CONTROL IMROVEMENT OF SHUNT ACTIVE POWER FILTER USING AN OPTIMIZED-PI CONTROLLER BASED ON ANT COLONY ALGORITHM AND SWARM OPTIMIZATION

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Abstract:

In the last years, there has been a increase currents harmonics on electrical network injected by nonlinear loads, such as rectifier equipment used in telecommunication system, power suppliers, domestic appliances, ect.

This paper makes a comparison of the effectiveness of the two methods on particular optimization problem, namely.

The tuning of the parameters for PI DC link voltage to a shunt active power filter. The simulation results demonstrates that the optimized PI controller by ant colony (ACO) presents a advantage of little response time and best control performances compared to the optimized PI with Particle swarm (PSO). This comparison is shown on reducing harmonic current supply (THD).

Keywords: *ant colony optimization, particle swarm optimization, shunt active power filter, harmonic compensation, PI controller.*

1. Introduction

The advancements of electronic devices technology and its use in the industry has produced harmonic in line distribution network [1]. In order to eliminate theses troubles, researchers has proposed new technique to eliminate theses harmonics. One of the theories is the instantaneous power theory (p-q theory). This theory was introduced by Akagi, Kanazawa and Nabae in 1983 [2] in Japanese.

By tradition, passives filters have been used to eliminate the current harmonic distortion and compensate the reactive power, but can resonate with supply impedance.

The correct implantation of PI controller DC link voltage of (SAPF) depends two parameters proportinnal gain (K_p) and integral gain (K_i) which are tuned by trial and error. In the other hand has a problem in the time needed to accomplish this task.

To trounce this problem many methods have been developed, such as Ziegler-Nichols [3].

An improvement in tuning can be achieved using optimization techniques, and in particular those based on artificial intelligence.

In this paper, we formulate the problem of design DC link voltage PI controller as an optimization problem. The problem formulation adopts three performances indexes, the maximum overshoot, the rise time and the integral absolute error of step response as the objective function to determine the PI control parameters for getting a well performance under a given system, the primary design goal is to obtain good load disturbance response by minimizing the integral absolute control error. At the same time, the transient response is assured by minimizing the others three performance indexes.

Two approach methods has been used to show its impact on SAPF the ant colony algorithm and particle swarm algorithm.

2. Ant colony optimization

The main idea of ACO is to model the problem as the search for a minimum cost path in a graph that base the evolutionary meta-heuristic algorithm. The behavior of artificial ants is inspired from real ants. They lay pheromone trails and choose their path using transition probability. Ants prefer to move to nodes which are connected by short edges with a high among of pheromone. The algorithm has solved traveling salesman problem (TSP), quadratic assignment problem (QAP) and job-shop scheduling problem (JSSP) and so on [4]-[5].

The problem must be mapped into a weighted graph, so the ants can cover the problem to find a solution. The ants are driven by a probability rule to choose their solution to the problem (called a tour). The probability rule (called Pseudo-Random-Proportional Action Choice Rule) between two nodes i and j.

$$P_{ij} = \frac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{h \in s}[\tau_{ij}]^{\alpha}[\eta_{ih}]^{\beta}} \tag{1}$$

The heuristic factor η_{ij} or visibility is related to the specific problem as the inverse of the cost function. This factor does not change during algorithm execution; instead the metaheuristic factor τ_{ij} (related to pheromone which has an initial value τ_0) is updated after each iteration. The parameters α and β enable the user to direct the algorithm search in favor of the heuristic or the pheromone factor. These two factors are dedicated to every edge between two nodes and weight the solution graph.

The pheromones are updated after a tour is built, in two ways: firstly, the pheromones are subject to an evaporation factor (ρ), which allows the ants to forget their past and avoid being trapped in a local minimum (equation 2). Secondly, they are updated in relation to the quality of their tour (equations 3 and 4), where the quality is linked to the cost function.

$$\tau_{ij} \to (1-\rho)\tau_{ij} \qquad \forall (i,j) \in L \tag{2}$$

$$\tau_{ij} \to \tau_{ij} + \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \qquad \forall (i,j) \in L \tag{3}$$

$$\Delta\tau_{ij} = \begin{cases} \frac{1}{c^k}\ if & arc(i,j) \quad belong\ to\ T^k \\ 0 & otherwise \end{cases} \tag{4}$$

Where m is the number of ants, L represents the edges of the solution graph, and C_k is the cost function of tour T_k, built by the k_{th} ant.

3. Particle swarm optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling [6]. PSO learns from the scenario and uses it to solve the optimization problems. In PSO, each single solution is a "bird" in the search space.

We call it "particle". All particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which direct the flying of the particles. The particles fly through the problem space by following the current optimum particles.

PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In each iteration, every particle is updated by following two "best" values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called $Pbest$. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called $gbest$.

For example, the $i.th$ particle is represented as $xi = (xi1, xi2, ..., xid)$ in the d-dimensional space. The best previous position of the $i.th$ particle is recorded and represented as:

$$Pbest_i = (Pbest_{i1}, Pbest_{i2}, ..., Pbest_{id}) \tag{5}$$

The index of best particle among all of the particles in the group is $gbest_d$. The velocity for particle i is represented as $vi = (vi1, vi2, ..., vid)$.

The modified velocity and position of each particle can be calculated using the current velocity and the distance from $Pbest_{id}$ to $gbest_d$ as shown in the following formulas [8].

$$v_{i,m}^{(t+1)} = wv_{i,m}^{(t)} + c_1 rand()(Pbest_{i,m} - x_{i,m}^{t}) + c_2 rand()(gbest_m - x_{i,m}^{(t)})$$

$$x_{i,m}^{(t+1)} = x_{i,m}^{(t)} + v_{i,m}^{(t+1)} \tag{6)-(7}$$

$i = 1,2,...,n;$
$m = 1,2,...,d;$

Where:

n - Number of particles in the group,
d - Dimension,
t - Pointer of iterations (generations),
$v_{i,m}^{(t)}$ - Velocity of particle i at iteration t,
w - Inertia weight factor,
c_1, c_2 - Acceleration constant,
$rand()$ - Random number between 0 and 1,
$v_{i,d}^{(t)}$ - Current position of particle i at iterations,
$Pbest_i$ - Best previous position of the $i.th$ particle,
$Gbest$ - Best particle among all the particles in the population.

4. Organization of objective function

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

$$G_c(s) = K_p + \frac{K_i}{s} \tag{8}$$

The gains K_p and K_i of PI controller are generated by the ACO and PSO algorithm for a given plant. As shown in Fig. 1. The output u(t) of PI controller is given by (equation 9):

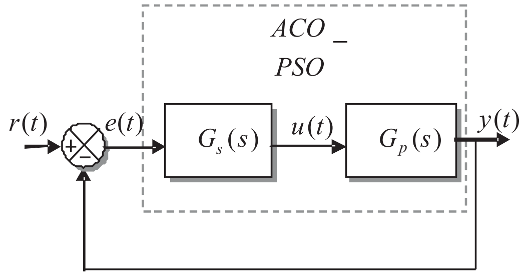

Fig.1. PI control system.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{9}$$

For a given plant, the problem of designing a PI controller is to adjust the parameters K_p and K_i for getting a desired performance of the considered system. Both the amplitude and time duration of the transient response must be kept within tolerable or prescribed limits, for this condition, three key indexes performance of the transient response are utilized to characterize the performance of PI control system. These key indexes maximum overshoot, rise time and integral absolute control error are adopted to create objective function which is defined as:

$$F = f_{os} + f_{rt} + f_{ias} \tag{10}$$

The maximum overshoot is defined as:

$$f_{os} = y_{\max} - y_{ss} \tag{11}$$

y_{max} characterize the maximum value of y and y_{ss} denote the steady-state value of y.

For y_{rt} represent the function of the rise time is defined as the time required for the step response.

In the other hand, the integral of the absolute magnitude of control error is written as:

$$f_{ias} = \int_0^\infty |e(t)|dt \tag{12}$$

5. Configuration of shunt active power filter

The most important objective of the APF is to compensate the harmonic currents due to the non linear load. Exactly to sense the load currents and extracts the harmonic component of the load current to produce a reference current Ir as shown in Fig. 2, The reference current consists of the harmonic components of the load current which the active filter must supply [7].

This reference current is fed through a controller and then the switching signal is generated to switch the power switching devices of the active filter such that the active filter will indeed produce the harmonics required by the load. Finally, the AC supply will only need to provide the fundamental component for the load, resulting in a low harmonic sinusoidal supply.

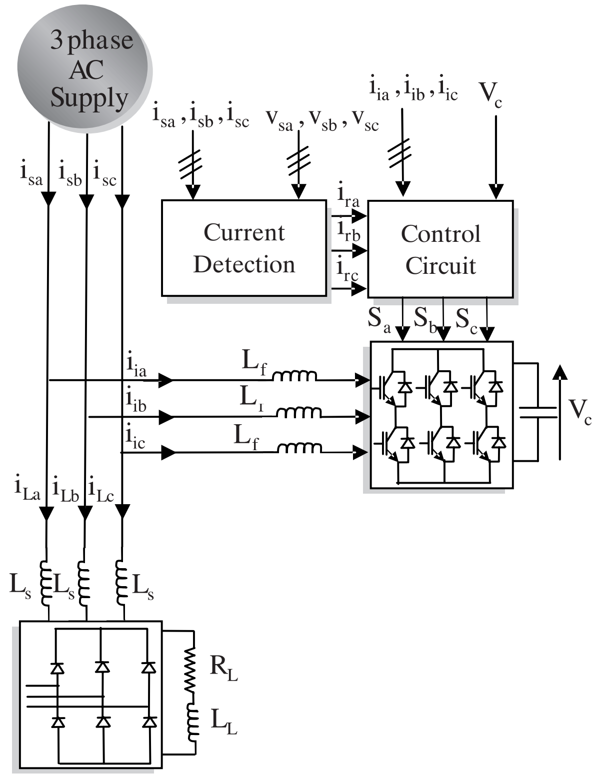

Fig. 2. Equivalent schematic of shunt APF.

6. Instantaneous active and reactive p-q power theory

The identification theory that we have used on shunt APF is known as instantaneous power theory, or PQ theory.

It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms.

Inputs:
Vector of tension: $v_a(t)$, $v_b(t)$ and $v_c(t)$
Vector of current: $i_a(t)$, $i_b(t)$ and $i_c(t)$

The PQ theory consists of an algebraic transformation (Clarke transformation) of the three phase voltages and current in the abc coordinates to the $\alpha\beta$ coordinates [8].

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{14}$$

The instantaneous power is calculated as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{15}$$

The harmonic component of the total power can be extracted as:

$$p_L = \overline{p}_L + \widetilde{p}_L \tag{16}$$

Where,
$\overline{p}_L$: The DC component

$\widetilde{p}_L$: Harmonic component

Similarly,

$$q_L = \overline{q}_L + \widetilde{q}_L \tag{17}$$

Finally, we can calculate reference current as:

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{18}$$

Here,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \widetilde{p} \\ \widetilde{q} \end{bmatrix} \tag{19}$$

7. ACO and PSO applied to optimize PI parameters of dc-link capacitor

In this paper, we present the SAPF as controlled plant, the SAPF diagram is shown in Fig. 3.

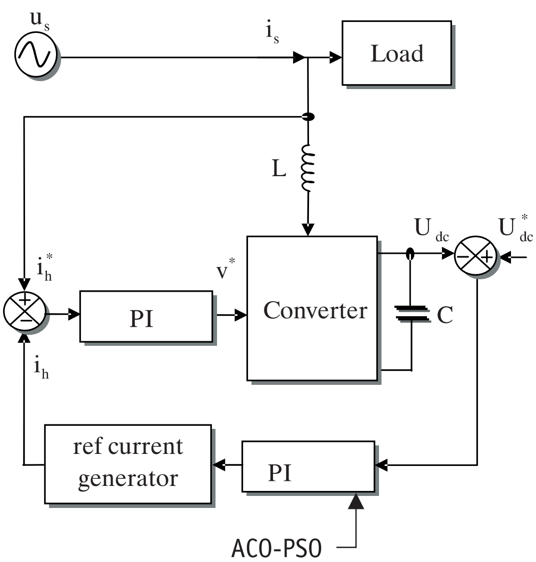

Fig. 3. Control diagram of APF system.

The estimation of the reference currents from the measured DC bus voltage is the basic idea behind the PI controller based operation of the SAF. The capacitor voltage is compared with its reference value v^*_{da} in order to maintain the energy stored in the capacitor constant.

The DC link voltage discretely at the positive zero-crossing point of respective phase source voltage, computes the variation of power according to difference of DC link voltage between two sampling points. The regulation of the error between the capacitor voltage and its reference is assured by The PI controller which its output is multiplied by the mains voltage waveform V_{s1}, V_{s2}, V_{s3} in order to obtain the supply reference currents.

The equivalent schematic diagram of system which is used to maintain the DC link voltage constantly is shown in Fig. 4.

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

For ACO approach, each parameter of K_p and K_i is hinted by 100 nodes respectively and there is resolution 0.0001 among each node, one node represents a solution value of parameters K_p and K_i. Thus, the more accuracy trails are updated after having constructed a complete path and the solution found.

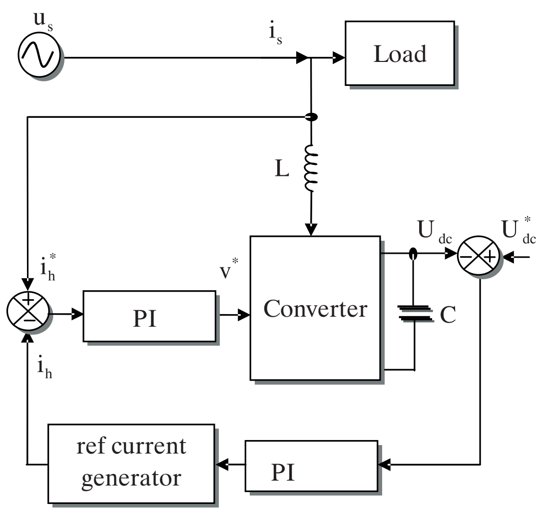

Fig. 4. Equivalent schematic diagram system.

For PSO approach, the evolution procedure of PSO Algorithms is presented as follow Fig. 5. Producing initial populations is the first step of PSO. The population is composed of the chromosomes that are real codes. The corresponding evaluation of a population is the "fitness function" which is the performance index of a population.

The fitness value is bigger, and the performance is better. After the fitness function has been calculated, the fitness value and the number of the generation determine whether or not the evolution procedure is stopped (Maximum iteration number reached?). After this, calculate the $Pbest$ of each particle and $Gbest_{id}$ of population (the best movement of all particles). The update the velocity, position, $gbest$ and $Pbest$ of particles give a new best position.

8. Design of optimizing algorithm

In this work, we have used the following parameters values for the ant colony optimization which is step in the Table 1.

Table 1. Initial values parameters of ACO.

Ant Number	20
Maximum Cycle Time	100
Initial Value of Nodes Trail Intensity	0.1
Coefficient ρ	0.6
Relative Important Parameter of Trail Intensity α	3
Relative Important Parameter of Visibility β	2

And for the particle swarm the parameters values are presented Table 2.

Table 2. Parameters of PSO algorithm.

Population Size	60
Number of Iterations	150
$w$max	0.7
$w$min	0.1
$c_1 = c_2$	1.5
Min-offset	200

9. Simulation result

The proposed PI controller of DC link capacitor designed by ACO and PSO on filtering system that was set in Matlab Simulink environment to predict performance of the proposed method. The SAPF model parameters are shown in the following Table 3.

Table 3. SAPF parameters.

Supply phase voltage U	220 V
Supply frequency fs	50 Hz
Filter inductor Lf	1mH
Dc link capacitor Cf	4.4 mF
Smoothing inductor	0.1 mH
Sample time Ts	4 µs

A number of simulation results were developed with different cases. The SAPF is connected in parallel with nonlinear load, the first case is the PI-classical using on the system to allow us to see the regulation of DC link voltage and its effect for damping harmonics current and reducing total harmonic distortion (THD). For the second case the proposed optimized PI-controller with ACO and PSO has been introduced in order to improve a SAPF performance and meet the requirements of harmonic elimination and reactive compensation.

10. A Case of classical PI-controller

In the conventional PI controller the parameters K_p and K_i has been determined by classical method which is Ziegler-Nichols method for tuning PI controller. This procedure is now accepted as standard in control system and is based on plant step responses.

The method used in this work known as the continuous cycling which integration and derivative terms of the controller are disabled and the proportional gain is increased until a continuous oscillation. Considering Ku and its related oscillating period Tu, the PI parameters can be calculated from the following equation:

$$k_p = 0.45 * k_u$$

$$k_i = 0.5 * T_u \qquad (20)$$

The PI control scheme involves regulation of the dc link voltage to set the amplitude of reference current for harmonic and reactive power compensation [9], [10]. In this study, we have simulated only the network supply connected on the nonlinear load, the total harmonic distortion found is 20.90 % which indicate the harmonic presence in the current source caused by nonlinear load. In the first case, the SAPF has been introduced in order to compensate these harmonics and has reduced the THD from 20.90% to 0.99%. The results founded are shown in the following figures.

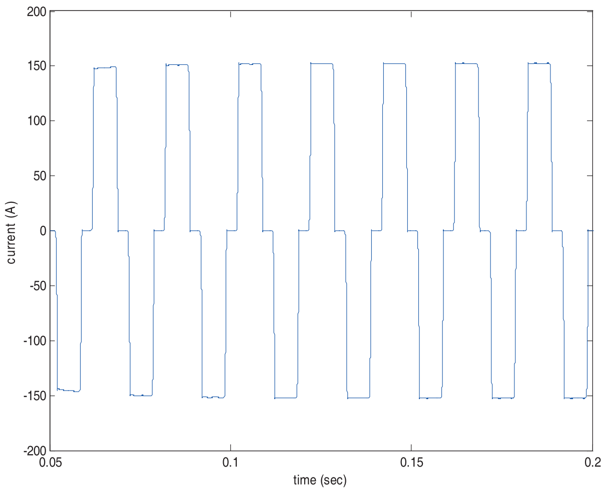

Fig. 6. Load current waveform.

Table 4. Harmonic supply current phase-a-component with traditional PI controller method.

Harmonic supply current components	
N	Isa(n)/Isa(1) [%]
5	0.18
7	0.34
11	0.24
13	0.21
17	0.21
19	0.17
23	0.18
25	0.13
29	0.16
31	0.11
35	0.12
37	0.11
41	0.12
43	0.10
47	0.11
49	0.10
THD	0.99

Table. 5. THD results.

	Without filtering	FSAPF filtering with classical PI DC link voltage	Robustness
THD_i (%)	20.90	0.99	3.90

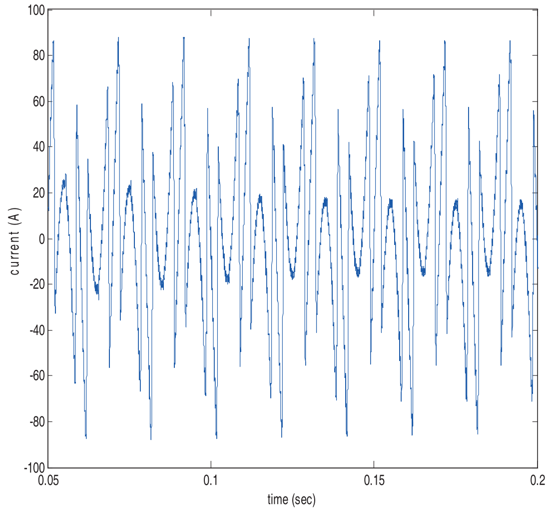

Fig. 7. Injected current waveform.

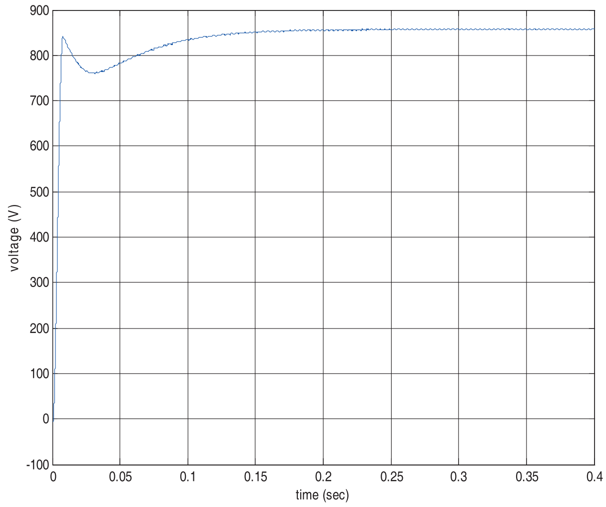

Fig. 8. DC link voltage waveform.

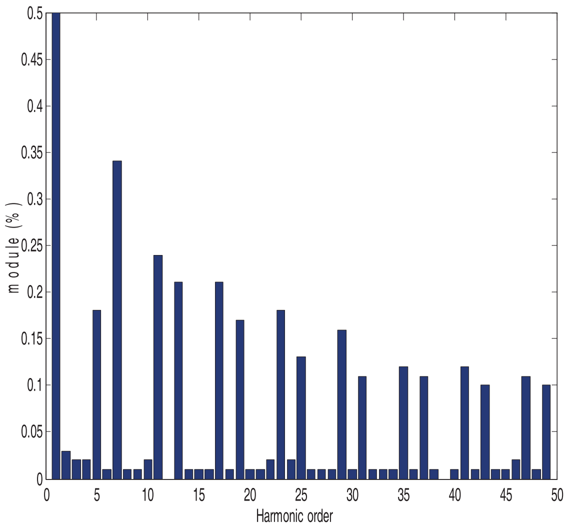

Fig. 9. Harmonic spectrum of supply current.

11. B Case of optimized PI-controller

In the second case, the shunt active power filter was examined using optimized PI - controller DC link voltage, the optimal parameters has been determined by using ant colony optimization (ACO) and particle swarm optimization (PSO). The main objective is to minimize the fitness function that is defined by the equation (10).

In this paper, we have based on the minimizing integral absolute error, so it has been multiplied by coefficient α. The objective function is returned by the following equation:

$$F = f_{os} + f_{rt} + \alpha * f_{ias} \tag{21}$$

In this case, we have fixed α value: $\alpha = 2.5$ and that to give an importance for the integral error in formulation function. Simulation studies are carried out to predict performance of the proposed method. The Fig. 10 shows the DC link voltage response curves of system used primal PI parameters and optimized PI parameters, and the value of system indexes are compared in Tab. 5. The source voltage, current, load current, harmonic order and Dc link voltage waveforms are shown in the following figures after adopted the optimized system.

In Fig. 10, the stability convergence and robustness. Hence, the high performance can be achieved.

Table. 5 comparisons of SAPF indexes between used and unused ant colony algorithm and particle swarm algorithm.

Parameter and indexes	**PI non optimized**	**PI with ACO**	**PI with PSO**
Proportional gain	120	190	180
Integral gain	1.05	0.0004	0.00028
Overshoot (%)	85.66	88.52	87.99
Rise time (sec)	0.0009	0.000869	0.00087
Integral absolute error	$1.0182e^{+001}$	$6.8543e^{+000}$	$7.0013e^{+000}$

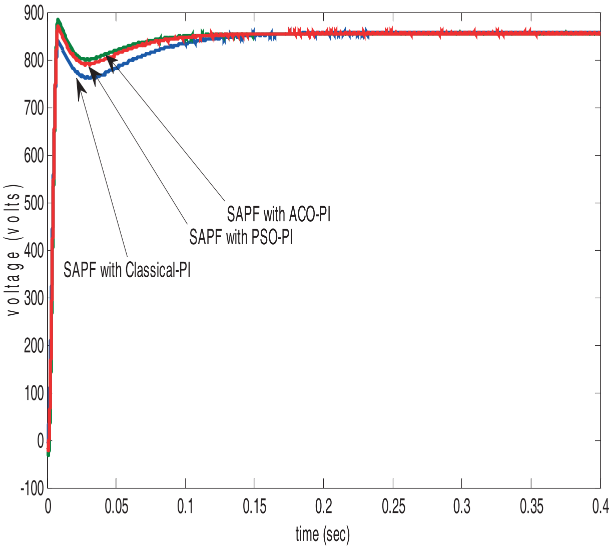

Fig. 10. DC link voltage response curve of SAPF used ant colony optimization and particle swarm optimization.

The results we obtained demonstrate that a low THD value can be reached by using the optimized system studied in this paper.

The current source represented by Fig. 12 takes the sinusoidal form, as well as the spectral analysis Table 6 shows the absence of the more share of the harmonics rows which implies the good performances of the optimized PI-controller compared with classical PI.

Table 6. Harmonic supply current phase-a-component with optimized PI controller methods.

Harmonic supply current components		
N	Isa(n)/Isa(1) [%] using ACO	Isa(n)/Isa(1) [%] using PSO
5	0.13	0.14
7	0.33	0.33
11	0.20	0.21
13	0.20	0.21
17	0.19	0.19
19	0.15	0.15
23	0.17	0.18
25	0.11	0.11
29	0.14	0.15
31	0.09	0.09
35	0.11	0.11
37	0.09	0.09
41	0.10	0.10
43	0.09	0.09
47	0.09	0.10
49	0.09	0.10
THD	0.91	0.93

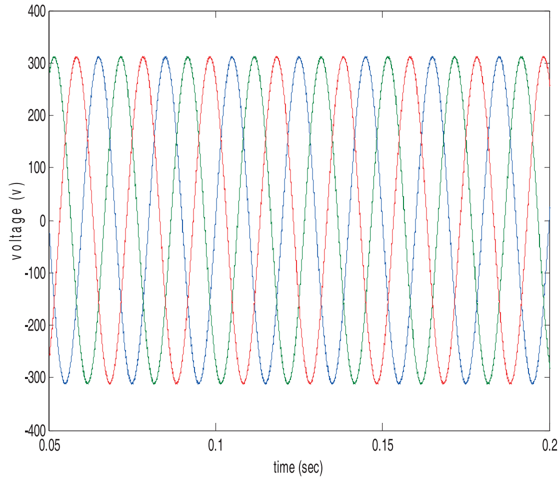

Fig. 11. Source voltage waveform.

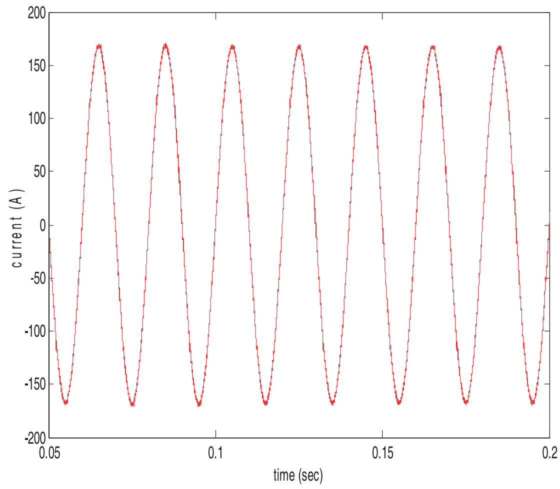

Fig. 12. Supply current waveform of single phase.

Table 7. THD results.

	Without filtering	SAPF using optimized PI with PSO	SAPF using optimized PI with ACO	Robustness
THD_i (%)	20.90	0.93	0.91	4.25/ACO 4.09/PSO

12. C Comparative Study

In this paper we have presented a comparative between two optimization approach ant algorithm and swarm algorithm for design PI controller DC link voltage of SAPF.

The PI-ACO control method has improved the active power filter performance compared with PI-PSO and traditional PI controller, and it can be seen in the Supply current filtering result Fig. 12.

The deformations have been clearly reduced and also the harmonic distortion has been decreased compared with the SAPF filtering using traditional PI controller method, so this comparison can been shown in the following figure.

13. Conclusion

According to the results of the computer simulations, the optimized PI using ACO is better than the traditional PI and also PI with PSO.

The PI with ACO algorithm is the best controller which presents satisfactory performances, less overshoot and minimal rise time compared with classical PI and optimized PI with PSO.

Furthermore, results has demonstrated that the control strategy with ACO for DC link voltage is efficient for compensating the current harmonics, and the proposed system has reduced the THD with 8 % less than primal system and 2% less than system using particle swarm optimization (SAPF without ACO) as shown in Fig. 13. So we can say that the PI-ACO is the best controller which presented satisfactory performance and good robustness.

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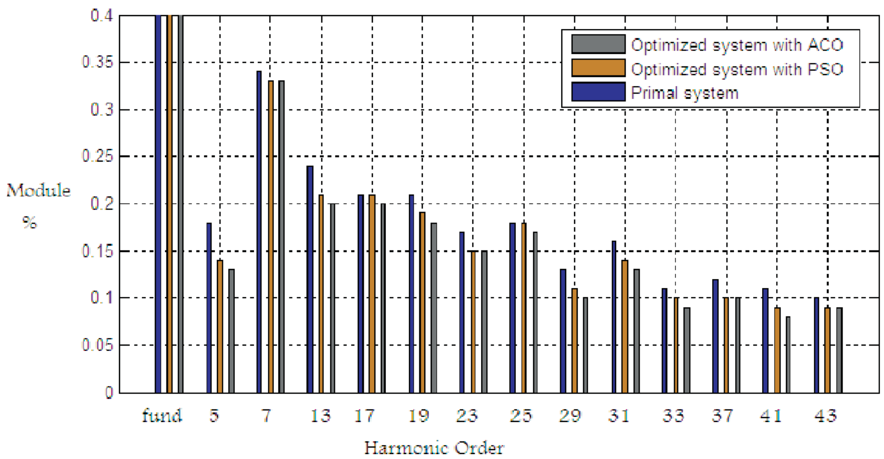

Fig. 13. Comparative harmonic spectrum of supply current for both with classical PI, PI-AO and PI-PSO.