OPTIMIZATION OF SHUNT ACTIVE POWER FILTER SYSTEM FUZZY LOGIC CONTROLLER BASED ON ANT COLONY ALGORITHM

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ABSTRACT

This paper presents the design of optimal fuzzy logic controller (FLC-ACO) – controlled shunt active power filter (SAPF) for harmonics compensation which is injected by nonlinear loads, such as rectifier equipment used in telecommunication system, power suppliers, domestic appliances, ect. Firstly, the controller designed according to Fuzzy logic rules is such that the system is fundamentally robust. In the second case, the optimal adjustment of the membership functions and normalization gains are realized by using Ant Colony Optimization. Simulations results show the best dynamic behaviour and performance control compared with traditional Fuzzy controller, as well as effective in reducing harmonic.

Keywords: *Shunt active power filter, Harmonic compensation, PI controller, Ant colony optimization*

1. INTRODUCTION

In the last years, the current take a non-sinusoidal form caused by injected harmonic from no-linear loads such as converters, home applications as TVs, electromagnetic cookers and fluorescent lights [1]. Shunt active filter is proposed as a way of removing current harmonics. In active power filter two controllers are used, the first is to regular the DC link voltage and the second to determine the harmonics that are to be eliminated. The output of this controller is the reference of a three-phase current controlled inverter. The principle of shunt active filter is presented in fig.1. the no-linear load which is coupled to the power system pollute the network by producing current harmonics, the active power filter is connected in parallel to the mains supplies the current harmonics needs to maintain the source current sinusoidal. Different theories have been introduced such as the instantaneous power theory (p-q theory), notch algorithm, synchronous reference method and kalman filter method.

In this study, the instantaneous power theory (p-q theory) is used to identify the injected current harmonics, this theory was introduced by Akagi, Kanazawa and Nabae in 1983 [2] in Japanese.

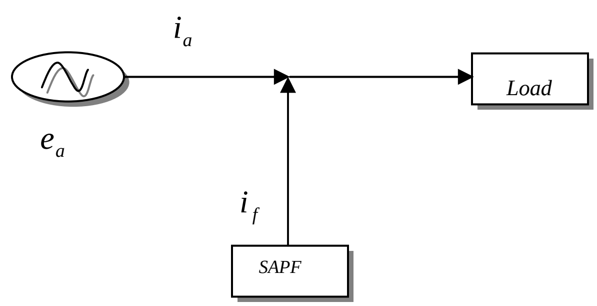


Fig.1: Principle of an active power filter

In this work, The proposed optimized shunt active power filter system is a great tool for the compensation not only of current harmonics produced by distorting loads, but also of reactive power of non-linear loads [3]. The DC-link voltage of SAPF can be adjusted to a great extent so as to provide easy control and high performance Fuzzy theory was first proposed and investigated by Prof. Zadeh in 1965.The Mamdani fuzzy inference system was presented to control a steam engine and boiler combination by linguistic rules [4]-[5]. Fuzzy logic is expressed by means of if-then rules with the human language.

In the design of a fuzzy logic controller, the mathematical model is not necessary. Therefore the fuzzy logic controller is of good robustness. Owing to its easy application, it has been widely used in industry.. However, the rules and the membership functions of a fuzzy logic controller are based on expert experience or knowledge database.

The ant colony algorithm has been used to find the optimal values and parameters of our fuzzy logic controller (FLC), this algorithm was proposed by Marco Dorigo and his co-workers. Since having features of positive feedback, strong robust and parallel processing, the algorithm has solved traveling salesman problem (TSP), quadratic assignment problem (QAP) and job-shop scheduling problem (JSSP) and so on [6]-[7]. In this paper, a novel approach is proposed for designing the optimal fuzzy controller for DC link voltage, ACO algorithms are applied to look for globally optimal parameters of fuzzy logic.

The best ranges of membership functions, the greatest shapes of membership functions and the best fuzzy inference rules. Moreover, the two different fuzzy logic controllers are compared and then simulations results are offered to show the efficacy of FLC-ACO controller.

2. 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 [8].

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.

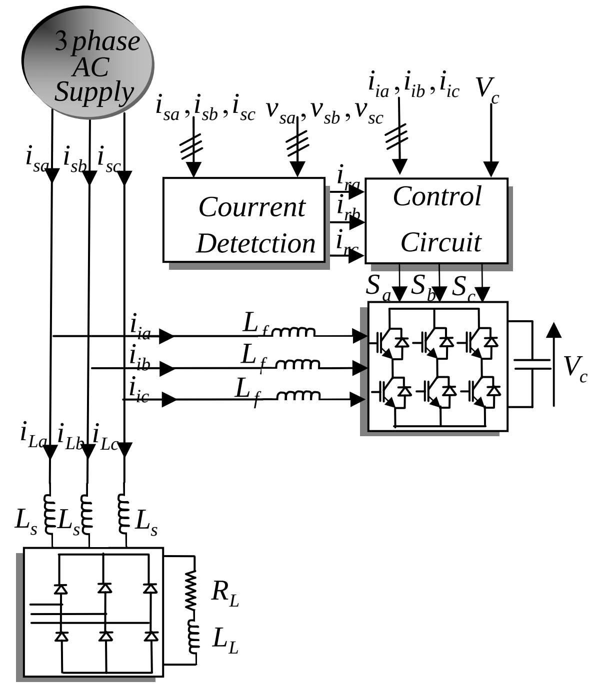


Fig.2 Equivalent schematic of shunt SAPF

3. 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 αβ coordinates [9].

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

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

The instantaneous power is calculated as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

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

$$p_L = \overline{p}_L + \tilde{p}_L \quad (4)$$

Where,

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

$\tilde{p}_L$: Harmonic component

Similarly,

$$q_L = \overline{q}_L + \tilde{q}_L \quad (5)$$

Finally, we can calculate reference current as:

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

Here,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (7)$$

4. FUZZY LOGIC CONTROLLER

The concept of Fuzzy Logic (FL) was proposed by Professor Lotfi Zadeh in 1965, at first as a way of processing data by allowing partial set membership rather than crisp membership. Soon after, it was proven to be an excellent choice for many control system applications since it mimics human control logic[10]-[11]. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, the error $e(t)$ and the variation error $\Delta e(t)$ have been placed of the angular velocity to be the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control voltage $u(t)$.

In this work, the type of fuzzy inference engine used is Mamdani. The linguistic variables are defined as (NB, NS, Z, PS, PB) which mean big, negative small, zero, positive small and positive big respectively. The membership functions of the fuzzy logic controller are shown in Fig. 3

The fuzzy inference mechanism used in this work is presented as following. The fuzzy rules are summarized in Table 1.

$$\mu_\beta(u(t)) = \max_{j=1}^{m} [\mu_{A1^j}(e(t)), \mu_{A2^j}(\Delta e(t)), \mu_{B^j}(u(t))] \quad (8)$$

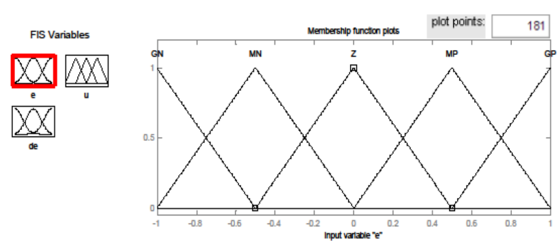
Fuzzy output $u(t)$ can be calculated by the center of Gravity defuzzification as:

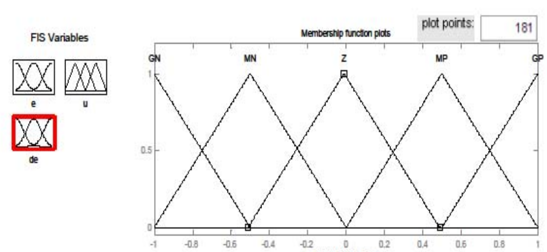
$$u(t) = \frac{\sum_{i=1}^{m} \mu_B(\mu_i(t))\, u_i}{\sum_{i=1}^{m} \mu_B(\mu_i(t))} \quad (9)$$

Where i is the output rule after inferring.

u(t)		*e(t)*				
		NB	**NS**	**Z**	**PS**	**PB**
	NB	NB	NB	NS	NS	Z
	NS	NB	NS	NS	Z	PS
de(t)	**Z**	NS	NS	Z	PS	PS
	PS	NS	Z	PS	PS	PB
	PB	Z	PS	PS	PB	PB

Tab.1. Fuzzy inference rules





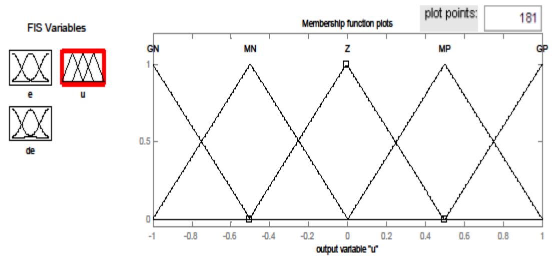


Fig. 3 – Membership function of fuzzy logic controller

5. 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. 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) [12]. The probability rule (called Pseudo-Random-Proportional Action Choice Rule) between two nodes i and j.

$$P_{ij} = \frac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{h \in s}[\tau_{ij}]^{\alpha}[\eta_{ih}]^{\beta}} \qquad (10)$$

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 12 and 13), where the quality is linked to the cost function.

$$\tau_{ij} \rightarrow (1-\rho)\tau_{ij} \qquad \forall (i, j) \in L \qquad (11)$$

$$\tau_{ij} \rightarrow \tau_{ij} + \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \qquad \forall (i, j) \in L \qquad (12)$$

$$\Delta\tau_{ij} = \begin{cases} \frac{1}{c^{k}} \text{ if} & arc\ (i, j) beong\ \ to\ T^{k} \\ 0 & othrwise \end{cases} \qquad (13)$$

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,uilt by the k^{th} ant.

6. ACO APPLIED TO OPTIMIZE FLC PARAMETERS OF DC LINK CAPACITOR

In this paper, The SAPF as controlled plant, the SAPF diagram is shown in Fig.4.

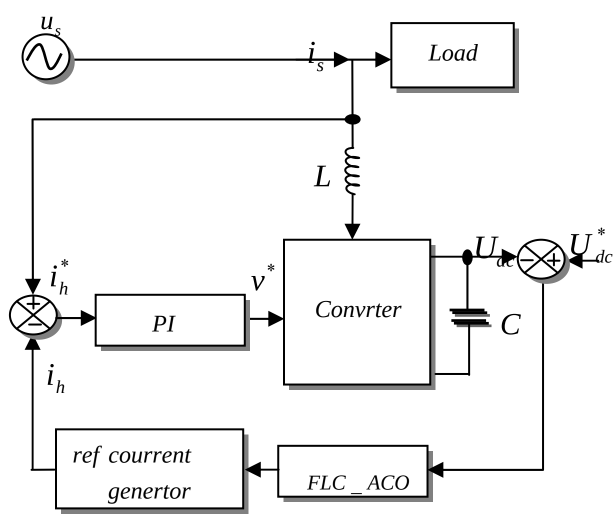


Fig.4 Control diagram of APF system

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_{dc}^* 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 FLC controller which its output is multiplied by the mains voltage waveform Vs1, Vs2, Vs3 in order to obtain the supply reference currents found. In this paper, all parameters of FLC controller such as, the range of the membership functions K_e and K_{de} , the shape of the membership functions (e1-e5, de1-de5 and u1-u5) are hinted by 150 nodes respectively and there is resolution 0.0001among each node.

The more accuracy trails are updated after having constructed a complete path and the solution. In this study, there are 2552 nodes including the start node and the end node to form a graph representation Fig.5. Each path defines the performance indexes on the load disturbance response and transient response for a set of K_e , K_{de} , e1…..e5, de1….de5 and u1……u5.

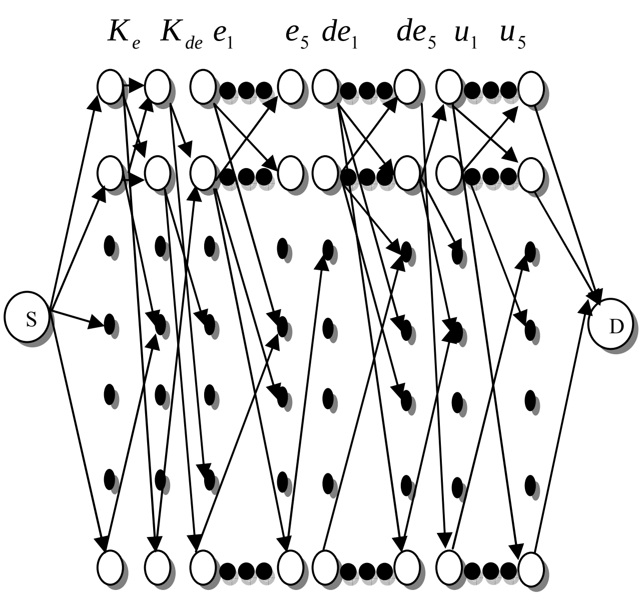


Fig.5 ACO graph representation for parameters FLC controller

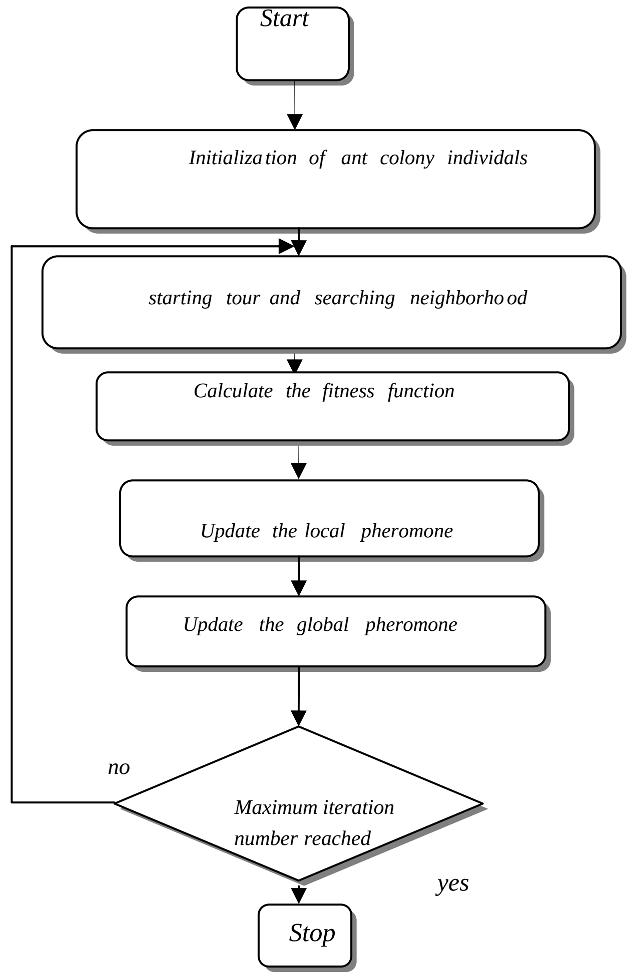
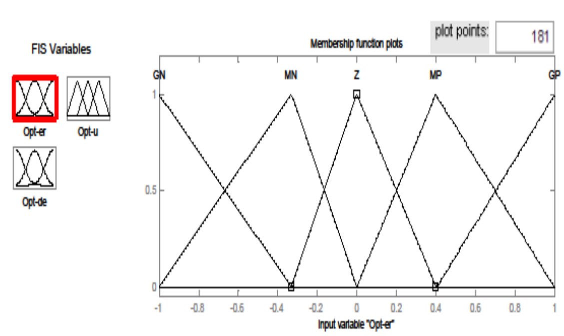


Fig.6 ACO graph representation for parameters FLC controller

Finally, the optimal membership functions found using ACO algorithm of fuzzy controller are shown on the following figure.



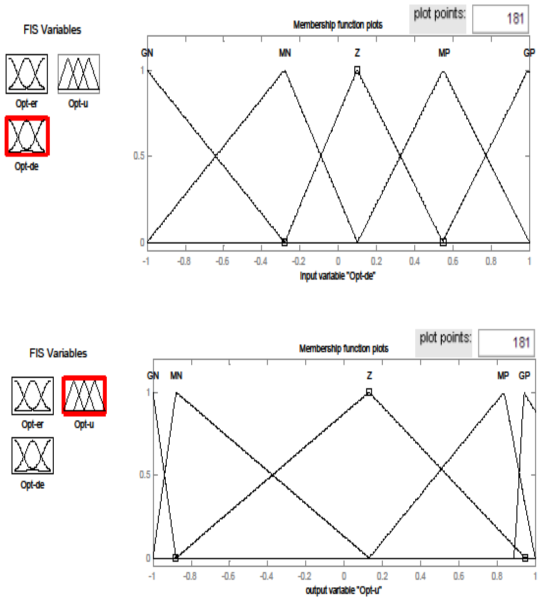


Fig. 7 – The optimal membership functions

7. 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.2.

Table.2 initial values parameters of ACO

Ant Number	30
Maximum Cycle Time	200
Initial Value of Nodes Trail Intensity	0.05
Coefficient ρ	0.4
Relative Important Parameter of Trail Intensity α	1.5
Relative Important Parameter of Visibility β	2

8. SIMULATION RESULT

The optimal fuzzy controller design by ACO of DC link capacitor has been set in Matlab Simulink environment to predict performance of the proposed approach. The SAPF model parameters are shown in the following.

Table.2 SAPF parameters

Supply phase voltage U	220 V
Supply frequency fs	50 HZ
Filter inductor Lf	1mH
Dc link capacitor Cf	5.3 mF
Smoothing inductor	0.12 mH
Sample time Ts	4 µs

Two different fuzzy controllers are implanted for the computer simulation. Firstly, conventional fuzzy logic controller is based on the expert experience has been used on the system SAPF which is connected in parallel with nonlinear load. Secondly, the proposed optimized fuzzy logic controller with ACO has been examined to see its effect for damping harmonics current and reducing total harmonic (THD).

The main objective is to minimize the fitness function that is defined by the following equation.

$$F = f_{os} + f_{rt} + f_{ias} + f_{st} \qquad (14)$$

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:

$$F = f_{os} + f_{rt} + \alpha * f_{ias} + f_{st} \qquad (15)$$

In this case, we have fixed α value: $\alpha = 1.5$ and that to give an importance for the integral error in formulation function.

The maximum overshoot is defined as:

$$f_{os} = y_{\max} - y_{ss} \qquad (16)$$

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

For f_{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:

$$f_{ias} = \int_0^\infty |e(t)|\,dt \qquad (17)$$

Simulation studies are carried out to predict performance of the proposed method. The Fig. 8 shows the DC link voltage response curves of system used conventional fuzzy logic and optimized fuzzy logic controller, and the value of system indexes are compared in Tab. 3.The source voltage, current, load current, harmonic order and Dc link voltage waveforms are shown in the following figures after adopted the optimized system.

Table .3 comparisons of SAPF indexes between used and unused ant colony algorithm

Parameter and indexes	Conventional FLC controller	Optimized FLC controller with ACO
Gain K_e	0.1	0.998
Gain K_{de}	$1/6e^7$	$1/5.88e^7$
Gain K_u	$35e^4$	$33e^4$
Overshoot (%)	11.0247	3.7920
Rise time (sec)	0.0068	0.006798
Setting time	0.0048	0.0046
Integral absolute error	$4.4629e^{+000}$	$4.0341e^{+000}$

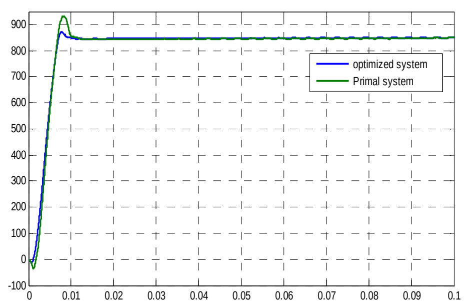


Fig.8 DC link voltage response curve of SAPF used ant colony optimization

The source voltage, current, load current, harmonic order and Dc link voltage waveforms are shown in the following figures after adopted the optimized system.

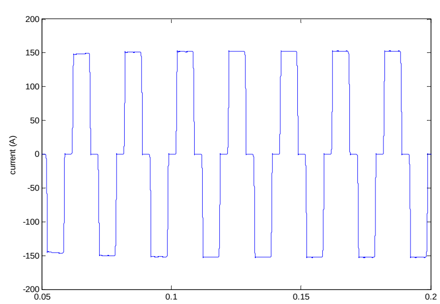


Fig.9 Load current waveform

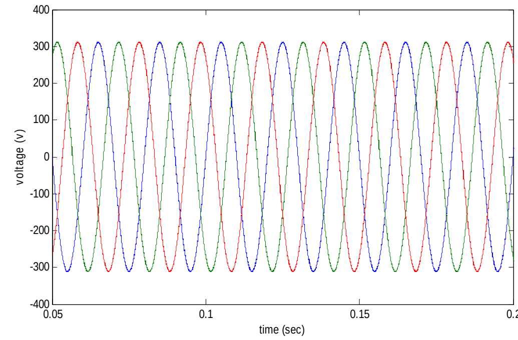


Fig.10. Source voltage waveform

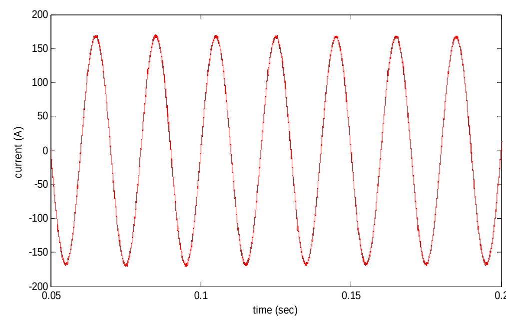


Fig.11 Supply current waveform of single phase

9. COMPARATIVE STUDY

The main objective in this study is to see the effect of ant colony algorithm applied on shunt active power filter (SAPF). The total harmonic distortion (THD) has been reduced clearly Tab.4 compared with primal system by using FLC-controller DC link voltage of SAPF. The FLC-ACO control method has improved the active power filter performance, and it can be seen in the Supply current filtering result Fig.11.

In Fig. 8, the rise time and regulation time are shorter, and the overshoot is reduced after optimization.

Table.4 THD results

	Without filtering	SAPF using Conventional FLC	SAPF using Optimized FLC
THD_i (%)	20.90	3.68 Robustesse 4.55	2.31 Robustess 5.89

10. CONCLUSION

In this paper, the ACO algorithm is applied to optimize FLC parameters of SAPF.

The simulation 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 6.54 % less than primal system (SAPF without ACO).

According to these results, the FLC controller with ACO algorithm is better than the conventional FLC without ACO algorithm, and then we can say that the FLC-ACO is the best controller which presented satisfactory performance and good robustness.

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