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Optimal Design for Hybrid Active Power Filter Using Particle Swarm Optimization

Nada Alloui[†] and Cherif Fetha
Department of Electrical Engineering, Batna University, Batna 05000, Algeria

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This paper introduces a design and a simulation of a hybrid active power filter (HAPF) for harmonics reduction given an ideal supply source. The synchronous reference frame method has been used here to identify the reference currents. The proposed HAPF uses a new artificial- intelligence technique called Particle Swarm Optimization (PSO) for tuning the parameters of a proportional and integral controller called PI-PSO. The PI-PSO controller is used to archive optimality for the DC-link voltage of the HAPF-inverter. The hysteresis non-linear current control method is used in this approach to compare the extracted reference and the actual currents in order to generate the pulse gate required for the HAPF. Results obtained by simulations with Matlab/Simuling show that the proposed approach is very flexible and effective for eliminating harmonic currents generated by the non-linear load with the HAPF based PSO tuning.

Keywords: Particle swarm optimization (PSO), Hybrid active power Filter (HAPF), PI-PSO controller, Total harmonic distortion (THD), Objective function

1. INTRODUCTION

Developments in power electronics, the increase in power consumption and flexible use of semiconductors has encouraged electro technologists to apply power static inverters to electric machines. Generally, these devices represent nonlinear loads, which absorb a non sinusoidal current and behave like harmonics generators. Moreover, they sometimes consume reactive energy. Consequently the wave of the source current loses its sinusoidal form and degrades the power-factor [1].

To lessen the effect of harmonic distortion, two different filters are provided namely active and passive filters. Passive filters have been conventionally used for mitigating harmonic distortion in industrial power systems. However they have drawbacks such as undependable performance, undesired absorption of the harmonic currents of nearby non linear loads, and risk of harmonic resonance with system series impedance which could lead to further harmonic propagation throughout the power system [2]. The recent advances in power semiconductors devices have resulted in the development of active power filters (APF) for harmonic suppression [3].The shunt active filters are functioned as a current source parallel to the non-linear load. The power converter of active filters is controlled to develop a reimbursement current that is identical to but opposite to the harmonic and reactive currents generated by the non-linear burden [4]. However, the cost of building active filters in functional commerce is too high. The power ranking of the power converter in active filters is very large. These limit the application of active filters power schemes [4].

Therefore use of hybrid filters would be the best solution for improving power quality because using passive or active filters alone will not solve any problems in such a structure, whereas the advantages of both types of filters can be synergized [5].

In this paper, a hybrid active power filter is proposed to suppress harmonics caused by non linear loads. The DC-link of the HAPF is controlled by using a PI-controller.

The coefficients of a PI controller employed to control a HAPF obtained by a conventional approach may not give satisfactory results for a wide variety of operating conditions. In this paper, a PSO algorithm is proposed to improve the PI controller tuning in order to overcome the drawbacks in existing conventional methods.

[†] Author to whom all correspondence should be addressed:
E-mail: nada.alloui @gmail.com

The optimization of a PI regulator's parameters is crucial in this paper, the problem of designing a PI controller is formulated as an optimization problem, which assumes two performance indexes, the integral of the time-weighted absolute error of the step response and the maximum overshoot as the objective functions to establish the PI control parameters needed for good performance in a given system. We propose an optimization method for HAPF in order to improve the compensation performances and reduce harmonic distortion through electrical-lines distribution under ideal voltages conditions.

2. PRINCIPLE OF A HYBRID POWER FILTER

Figure 1 shows the system under study. It consists of three-phase supply voltages, a hybrid active power filter and a non linear load. The HAPF combines an active shunt power filter and a shunt passive filter. The APF's rule consists of identifying all the harmonic components present and separating the fundamental component from the other harmonic components which are converted into the resulting reference currents. A control strategy injects these reference currents in real-time into the utility source with opposite phase by means of a power circuit, i.e., an inverter and an output filter.[6].The shunt passive filter is connected in parallel with the non linear load. It includes LC branches tuned for the 5th and 7th harmonics.

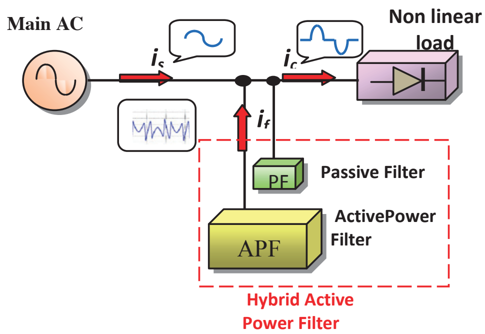

Fig. 1. Basic configuration of a hybrid active power filter.

The values of the L_n and C_n parameters of a branch tuned for an "n" order harmonic must satisfy the following equation: [5]

$$\omega_n = 2\pi f_n = \frac{1}{\sqrt{L_n C_n}} \qquad (1)$$

where f_n corresponds to the fundamental frequency, which was taken to be 50 Hz in this paper.

3. PROPOSED CONTROL ARCHITECTURE

Figure 2 shows the proposed control scheme of the HAPF. The components of this control are as follow:

3.1 SRF method for reference current extraction

The control strategy to compensate for the harmonic currents used in this paper is based on the synchronous reference frame detection method. The principle of this technique is described below:

The three phase currents i_{ca}, i_{cb} and i_{cc} are transformed from three phase (abc) reference frame to two phase's ($\alpha\beta$) stationary reference frame currents i_α and i_β using:

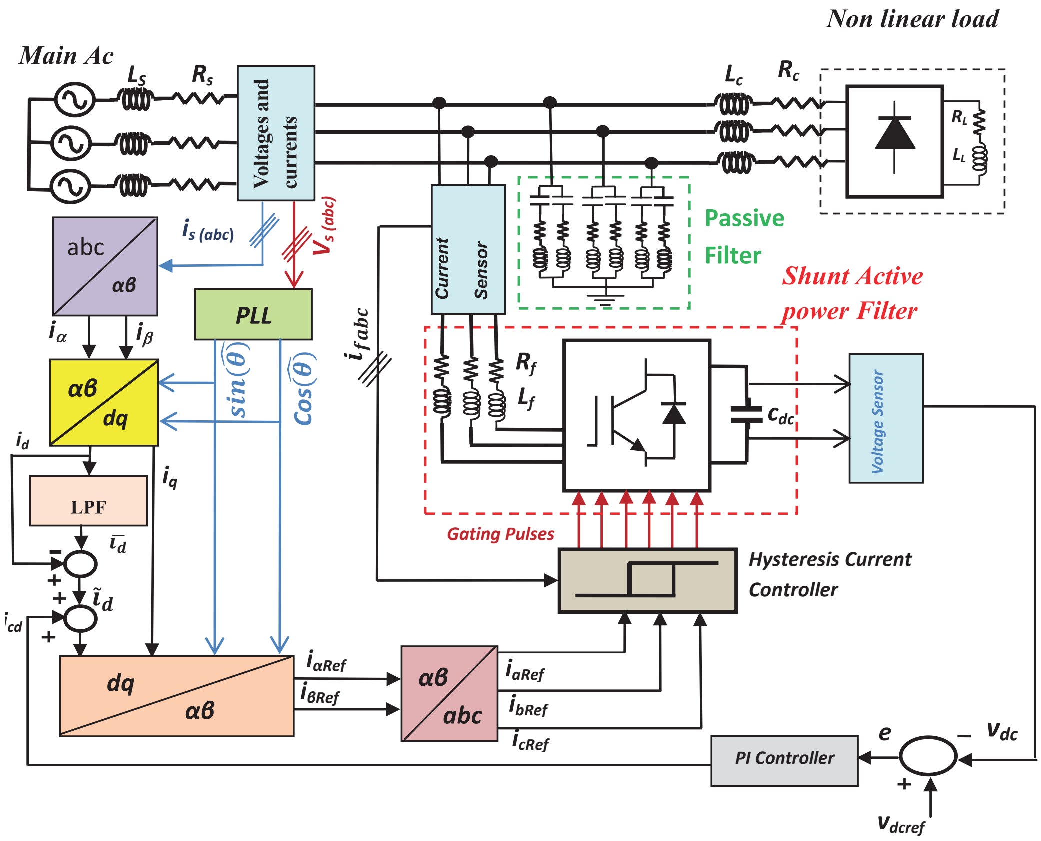

Fig. 2. The system with control scheme of HAPF.

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} \quad (2)$$

Using a PLL (phase locked loop), we can generate $\cos\hat{\theta}$ and $\sin\hat{\theta}$ from the phase voltage source v_{sa}, v_{sb}, v_{sc}.

The currents expression i_α and i_β in (d-q) reference frame are given by:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\hat{\theta} & -\sin\hat{\theta} \\ \sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

The DC quantities and all other harmonics are transformed to non DC quantities using a low pass filter:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \bar{I}_d + \tilde{I}_d \\ \bar{I}_q + \tilde{I}_q \end{bmatrix} \quad (4)$$

The expression of the reference current $i_{ref\alpha}$ and $i_{ref\beta}$ is given by:

$$\begin{bmatrix} i_{ref\alpha} \\ i_{ref\beta} \end{bmatrix} = \begin{bmatrix} \sin\hat{\theta} & \cos\hat{\theta} \\ -\cos\hat{\theta} & \sin\hat{\theta} \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_d + \tilde{I}_d \\ i_q \end{bmatrix} \quad (5)$$

The reference currents in the (abc) frame are given by:

$$\begin{bmatrix} i_{refa} \\ i_{refb} \\ i_{refc} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_{ref\alpha} \\ i_{ref\beta} \end{bmatrix} \quad (6)$$

Finally, the reference currents (i_{refa}, i_{refb}, i_{refc}) are compared with the filter currents (i_{fa}, i_{fb}, i_{fc}), to generates the corresponding gating pulses.

3.2 Control of DC-link voltage

In this paper, to compensate for the inverter losses and to keep the DC-link voltage V_{dc} constant, a proportional and integral controller PI is used. The control loop compares the measured voltage V_{dc} with the reference voltage $V_{dc\text{-}Ref}$ and generates a corresponding current i_{cd}. The equivalent schematic diagram of the system that is used to keep the DC link voltage constant is shown in Fig. 3.

In this paper, the objective of an optimal design of a PI controller DC-link for a given plant is to find the best parameters K_P and K_i of a PI control system such that the performance indexes on the transient response are minimum.

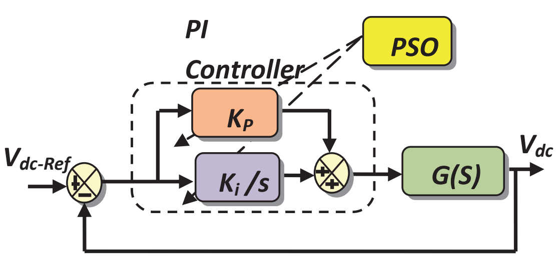

Fig. 3. Equivalent schematic diagram system.

3.3 Hysteresis non-linear current controller

Various current-control methods are proposed for the hybrid active power filter.

Among the current-control methods hysteresis band current control has the highest rating because of its quick current controllability and easy implementation [7].

In this method, the reference and actual three phase source currents are compared with each other to obtain the gating pulses to the devices of the HAPF (Fig. 4). The current controller decides the switching pattern of the HAPF devices. The switching logic is determined as follows:

If $i_f < (i_{Ref} - HB)$ upper switch is OFF and lower switch is ON

If $i_f > (i_{Ref} + HB)$ upper switch is ON and lower switch is OFF .

where i_f is the filter current, i_{Ref} is the reference current and HB is the hysteresis band width.

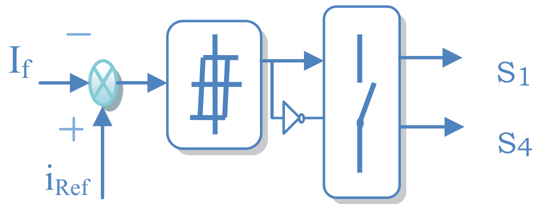

Fig. 4. Hysteresis control principle.

4. PARTICLE SWARM OPTIMISATION

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Eberhart and Kennedy in 1995, inspired by the social behavior of bird flocking or fish schooling. PSO learns from the scenario and uses it to solve the optimization problems. In the optimization problem the goal is to find the maximum or the minimum of a function operating with certain constraints [8,9].

In PSO each single solution is a "bird" in the search space. We call it a "particle". Each particle represents a given random velocity and is flown through the problem space.

The particles have memory and each particle keeps track of its previous best position(called the P_{best}) and its corresponding fitness [10,11].

There exist several P_{best} for the respective particles in the swarm and the particle with the greatest fitness is called the global best (G_{best}) of the swarm. The basic concept of the PSO technique lies in accelerating each particle towards its P_{best} and G_{best} locations, with a random weighted acceleration at each time step.

4.1 Particle swarm optimization algorithm

The steps of the PSO algorithm can be represented as follows [12]:

- ***Step. 1*** Initialize an array of particles with random positions and their associated velocities to satisfy the inequality constraints.
- ***Step. 2*** Check for the satisfaction of the quality constraints and modify the solution if required.
- ***Step. 3*** Evaluate the fitness function of each particle.
- ***Step. 4*** Compare the current value of the fitness function with the particles previous best value (P_{best}). If the current fitness value is less, then assign the current coordinates (positions) to P_{bestx} .
- ***Step. 5*** Find the current global minimum fitness value among the current positions.
- ***Step. 6*** Compare the current global minimum with the previous global minimum (G_{best}). If the current global minimum is better than G_{best}, then assign the current global minimum to G_{best} and assign the current coordinates (positions) to G_{bestx}.
- ***Step. 7*** Change the velocities according to Eq.7.

$$v_i^{k+1} = wv_i^k + c_1 rand_1\left(pbest_i - s_i^k\right) + c_2 rand_2(Gbest - s_i^k) \quad (7)$$

where $c_{1,2}$: acceleration factors.
Gbest : Gbest of the group.
$Pbest_i$: *Pbest of agent i.*
Rand : *random number between 0 and 1.*
s_i^k : *current position of agent i at iteration k.*
v_i^k : *velocity of agent I at iteration k.*
W : *weighting function.*

- ***Step. 8*** Move each particle to the new position according to Eq. 8 and return to **Step. 2**

$$S_i^{k+1} = S_i^k + v_i^{k+1} \quad (8)$$

where S_i^{k+1} : new current position of agent i at iteration k+1.
v_i^{k+1} : new velocity of agent i at iteration k+1.

- ***Step. 9*** Repeat Steps 2~8 until a stopping criterion is satisfied or the maximum number of iterations is reached.

4.2 Flowchart of particle swarm optimization

The steps of the particle swarm optimization algorithm can be represented by the flowchart shown in Fig. 5.

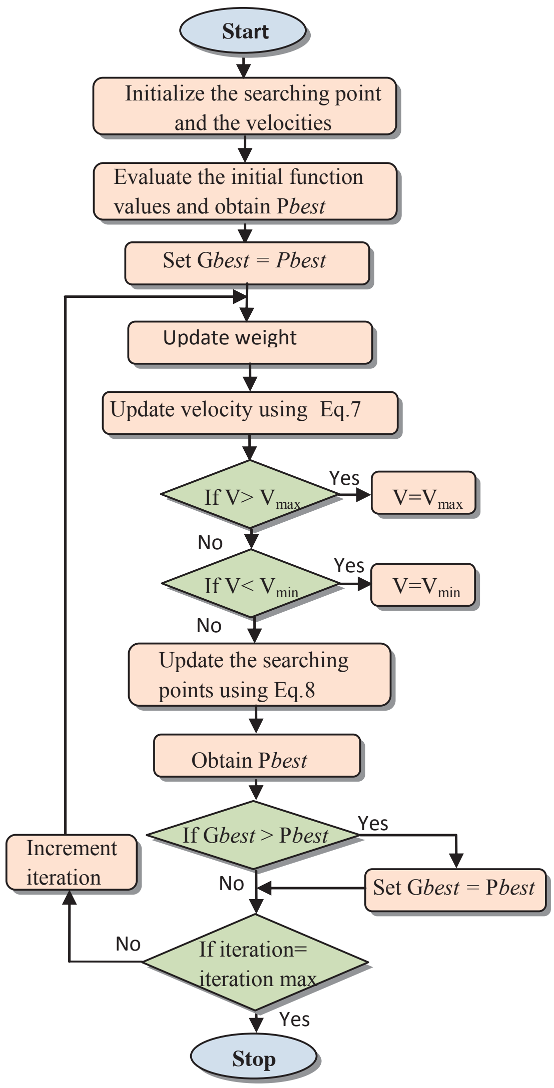

Fig. 5. Flowchart of PSO.

5. ESTABLISHMENT OF OBJECTIVE FUNCTION

In this paper, the optimized parameters are proportional gain K_P and integral gain K_i, and the transfer function of the PI controller is defined by:

$$G_s(s) = K_P + \frac{K_i}{s} \quad (9)$$

The gains K_P and K_i of the PI controller are generated by the PSO algorithm for a given plant as shown in Fig. 6. The output $u(t)$ of the PI controller is (Eq 10):

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \quad (10)$$

For a given plant, the problem of designing a PI controller is to adjust the parameters K_p and K_i to get a desired performance of the system. In this paper, the performance of two key indexes of the transient response are used to characterize the performance of the PI control system. These key indexes are the integral absolute control error and the maximum overshoot which are adopted to create an objective function that is defined as:

$$F = f_{os} + f_{ias} \quad (11)$$

The maximum overshoot is defined as:

$$f_{os} = y_{max} - y_{as} \quad (12)$$

y_{max}: Characterize the maximum value of y and y_{as} denote the steady-state value of y .

The integral of the time-weighted absolute error is written as:

$$f_{ias} = \int_0^{\infty} t\,|e(t)| \quad (13)$$

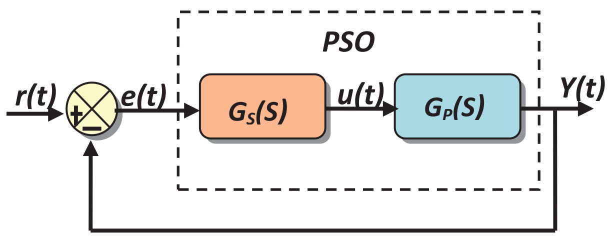

Fig. 6. PI control system.

6. SIMULATION RESULTS AND DISCUSSIONS

The idea of simulation is to show the effectiveness of the HAPF in diminishing the harmonic pollution produced by a nonlinear load, using the PSO algorithm. To design a PI controller for DC-link regulation, the initial values of the parameters of the proposed algorithm are presented in Table 1. The HAPF model parameters are shown in Table 2.

6.1 The case of a classical PI-controller

In the conventional PI controller the parameters K_P and K_i have

Table 1. Parameters of the PSO algorithm.

Population size	20
Number of iterations	30
W_{max}	0.9
W_{min}	0.4
C1= C2	2

Table 2. HAPF parameters.

Supply phase voltage	220 V
Supply frequency	50 HZ
Supply resistor	R_S = 0.3 Ω
Supply inductor	L_S = 1.5 mH
Non linear load	A Graetz bridge with RL branches and six functions with an angle α=0^0 R_L = 7.2 Ω L_L = 1mH
Line characteristics	R_C = 0.41 Ω L_C = 0.3 mH
Output Filter	R_F = 1 mΩ L_F = 1.3 mH
Capacitor (Regulation)	C_{dc} = 2,000 μF V_{dc} =470 V
Passive Filter characteristic: The fifth filter The seventh filter	C_5 = 406 μF L_5 = 1 mH R_5 = 0.01 Ω C_7 = 1,708 μF L_7 = 0.12 mH R_7 =0.01 Ω

been chosen by the classical method. In this case the conventional PI controller is used to see the DC- link regulation and its effect in damping harmonic currents and reducing total harmonic distortion. Simulation results show the line currents and their spectrum before compensation (Fig. 7 and 8), the line current and its spectrum after compensation (Fig. 9 and 10), and the injected current and DC-link voltage waveforms (Fig. 11 and 12) using a HAPF based on a conventional PI controller, the total harmonic distortion (THD) has been reduced from 19.90% to 2.60%.

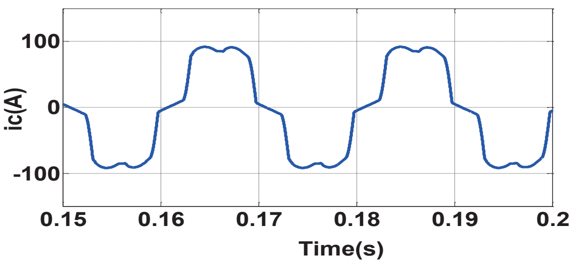

Fig. 7. Load current waveform of single phase a.

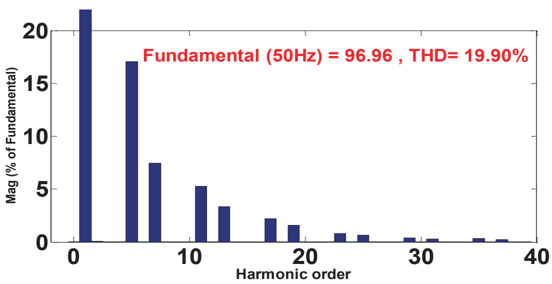

Fig. 8. Harmonic spectrum of supply current.

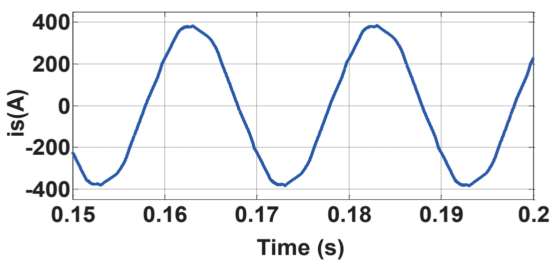

Fig. 9. Supply current waveform of single phase with PI Controller.

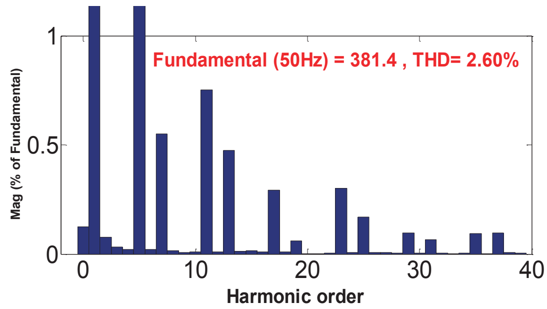

Fig. 10. Harmonic spectrum of supply current using HAPF with PI controller.

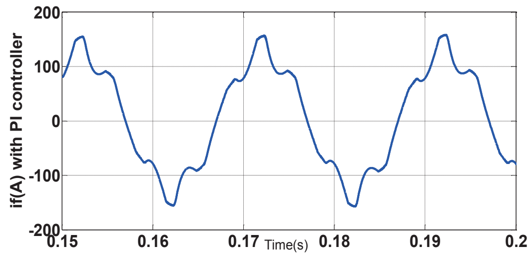

Fig. 11. Injected current waveform with PI controller.

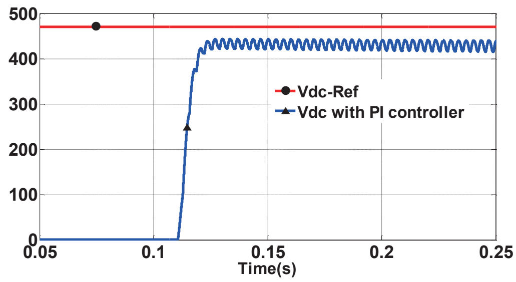

Fig. 12. DC link voltage waveform with PI controller.

6.2 The case of an optimized PI-controller

The proposed idea is to improve the power quality using an optimal hybrid active power filter based on the PSO algorithm. The main objective for the system control to minimization of fitness functions as defined in Eq (11) based on the integral of the time-weighted absolute error and the maximum overshoot.

To better evaluate the fitness function, the term of the integral of the time-weighted absolute error was multiplied by coefficient α. The novel objective function is then defined by:

$$F = f_{os} + \alpha * f_{ias} \quad (14)$$

where α = 10.

The evolution of the fitness function employing the PSO algorithm is presented in Fig. 13.

Simulation studies were carried out to predict the performance of the proposed method. The supply current waveform and its spectrum are shown in Fig. 14 and 15.

The injected currents waveform and DC-link voltage waveform are shown in Fig. 16 and 17 after adopting the optimal system.

Figs. 18~20 compares the performances of the HAPF before and after optimization and the values of the system indexes are compared in Table 3.

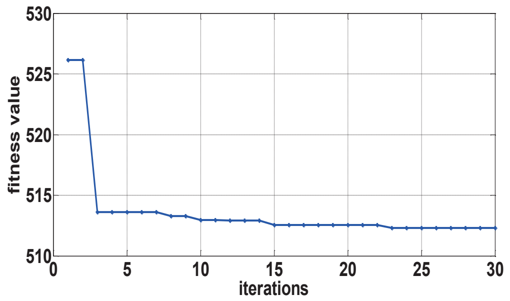

Fig. 13. The evolution of the objective function.

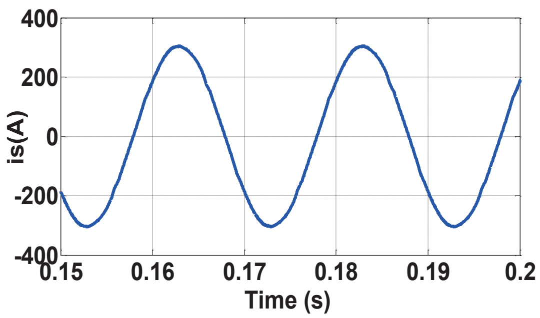

Fig. 14. Supply current waveform of single phase with optimized PI controller.

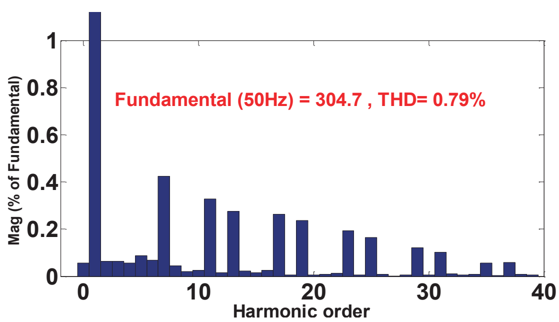

Fig. 15. Harmonic spectrum of suply current with optimized PI controller.

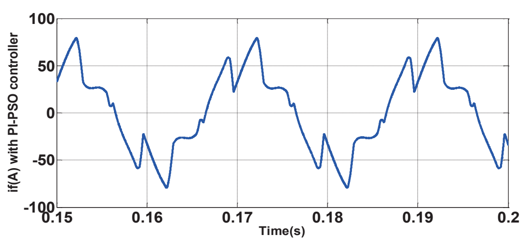

Fig. 16. Injected current waveform with optimized PI controller.

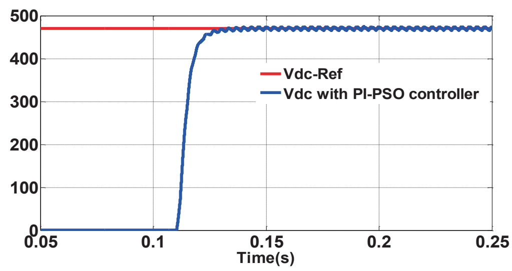

Fig. 17. DC link voltage waveform with optimized PI controller.

Table 3. Comparison of HAPF indexes between used and unused PSO algorithm.

Parameters and indexes	PI not optimized	PI optimized
Proportional gain	0.2	0.01
Integral gain	3	1.3
Overshoot %	97.22	99.60
Integral of time-weighted absolute error	4.6	3.2
Objective function	545.56	512.4

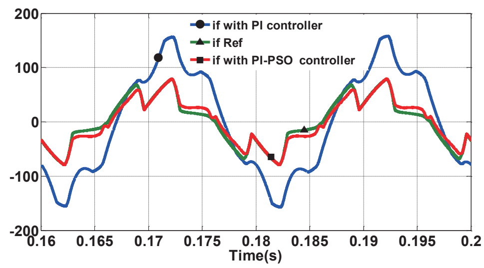

Fig. 18. The HAPF compensation current compared to its reference current.

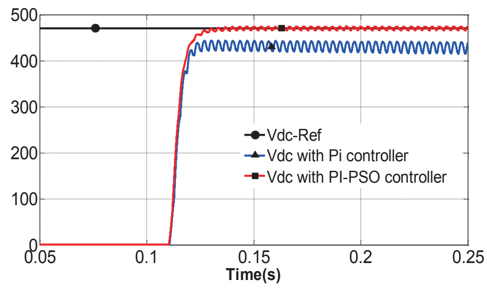

Fig. 19. The HAPF DC-link voltage regulation compared to its reference voltage.

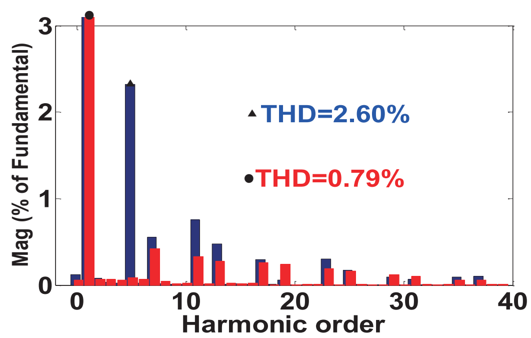

Fig. 20. Harmonic spectrum of supply current of HAPF before and after optimization.

Given the figures and calculation the THD of the source current with HAPF is reduced from 2.6% obtained by means of the PI controller to 0.79% as obtained by the proposed control algorithm.

7. CONCLUSIONS

To improve the power quality and to reduce the current source harmonics, an hybrid active power filter configuration using PSO for DC-link regulation under ideal voltage conditions has been proposed in this paper. The simulation was performed using matlab/simulink.

Generally, the results presented indicate that the PSO can find the optimal fitness function and has proved its effeteness in finding optimal parameters K_p and K_i for the DC-link voltage-HAPF controller. It can be seen that after HAPF with PSO-PI controller runs, the current total harmonic distortion decreases from 2.60 to 0.79.

According to the previous results the proposed controller (PI-PSO) has better dynamic performance and robustness.

The control method applied to HAPF has demonstrated good performance for harmonic elimination.

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