

Results and discussion

In order to validate the effectiveness of the DPC based on PI_GA control on the DC side and a Fuzzy switching table applied to a SAPF, the simulation tests were performed under the MATLAB\SIMULINK environment and using the Fuzzy Logic Toolbox. The proposed control system was applied to an SAPF powered by a balanced and sinusoidal three-phase voltage source. The parameters of the simulated system are given in Table 3.

Table 3. The parameters of the simulated system

Power grid	V_s = 400V, R_s=0Ω, L_s=400μH
nonlinear load (Graëtz bridge with diodes	R_{ch}= 0Ω, L_{ch}= 566μH R_d= 7Ω, L_d= 1mH
Shunt active power filter	R_f=32$m\Omega$, L_f=500μH, V_{dc}=700V

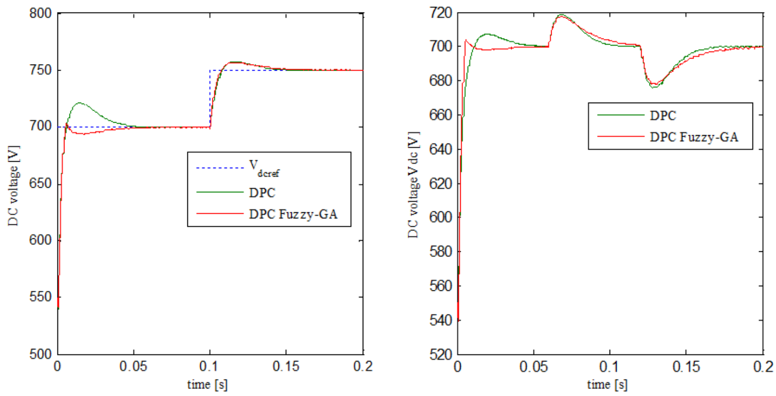

Fig.9. Waveform of the DC voltage $V_{dc}(V)$

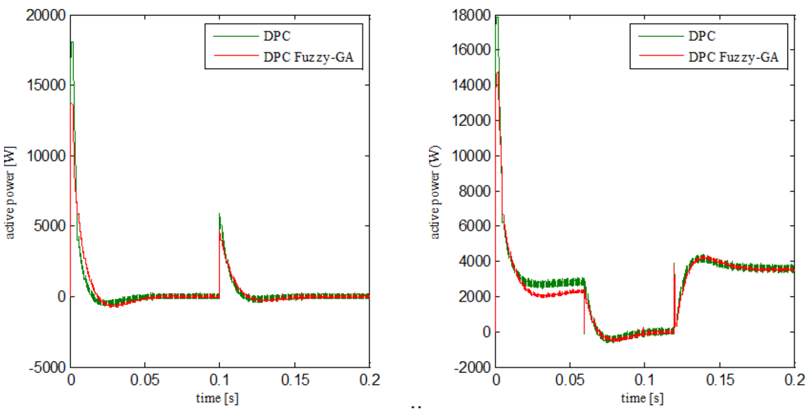

Fig.10. Waveforms of the instantaneous active power of the line (W)

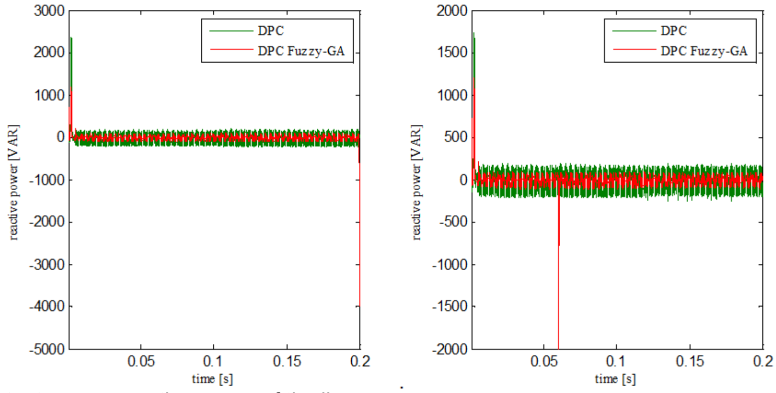

Fig.11. Waveforms of the instantaneous reactive power of the line *(VAR)*

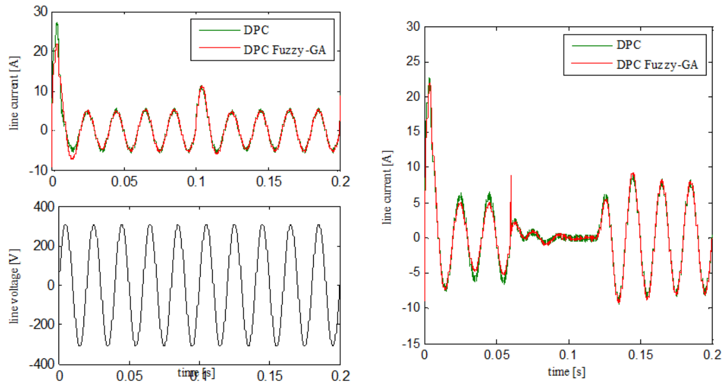

Fig.12. waveforms of the source voltage and the source current

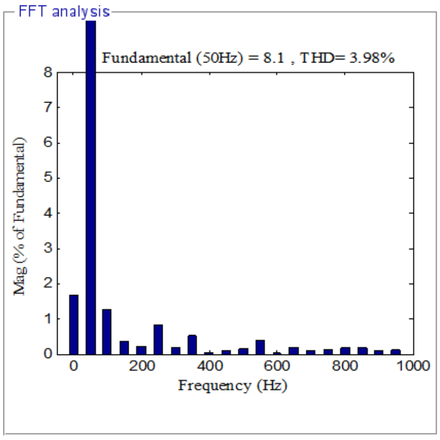

Fig.13. FFT Source current with conventional DPC

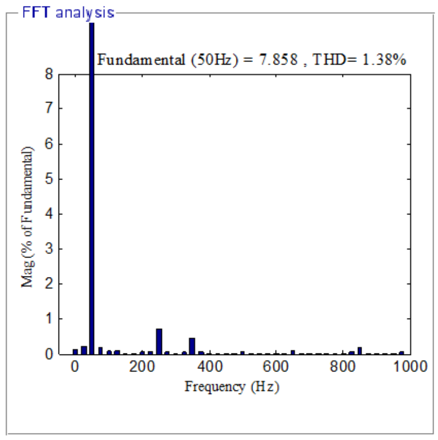

Fig.14. FFT Source current with DPC fuzzy-GA

The simulation is carried out in two steps:
1- The DC voltage control system as well as the DPC strategy are tested following a step change in the DC voltage at t=0.1*s* from 700*V* to 750*V* on the left side
2- The electrical network supplies an inductive linear load, and then the load is eliminated between 0.06 *s* and 0.12 *s*. Finally, the voltage source supplies a non-linear load between 0.12 and 0.2 *s* on the right side

The effectiveness of DC voltage control is illustrated in Fig. 9, it can be seen that the system is becoming more stable and robust compared to the system with conventional DPC. In this figure, the overshoot disappears completely and the response time is reduced.

From fig. 10 to fig. 14, it can be said that the DPC provides a certain quickness and robustness to the system response. These figures illustrate clearly the main advantage of the association of genetic algorithms and fuzzy logic based on the DPC concept. This advantage lies in the fact that the ripples at the different waveforms are significantly minimized.

These figures show us that the control technique used acquires a double role for the SAPF; namely the reactive power compensation in fundamental regime, and the attenuation of dominant harmonics by pushing them towards the higher frequencies. We can see that the THD is sensibly reduced from 3.98% to 1.38%.

Conclusion

This paper was the subject of a study on the association of the DPC technique with a fuzzy inference system, and optimization by genetic algorithms. This is in order to control an SAPF powered by a balanced and sinusoidal three-phase voltage source.

All the numerical simulation results, obtained under Matlab/Simulink, confirmed the supremacy of the DPC Fuzzy-GA over the conventional DPC, in terms of reducing ripples in different variables of the system studied, as well as improving system performance. These improvements affect the performance of the system response (overshoot and response time), as well as the THD of the line current.

***Authors**: DAHMANI Samira, Djillali Liabes University of Sidi Bel Abbes 22000, Algeria, E-mail: belsam021992@outlook.fr, SEMMAH Abdelhafid, Djillali Liabes University of Sidi Bel Abbes 22000, Algeria, E-mail: hafid.semmah@yahoo.fr, Mohamed Kadem, Djillali Liabes university of Sidi Bel-Abbes 22000 Algeria, E-mail: kadem.mohamed.ing@gmail.com WIRA Patrice, Haute Alsace university, Mulhouse, France, E-mail: patrice.wira@uha.fr*

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