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Optimum Shunt Active Power Filter For Load Compensation: A Comparitive Study

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Abstract : Today the uses of non-linear loads in industrial, commercial and domestic areas have risen to harmonic problems. Harmonics leads to disoperation in loads connected at Point of Common Coupling (PCC). Shunt Active Power Filter (SAPF) is proposed to improve Power Quality under non linear load condition by compensating the current harmonics. The performance of SAPF depends on the controller adopted for SAPF. Recently Artificial Bee Colony (ABC) optimization technique proposed by the inspiration of the foraging behavior of honey bees. ABC optimization is a meta-heuristic approach of swarm intelligence. In this paper the performance of ABC-SAPF is compared with conventional, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bacterial Foraging(BF) tuned SAPF.

Keywords : Harmonics; Shunt Active power Filter; PI controller; Optimization Techniques; Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bacterial Foraging(BF) ; Artificial Bee Colony(ABC).

1. INTRODUCTION

Now a days, the power electronics applications have grown tremendously. The characteristics of these power electronic systems are highly nonlinear. These non linear characteristics lead to increase in harmonics and reactive power components of current from AC mains, low system efficiency and a poor power factor. They also cause disturbance to other consumers and interference in nearby communication networks. These power electronic devices mainly consume harmonic distorted currents, even in case of sinusoidal voltage. This harmonic pollution mainly affects the distribution networks leading to problems like harmonic power flows, electromagnetic interferences, protection misoperation, insulation failures, harmonic resonances, etc. [1] Harmonic reduction can be done in two ways. One is by improving the design of the non-linear loads. Example for this is using multilevel topology for high power appliances. Second solution is installing harmonic filters.

Tuned passive filters, composed by inductors and capacitors, have been traditionally used for this task. The inductor and capacitor are chosen in order to create a resonance for the harmonic current that has to be reduced. In spite of tuned passive filters are a well-known technique, some problems (such as overload ,detuning due to aging of their components, appearance of resonances with the power system for a harmonic below the tuned frequency, fixed filtering characteristic, etc.) reduce their widespread use and establish a careful design process.

Research and development of SAPF became a feasible alternative over the Passive Filters to solve power quality problems like harmonics injection and reactive power requirement of nonlinear loads. The SAPF turns the non sinusoidal source current into sinusoidal waveform by injecting the harmonic currents

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demanded by the non-linear load. Current harmonics can be eliminated with SAPF.The accuracy and quickness in extraction of harmonic components from the load current mainly depends on the dynamic performance of SAPF. Much harmonic extraction techniques are available, and their responses have been explored. [2]-[3].

L. Gyugyi et al.[4] introduced Active Power Filter(APF) application in AC systems for compensation of Harmonics. Akagi et al. [5] proposed the instantaneous reactive power theory for estimating the reference compensation currents required to inject into the network at PCC where the nonlinear load is connected. S. Bhattacharya, et al. [6] presented a synchronous reference frame technique for obtaining sinusoidal source currents under non linear load condition. B. Singh, et al. [7] proposed Active power filter with sliding mode controller technique, for the calculation of compensating currents. All the aforementioned methodologies work well under ideal source voltages. If the source voltages are imbalanced and/or distorted, the generated SAPF reference compensation currents are incompatible therefore desired balanced/ sinusoidal source currents cannot be achieved.

Gary W. Chang, et al. [8] proposed a methodology which works under imbalanced source voltages. Most of these control methods involves number of transformations and hence implementation becomes difficult. System control also complex with this methodologies.Duke.et al. [9] has proposed a simple synthetic sinusoid generation technique to determine compensating currents by sensing the load currents. Further this methodology is adapted by the line currents. With this modification process became simple and easy to implement. The coefficients of PI controller used in the controller of SAPF got from conventional method may not give satisfactory result for varying operating condition s.

For the operation of the SAPFs under various load conditions, precise control scheme is required. Avik S.K. Jain, et al.[10] applied Fuzzy Logic to SAPF. Bhattacharya, et al.[11] applied predictive and adaptive properties of artificial neural networks (ANNs) to SAPF. But these strategies are mostly effective for a small range of loads alone and with these methodologies no detail analysis of the dynamics of the dc-link voltage is available. Then the algorithms derive by the inspiration from the nature which called as population-based evolutionary algorithms are proposed. They are being used more, as they are derivative free, simpler to execute and do not require any initial values for starting the search for the optimal values.

In this paper, Artificial Bee Colony algorithm is proposed to optimize gains of the PI controller. The genetic algorithm (GA), Particle Swarm Optimization (PSO) and Bacterial Foraging (BF) are well-established tools to obtain a global minimum optimal solution. In this paper the performance of ABC is compared with GA, PSO and BF. The proposed Artificial Bee Colony algorithm is giving better results than GA, PSO and BF to reach the solution.

2. SHUNT ACTIVE POWER FILTER

The use of Shunt Active Power Filter is an effective method to mitigate harmonic currents of non linear loads. SAPF improves the quality of the current waveform in distribution networks. Shunt active Power filters are connected in parallel with the nonlinear loads to prevent them from injecting non sinusoidal currents.

Electrical Circuit diagram of SAPF is shown in Fig. 1. Its main component is a voltage-source inverter (VSI) with dc link capacitor. At PCC, VSI is connected via a leakage inductance. The performance of SAPF depend on parameters like smoothing and decoupling element (L_c), energy storage element dimension (C_{dc}), the methods used to extract compensation reference currents (i_{sa}^*, i_{sb}^*, i_{sc}^*) and control technique used to regulate the compensation currents (i_{ca}, i_{cb}, i_{cc}) and the DC voltage Voltage (V_{dc}).

Shunt active Power Filter supplies the compensating current ic to the utility hence cancels current harmonics on the ac side, and makes the source current in phase with the source voltage. Fig 1 shows the basic compensation principle of a shunt Active power filter.

When nonlinear load is connected to the distribution system, the instantaneous load power can be given by

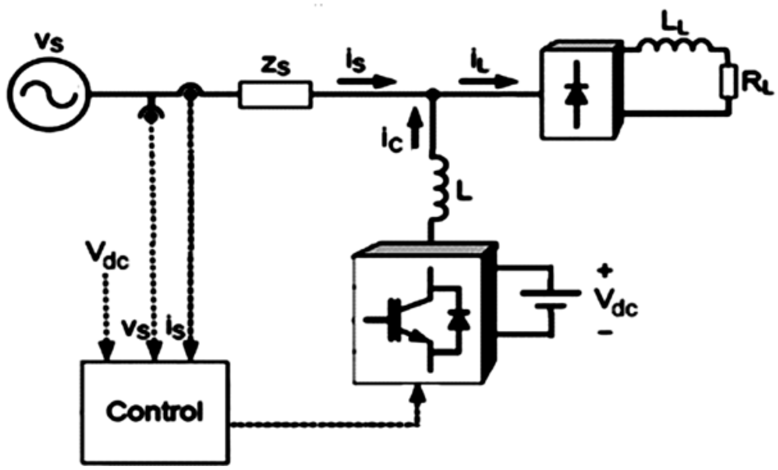

Fig. 1. Block diagram of Shunt Active Power Filter.

$$p_L(t) = vs(t) * i_L(t) \tag{1}$$

where $vs(t)$ instantaneous source voltage and $i_L(t)$ is instantaneous load current.

The instantaneous source current is given by

$$v_s(t) = V_m \sin \omega t \tag{2}$$

The instantaneous current can be written as

$$i_s(t) = i_L(t) - i_c(t) \tag{3}$$

When a nonlinear load is applied the load current has two components.They are fundamental component and harmonic components, which can be expressed as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t\ \varphi_n)$$

$$= I_1 \sin(\omega t + \varphi_1) + \sum_{n=2}^{\infty} I_1 \sin(n\omega t + \varphi_n)$$

Substitute equation (2) and equation (4) in equation (1),then The instantaneous load power can be given as

$$p_L(t) = vs(t) * i_L(t)$$

$$= V_m I_1 \sin^2 \omega t * \cos \varphi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin\varphi_1$$

$$+ V_m \sin\omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n)$$

$$= p_f(t) + p_r(t) + p_h(t) \tag{5}$$

from (5), the real power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos \varphi_1 = v_s(t) * i_s(t) \tag{6}$$

From (6), the current supplied by the source, after compensation is

$$i_s(t) = p_f(t))v_s(t) = I_1 \cos \varphi_1 \sin \omega t = I_{sm} \sin \omega t \tag{7}$$

Where I_{sm} the peak value of the loss current.For harmonic mitigation, SAPF is must provide compensating Current $i_c(t)$ such that $i_s(t)$ must be in phase with the utility voltage and purely sinusoidal. The compensating Current can be given as

$$i_c(t) = i_L(t) - i_s(t) \tag{8}$$

Hence, for accurate and instantaneous compensation, it is necessary to estimate $i_s(t)$. This $i_s(t)$ is the fundamental component of $i_L(t)$ as the reference current. The peak value of the reference current I_{sm} can be calculated by controlling the dc-side capacitor voltage. Irrespective of the load current nature, Ideal compensation requires the supply current to be sinusoidal and in phase with the source voltage. The source currents, after compensation, can be given as

$$i_{sa}^{*} = I_{sm} \sin \omega t$$

$$i_{sb}^{*} = I_{sm} \sin (\omega t - 120)$$

$$i_{sc}^{*} = I_{sm} \sin (\omega t + 120) \quad (9)$$

Where i_{sm} is the amplitude of the desired source current, while the phase angle is obtained from the source voltages. Hence, the magnitude of the source currents (i_{sm}) is needed to be calculated.

The PI controller is used to process the error between The DC side capacitor voltage and reference voltage. PI controller gives the amplitude of the desired source current. Unit sine vectors are generated from the source voltages. Multiplication of peak value with unit sine vectors gives the reference currents. Fig. 2 shows the schematic diagram of PI control scheme.

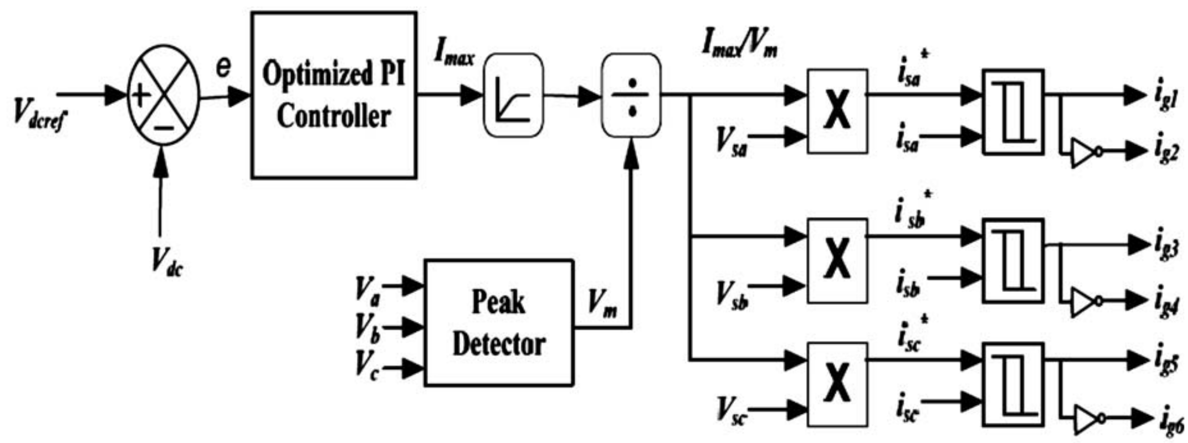

Fig. 2. Schematic diagram of PI control scheme.

3. FITTNESS FUCTION

The gains of the conventional PI controller are designed based on the assumption of linear model of PWM converter. The characteristic equation of PI controller along with PWM converter can be derived using small signal perturbation technique. The characteristic equation is as follows [6]:

$$1+\left(K_p+\frac{K_1}{s}\right)-\frac{3[V_s - sL_{fo} - 2I_{fo}R_f}{sC_{dc}V_{dco}} = 0 \quad (10)$$

Where K_p, K_i proportional and integral gain

C_{dc},V_{dc} *dc* side capacitor and its Voltage

V_s *ac* side voltage

L_f, R_f Filter inductance and resistance

I_{fo},V_{dco} Steady state operating points of I_f,V_{dc}

In this paper, the ABC optimization scheme has been used for the optimization of PI controller parameters and The integral time square error (ITSE) performance index presented in (11) is used as the objective function "J" for optimization

$$J = \text{ISTE} = \int_0^t (e_r^2 * t)dt \quad (11)$$

Where $e_r = V_{dcref} - V_{dc}$

The coefficients (K_p, K_i) optimized at a particular load condition may not give the satisfactory performance at all of the load conditions.

4. OPTIMAL TUNING OF PI CONTROLLER

Population-based optimization algorithms find near-optimal solutions to the difficult optimization problems by motivation from nature. The general feature of all population-based algorithms is that the population consisting of possible solutions to the problem is altered by applying some operators on the solutions depending on the information of their fitness. Hence, the population is moved towards better solution areas of the search space. Two important classes of population-based optimization algorithms are evolutionary algorithms and swarm intelligence-based algorithms. In recent years, swarm intelligence has also attracted the` interest of many research scientists of related fields. Bonabeau has defined the swarm intelligence as ". . .any attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insect colonies and other animal societies. . ." [13].

Many population based algorithms were proposed for solving unconstrained optimization problems. Genetic algorithms (GA), particle swarm optimization (PSO), and Bacterial Foraging (BF) are most popular optimization algorithms which employ a population of individuals to solve the problem on hand.

4.1. Genetic algorithms (GA)

A basic GA consists of five components. These are a random number generator, a fitness evaluation unit and genetic operators for reproduction; crossover and mutation operations.

The basic algorithm is summarized below :

1. Initialize Population
2. Repeat
3. Evaluation
4. Reproduction
5. Crossover
6. Mutation
7. Until requirements are met

4.2. Particle swarm optimization (PSO)

In PSO, a population of particles starts to move in search space by following the current optimum particles and changing the positions in order to find out the optima. The position of a particle refers to a possible solution of the function to be optimized. Evaluating the function by the particle's position provides the fitness of that solution. In every iteration, each particle is updated by following the best solution of current particle achieved so far(particle best) and the best of the population (global best).

Main steps of the procedure are :

1. Initialize Population
2. Repeat
3. Calculate fitness values of particles
4. Modify the best particles in the swarm
5. Choose the best particle
6. Calculate the velocities of particles
7. Update the particle positions
8. Until requirements are met

4.3. Bacterial foraging Algoritham (BF)

In recent years, the Bacterial foraging(BF) algorithm has gradually aroused the wide attention. The foraging strategy of E. coli bacteria is governed by four processes, which are chemotaxis, reproduction, elimination and dispersal, and swarming [7,8]. A basic GA consists of four components. Chemotaxis, Reproduction, Elimination and Dispersal Operation and Swarming.

Main steps of the procedure are :

1. Initialize parameters
2. Compute the initial fitness values of each bacterium.
3. Repeat
4. Chemotactic operator and quorum sensing mechanism
5. Reproduction

6. Elimination and dispersal operator
7. Check the terminal condition, and if satisfied, output optimal solution , otherwise, go to Step 4.
8. Until requirements are met

1.4. Artificial Bee Colony (ABC)

The artificial bee colony algorithm is a new meta heuristic approach, proposed by Karaboga [9]. It is inspired by the intelligent foraging behavior of honey bee swarm.In the ABC algorithm, the colony of artificial bees contains three groups of bees: employed bees, onlookers and scouts. A bee waiting on the dance area for making decision to choose a food source is called an onlooker and a bee going to the food source visited by it previously is named an employed bee.A bee carrying out random search is called a scout. In the ABC algorithm, first half of the colony consists of employed artificial bees and the second half constitutes the onlookers. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source is exhausted by the employed and onlooker bees becomes a scout.

The main steps of the algorithm are as below :

1 Initialize Population
2 Repeat
3 Place the employed bees on their food sources
4 Place the onlooker bees on the food sources depending on their nectar amounts
5 Send the scouts to the search area for discovering new food sources
6 Memorize the best food source found so far
7 Until requirements are met

5. SIMULATION RESULTS

Simulations are performed using MATLAB® Simulink. Simulated results are analyzed based fitness function and optimization algorithms. The parameters taken for simulation are: VS = 230V , f = 60Hz, R_f = 0.1 ohms, L_f = 0.66 mH, C_{dc} = 2000 mF, V_{dcref} = 200V, R_s = 1Ω , L_s = 0.15 mH, R_L = 10Ω , L_L = 20mH. The three-phase source voltages are assumed to be balanced and sinusoidal. For simplicity, only phase-quantities are shown in the simulation results. A load with highly nonlinear characteristics is considered for the load compensation. Source current contains harmonics due to Non Linear Load. Source current is equal to the load current when the compensator is not connected.

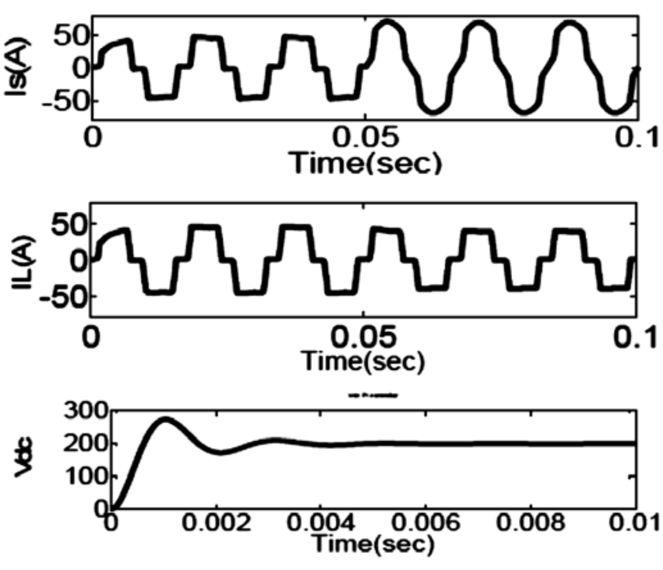

Fig. 3. The performance of the SAPF with conventional PI controller.

The performance of the conventional, GA–PI, PSO-PI, BF-PI controller and proposed ABC-PI controller for the regulation of APF is analyzed by considering that the compensator is switched on at 0.05s. The performance of the SAPF with conventional PI controller is shown in Fig. 3.

Genetic Algorithm (GA) is well known optimization technique to tune PI controller parameters. The performance of the SAPF with GA tuned PI controller is shown in Fig. 4. When GA is used for PI controller tuning, Vdc is settling faster than conventional PI controller.

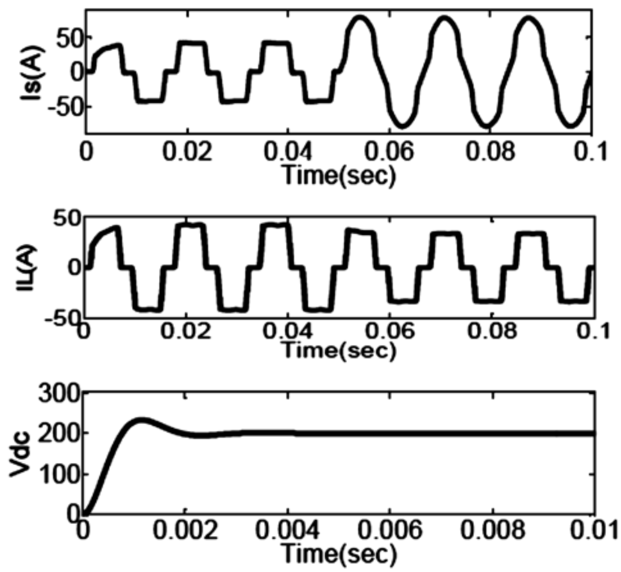

Fig. 4. The performance of the SAPF with GA tuned PI controller.

Partical Swarm Optimization (PSO) is another well known optimization technique to tune PI controller parameters. The performance of the SAPF with PSO tuned PI controller is shown in Fig. 5. When PSO is used for PI controller tuning, Vdc is settling faster than GA- PI controller.

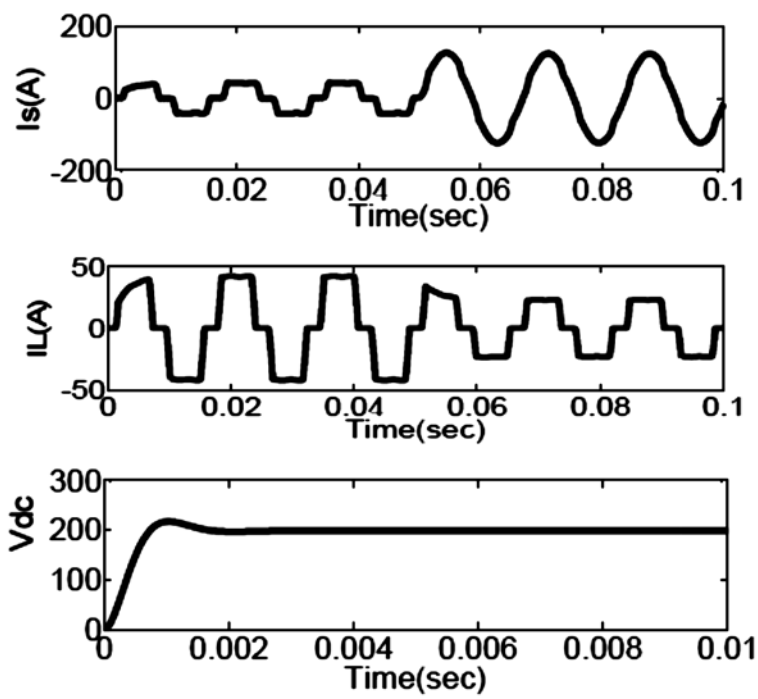

Fig. 5. The performance of the SAPF with PSO tuned PI controller.

Bacterial foraging Algoritham (BF) is another well known optimization technique to tune PI controller parameters. The performance of the SAPF with BF tuned PI controller is shown in Fig. 6. When BF is used for PI controller tuning, Vdc is settling faster than PSO- PI controller.

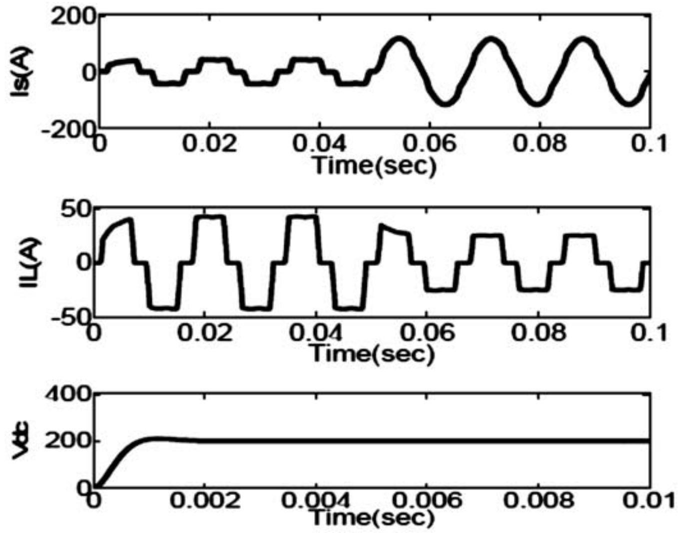

Fig. 6. The performance of the SAPF with PSO tuned PI controller.

The performance of the SAPF with ABC tuned PI controller is shown in Fig. 7. When ABC is used for PI controller tuning, Vdc is settling faster than conventional PI controller, GA, PSO and BF tuned PI controller.

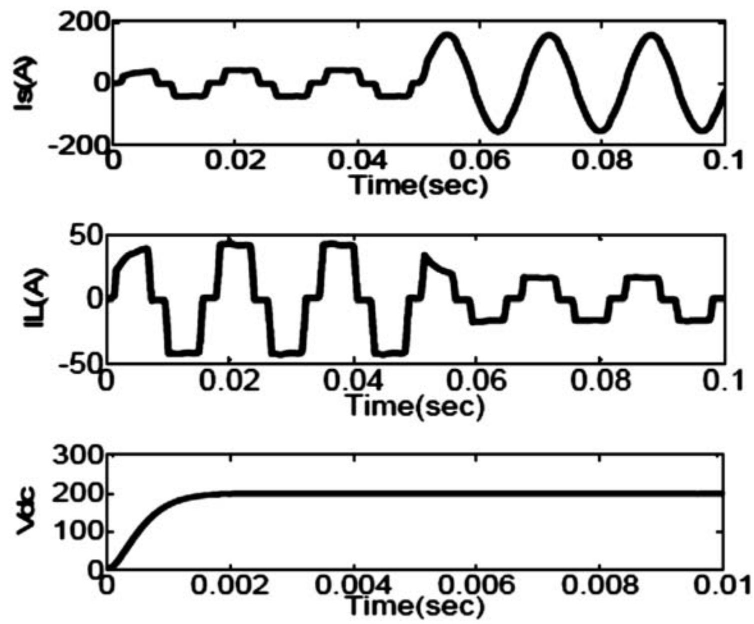

Fig. 7. The performance of the SAPF with ABC tuned PI controller.

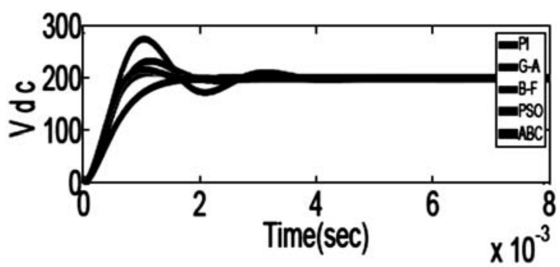

Fig. 8. The comparison of the DC capacitor voltage.

The comparison of the dc capacitor voltage regulation with the four optimization techniques is shown Fig. 8. It is observed that the performance of SAPF with ABC optimization technique is quite satisfactory in terms of the rise in dc capacitor voltage and settling time.

Table 1. Comparison Of Pi Controller Gain Values.

Optimization Method	*Kp*	*Ki*
PI	8.1658	9.0673
GA	3.7855	2.5852
PSO	3.7855	2.5852
BF	9.2489*e* + 13	–0.5441
ABC	–0.5441	9.2489*e* + 13

Table 2. Comparision of step responce.

Controller type	*PI*	*GA*	*PSO*	*BF*	*ABC*
Rise Time	0.57	3.82	3.59	3.42	3.48
Settling Time	5.96	5.82	6.80	5.76	5.98
Settling Min	95	65	79	66	65
Settling Max	112	65	83	70	67
Overshoot	12.38	81.53	49.36	68.57	76.11

Table 3. Comparision of THD

Controller type	With out SAPF	PI	GA	PSO	BF	ABC
THD %	23.92	13.10	3.51	3.51	4.07	2.07

Table 4. Detailed Harmonic Analysis

Harmonic Number	*With out SAPF*	*Conventional PI*	*GA*	*PSO*	*BF*	*ABC*
DC	0.06	0.89	0.008	0.04	0.03	0.06
1	50.20	81.52	81.32	125.77	117.65	156.74
2	0.07	0.72	0.00	0.05	0.04	0.04
3	0.04	0.36	0.00	0.03	0.02	0.01
4	0.03	0.32	0.00	0.02	0.02	0.01
5	9.42	8.41	5.48	3.17	3.47	2.32
6	0.02	0.04	0.00	0.02	0.02	0.01
7	6.18	5.39	3.66	2.29	2.47	1.72
9	0.02	0.16	0.00	0.01	0.01	0.02
11	3.16	2.56	2.04	1.39	1.50	1.00
13	2.17	1.77	1.57	1.09	1.18	0.79
15	0.00	0.03	0.00	0.01	0.01	0.00
THD	23.92	13.10	8.85	3.51	4.07	2.07

The comparison of PI controller gain values are shown in Table 1. The comparison of step response is given in Table 2. The comparison of THD is given in Table 3.Detailed Harmonic Analysis is given in Table 4.Hence the performance of ABC tuned SAPF is better than conventional PI controller, GA,PSO and BF tuned SAPF.

6. CONCLUSION

This paper presents a study of Artificial Bee Colony algorithm optimization to find optimum gain values of a PI controller for SAPF for different errors as variables of fitness function. The ABC algorithm performs better than conventional PI controller , GA, PSO and BF tuned SAPF in terms of tracking the reference voltage and tuning the PI for minimization of THD. The dc- link voltage settles in less than 1 cycle during load transients. The ABC algorithm with ITSE as performance index shows better dynamic response as well harmonic compensation in source current. Hence, ABC algorithm is recommended as good tool for finding optimized gains of the PI controller with ITSE as the fitness function.

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