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An efficient algorithm to tuning PI-controller parameters for shunt active power filter using ant colony optimization

Abstract – *This paper presents an optimal control method entitled ant colony PI controller (ACO-PI) for extracting the reference compensating currents to shunt active power filter (SAPF) under balanced voltages conditions, which is applied to eliminate line current harmonics and compensate reactive power. Two different control methods has been proposed for SAPF based on proportional-integral (PI) controller and intelligent PI-controller with ACO are presented. The identification theory based on instantaneous power (p-q) is used to establish the suitable current reference signals. The simulation results show that the new control method using ACO approach is not only easy to be implanted, but also very effective in reducing the unwanted harmonics and compensating reactive power. The studies carried out have been accomplished using the MATLAB Simulink Power System Toolbox.*

Streszczenie. *W artykule zaprezentowano wykorzystanie kontrolera PI bazującego na algorytmie mrówkowym ACO do sterowania aktywnym filtrem mocy. Zaproponowano dwie metody sterowania – z kontrolerem PI I kontrolerem ACO. Symulacje wykazały że nowy kontroler jest nie tylko łatwy do implementacji ale także efektywnie redukuje niepożądane harmoniczne i moc bierną. (**Skuteczny algorytm strojenia parametrów kontrolera PI wykorzystujący algorytm mrówkowy**).*

Keywords: Shunt active power filter, Total harmonic distortion, current control, PI controller, Ant colony optimization
Słowa kluczowe: filtr mocy, zniekształcenie harmoniczne, algorytm mrówkjowy.

Introduction

The raising use of power electronic equipment in industry and customers has caused harmonic propagation through electrical networks, and lower power factor [6]. Dynamic and flexible solutions to the power quality problems have been examined by researchers and power system [1]. Usually, passive filters have been used to eliminate current harmonics and to increase the power factor. However, the use of passive filter has many disadvantages of large size resonance and fixed compensation behavior so this conventional solution becomes ineffective [8]. The shunt active with several topologies [2]-[3] is generally used instead of passive filters to improve the power quality by injecting compensating currents [4],[14] and also, a very great for the compensation not only of current harmonics produced by distorting loads, but also of reactive power of non-linear loads [7]. In order to determine the current reference signals a proposed theory based on instantaneous power (p-q theory) has been used this theory was introduced by Akagi, Kanazawa and Nabae in 1983 [5] in Japanese. The presented work spotlights on novel control method for compensating current which known as PI-ACO optimized PI controller using ant colony algorithm.

The optimization of PI regulator's parameters is crucial [15]. In this work, the problem of design current PI controller is formulated as an optimization problem. The problem formulation assumes in this study two performance indexes are the integral absolute error of step response and maximum overshoot as the objective function to determine the PI control parameters for getting a well performance under a given system. We propose an optimization method for SAPF in the aim to improve the compensation performances and reduce harmonic distortion through electrical lines distribution under all voltages conditions. These objectives are obtained by minimizing the fitness function.

In addition, ant colony optimization (ACO) has developed as effective for combinatorial optimization problems [9] such as the traveling salesman problem, quadratic assignment problem, graph coloring problems with successful result.

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 [10]-[11].

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 ζ_{ij} (related to pheromone which has an initial value ζ_0) is updated after 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.

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

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

$$\Delta\tau_{ij} = \begin{array}{ll} \frac{1}{c^k} if & arc(i,j) beong\ to\, T^k \\ 0 & othrwise \end{array} \tag{4}$$

Where m is the number of ants, L represents the edges of the solution graph, and Ck is the cost function of tour Tk, built by the kth ant.

Arranged fitness function

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

(5)
$$G_c(s) = K_p + \frac{K_i}{s}$$

The gains K_p and K_i of PI controller are generated by the ACO algorithm for a given plant. As shown in fig.1. The output u(t) of PI controller is (equation 6):

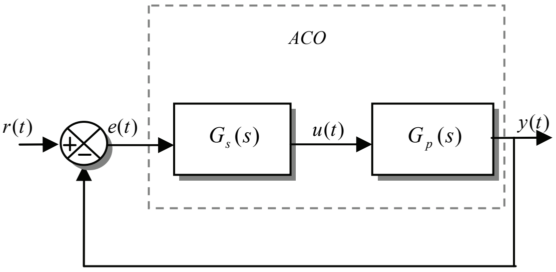

Fig.1 PI control system

(6)
$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt$$

For a given plant, the problem of designing a PI controller is to adjust the parameters Kp and Ki 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, two key indexes performance of the transient response is utilized to characterize the performance of PI control system.

These key indexes are integral absolute control error and maximum overshoot that are adopted to create objective function which is defined as:

(7)
$$F = f_{os} + f_{ias}$$

The maximum overshoot is defined as:

(8)
$$f_{os} = y_{\max} - y_{ss}$$

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

The integral of the absolute magnitude of control error is written as:

(9)
$$f_{ias} = \int_0^{\infty} |e(t)|dt$$

System configuration

The principal function of the shunt active power filter (SAPF) is to generate just enough reactive and harmonic current to compensate the nonlinear loads in the line. A multiplicity of methods is used for instantaneous current harmonics detection in active power filter such as FFT (fast Fourier technique) technique, instantaneous p-q theory, and synchronous d-q reference frame theory. The main circuit of the SAPF control is shown in Fig.2.

The reference current consists of the harmonic components of the load current which the active filter must supply. 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.

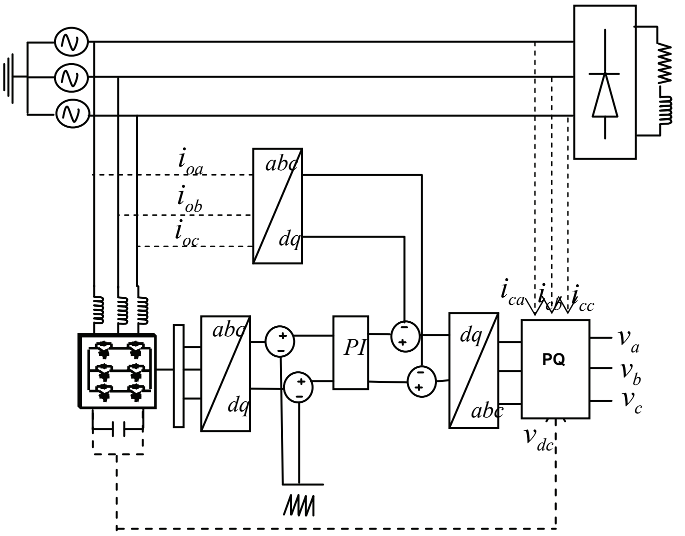

Fig.2 General Structure of the SAPF

Instantaneous active and reactive P-Q power method

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. The PQ theory consists of an algebraic transformation (Clarke transformation) of the three phase voltages and current in the abc coordinates to the αβ coordinates [5].

(10)
$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

(11)
$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix}$$

The instantaneous power is calculated as:

(12)
$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

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

(13)
$$p_L = \overline{p}_L + \widetilde{p}_L$$

where, $\overline{p}_L$: the DC component, $\widetilde{p}_L$: harmonic component.

Similarly,

(14)
$$q_L = \overline{q}_L + \widetilde{q}_L$$

Finally, we can calculate reference current as:

(15)
$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix}$$

Here,

(16)
$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \widetilde{p} \\ \widetilde{q} \end{bmatrix}$$

Shunt active filter control

Two control loops are studied, the internal loop responsible for the ac current control and the external loop responsible of dc voltage control with the consideration that the power is flowing from the capacitor source voltage to the grid.

A. Current Technique Control

The output currents of the inverter must track the reference currents produced by the current identification block. Consequently a regulation block is required and must be designed. In this work, the inverter is controlled using a PI regulator with a PWM modulator [12]–[13]; the control circuit system is shown in Fig. 3.

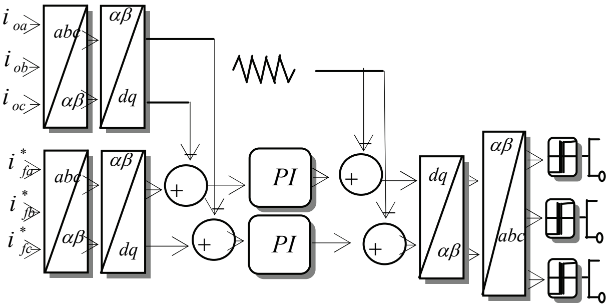

Fig.3 PI inverter controller block

i_{on} and i^*_{fn} $n=(a,b,c)$ are correspondingly the active power filter output currents and reference currents.

B. dc Link Voltage control

The closed-loop transfer function of dc voltage regulation (Fig. 4) is given by:

$$\frac{v_{dc}}{v_{dcref}} = \frac{k_p}{c}\,\frac{s + k_i/k_p}{s^2 + (k_p/c)s + (k_i/c)} \tag{17}$$

kp and ki are respectively the proportional and integrator gains of the PI controller. The design of the PI controller is realized by identifying (17) to a prototype of second order system given by equation (18).

$$\frac{v_{dc}}{v_{dcref}} = \frac{k_p}{c}\,\frac{s + k_i/k_p}{s^2 + (k_p/c)s + (k_i/c)} \tag{18}$$

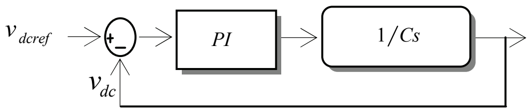

Fig.4 Dc link voltage control block

Optimized current controller PI parameters using ACO

The inconvenience of the traditional PI controller is its incapability to improve the transient response of the system. The conventional PI controller has the form as follow:

$$y(t) = k_p * e(t) + k_i \int_0^t e(t)\,dt \tag{19}$$

where: y : the control output, k_p : proportional gain, k_i : integral gain.

The control output is fed to inverter PWM signal generator. The difference between the injected current and the reference current.[1,5] is known by error signal. The design of the conventional PI controller dependent on the knowledge of the expert, in this work the trial and error method has been used to determine the parameters Kp and Ki.

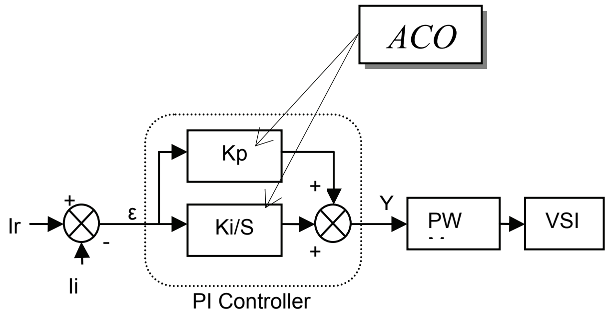

Fig.5. Control of the injected current using Optimized PI Controller

The key contribution in this paper is the proposed approach to find the optimal PI parameters fig.5 in order to ensure that the steady-state error of the system is reduced to minimum. The objective of an optimal design of currents PI controller for given plant is to find a best parameters Kp and Ki of PI control system such that the performance indexes on the transient response is minimum.

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

In this study, there are 202 nodes including the start node and the end node to form a graph representation Fig.6. Each path defines the performance indexes on the load disturbance response and transient response for a set of Kp and Ki.

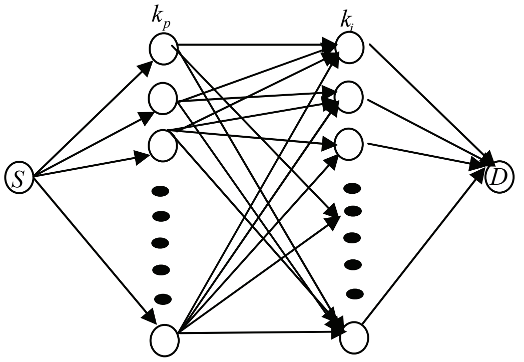

Fig.6 ACO graph representation for parameters PI controller

The following solution algorithm for designing PI controller is presented as:

Initialization.

An initial of ant colony individuals

X_i, i=1, 2….m, which is selected randomly. The m ants are placed on the n node. Format the pheromone trail intensity matrix, an initial value $\tau_{ij} = \tau_0$ for every edge between nodes i and j as well as $\Delta\tau_{ij} = 0$, generation counter n_g

We set the time counter $t = 0$

Starting tour.

Let node counter $s = 1$

For ant $k = 1$ to m do

We place the starting node of the k_{th} ant in t_list (k,s) that is initial tour list.

Searching neighborhood.

We repeat until the data t_list is full

```
    $s = s + 1$
    For $k = 1$ to m do
    Ant choose the node j to move to with probability $p_{ij}$ given in (1)
    Move the $k_{th}$ ant to the node j
    Insert node j into t_list (k,s)
•   Calculate the fitness function $F_k$ (cost) for each ant
    For $k = 1$ to m do
    Compute the function $F_k$ of the tour visited by $k_{th}$ ant
    Update the shortest path found
    For every edge
    For ant $k = 1$ to m
    The pheromone trail is calculated according to the equation (4)
•   Update the global pheromone
    For every edge (i,j) update the pheromone value according to the rule (2) and (3)
•   Check the stop criterion
    If ($n_g < n_{gmax}$) and stagnation behavior
    Then
    Record the best parameters of ants
    Empty t_list and Go To starting tour
    Otherwise
    Stop.
```

Simulation results

The idea of simulation is to show the effectiveness of the shunt active power filter in diminishing the harmonic pollution produced by nonlinear load, using ant colony algorithm to design PI controller of current control, the initial values parameters of the proposed algorithm are presented in Table.1

The SAPF model parameters are shown in the following Table 2.

Table.1 initial values parameters of ACO

Ant Number	30
Maximum Cycle Time	130
Initial Value of Nodes Trail Intensity	0.2
Coefficient ρ	0.4
Relative Important Parameter of Trail Intensity α	3
Relative Important Parameter of Visibility β	2

Table.2 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. First Case: Conventional current PI Controller

The SAPF is connected in parallel with nonlinear load, in this case the conventional PI controller is used to see the current regulation and its effect in damping harmonics current and reducing total harmonic distortion, the parameters Kp and Ki has been calculated by setting the desired dynamic parameters ω and ξ of the system, and by equating the above transfer functions (17) and (18). The PI control design involves regulation of injected current for harmonic and reactive power compensation. Simulation results show the line currents and its spectrum before compensation Fig.7, Fig.8 and the line current and its spectrum after compensation Fig.9, Fig.10 using shunt active power filter based on conventional PI controller. Fig.10 using shunt active power filter based on conventional PI controller, the total harmonic distortion (THD) has been reduced from 26.87 % to 1.16 %.

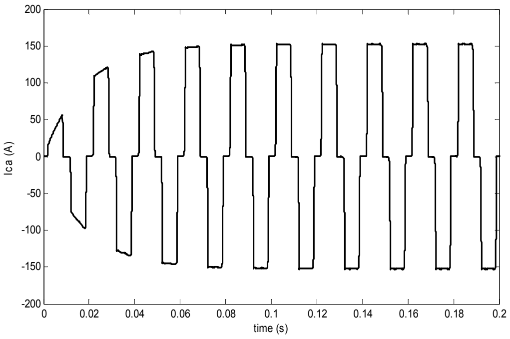

Fig.7 Supply current waveform of single phase

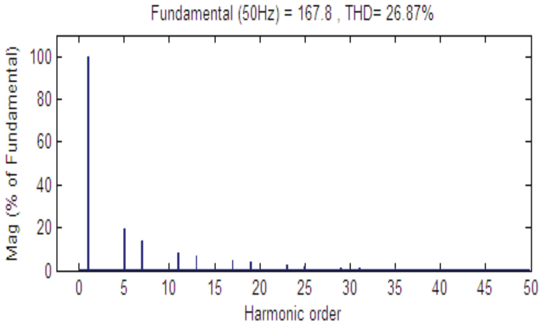

Fig.8 Harmonic spectrum of supply current

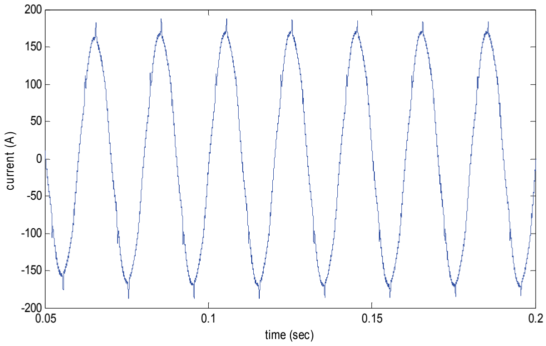

Fig.9 Supply current waveform of single phase after compensation using conventional PI control

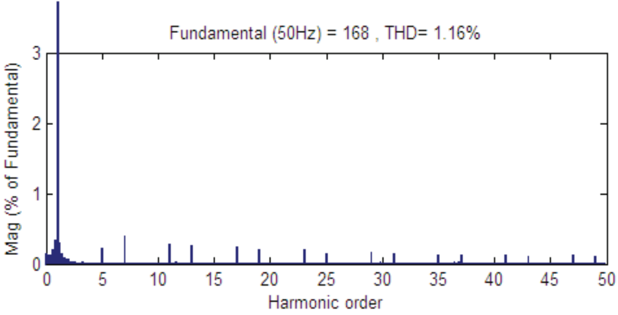

Fig.10 Harmonic spectrum of supply current after compensation using conventional PI control

Table.3 Harmonic contents of the supply currents

h	Ih/I1 (%) Before compensation	Ih/I1 (%) After compensation	IEC 1000-3-4 Ih/I1 (%)
5	19.58	0.22	9.5
7	13.55	0.39	6.5
11	8.04	0.29	3.1
13	6.46	0.26	2.0
17	4.36	0.24	1.2
19	3.61	0.21	1.1
23	2.48	0.20	0.9

Table 3 illustrates the individual amplitude of low-order harmonics in the supply current as a percentage of the fundamental component compared to individual harmonics given in IEC 1000-3-4.

B. Second Case: Optimal current PI Controller

The proposed idea is to improve the power quality using optimal shunt active power filter based on an ant colony optimization algorithm (ACO). The main objective for the system control hugged to minimization of fitness function which is defined by the following equation:

$$F = f_{os} + \alpha * f_{iae} \tag{20}$$

In this case, α value has been fixed have to 1.5 to give an importance for the integral error in formulation function.

The value of system indexes are compared in Tab4, in this novel contribution that has improved performance system, the optimal cost function reached employing ant algorithm after 130 iterations is presented in Fig .11.

Table .4 Comparisons of SAPF indexes between used and unused ant colony algorithm

Parameter and indexes	non optimized PI	Optimized PI
Proportional gain	295	370
Integral gain	35	50
Overshoot (%)	8.7956e+003	8.578e+003
Integral absolute error	1.088e+003	1.003e+003
Fitness function	1.097e+004	1.0584e+004

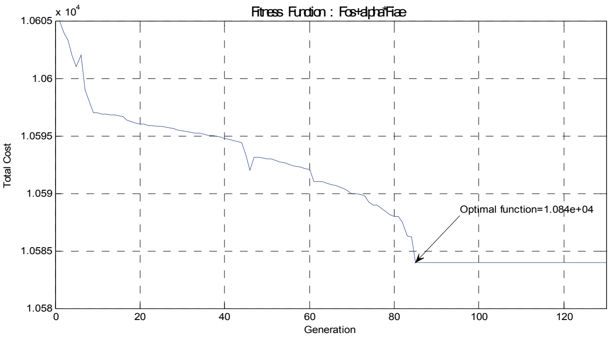

Fig: 11 the evolution of the cost function of system

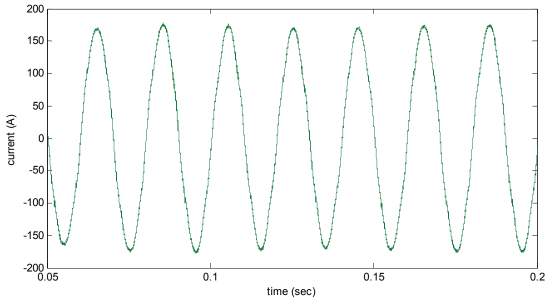

Fig.12.a Supply current waveform of single phase after compensation using optimal PI control

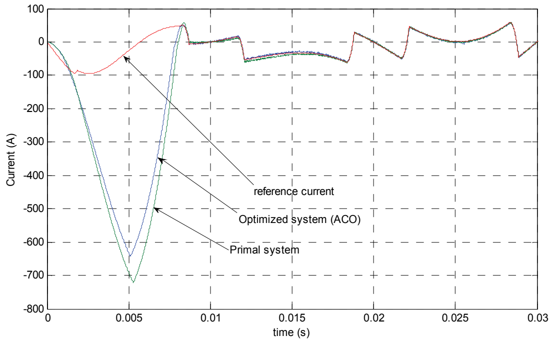

Fig.12.b the SAPF compensation current composed to its reference current

Simulation studies are carried out to predict performance of the proposed method. Fig.12 shows the simulation results which have been obtained under the same pervious condition of the conventional PI controller.

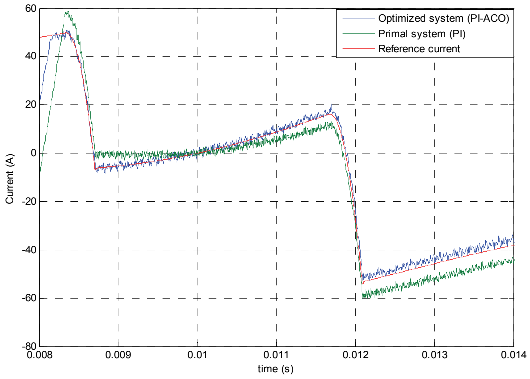

Fig.12.c the SAPF compensation current composed to its reference current in the interval (0.008 sec - 0.014 sec)

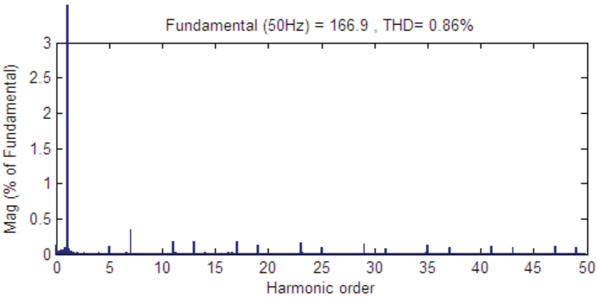

Fig.12.c Harmonic spectrum of supply current

Through the figures and calculation the THD of source current with SAPF, the THD is reduced from 1.16% value obtained by means of PI controller to 0.86% value obtained by proposed control algorithm.

The harmonic contents repartition in the supply current before and after compensation using the two methods, under balanced voltage source conditions Fig.13, is resumed in Table.4.

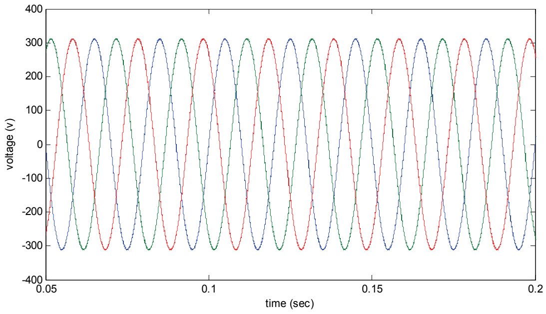

Fig.13. Source voltage waveform

Table.4 Harmonic contents of the supply currents

h	I_h/I_1 (%) without SAPF	I_h/I_1 (%) with SAPF (PI controller)	I_h/I_1 (%) with SAPF (PI_ACO)	IEC 1000-3-4 Ih/I1 (%)
5	19.58	0.22	0.12	9.5
7	13.55	0.39	0.35	6.5
11	8.04	0.29	0.19	3.1
13	6.46	0.26	0.19	2.0
17	4.36	0.24	0.18	1.2
19	3.61	0.21	0.14	1.1
23	2.48	0.20	0.17	0.9

Conclusion

This paper exhibits the validity of the proposed optimal current controller by ant colony algorithm for shunt active power filter, the results of simulations of optimized SAPF control technique presented in this work is discovered quite effective in the harmonic compensation and improving the input power factor. ACO technique is inspired by nature, and has proved itself to be effective solution to optimization problems. The main objective of this study is to design the parameters of SAPF-based current controller.

Generally, the results presented indicate that the ACO has a good sharp for finding the optimal fitness function and has proved its effeteness in finding optimal parameters Kp and Ki for current-SAPF controller, it can be seen that after SAPF with ACO-PI controller runs, the current total harmonic distortion to 0.86% from 1.16% and the power factor to 0.96 from 0.87.

Table 5 Source current total harmonic distortion: THD%

	Without SAPF	SAPF PI-Controller	SAPF PI-ACO controller	Robustness
THDi(%)	26.87	1.16	0.86	3.22/PI 4.34/PI-ACO
Power factor	0.63	0.87	0.96	

According to the previous results the proposed controller (PI-ACO) has better dynamic performance and robustness. The control method applied to SAPF has demonstrated good performance for harmonic elimination and reactive power compensation

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