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ORIGINAL ARTICLE

Real Time Implementation and Analysis of Enhanced Artificial Bee Colony Algorithm Optimized PI Control algorithm for Single Phase Shunt Active Power Filter

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Abstract

This paper proposes a new hybrid novel optimization approach, called Enhanced Artificial Bee Colony Algorithm (EABC) for designing an optimal PI controller for single-phase Shunt Active Power Filter (SAPF). The proposed EABC algorithm optimizes the gain values of the PI controller to improve the dynamic performance of SAPF. In this EABC, the adaptive real coded genetic algorithm (ARGA) is integrated with the Artificial Bee Colony (ABC) algorithm and this integration improves the exploration and exploitation ABC and speed up the convergence rate. The minimization of integral square error (ISE) is considered as an objective function to manipulate the gain values of the PI controller. The system tested with MATLAB simulation results are implemented in the hardware circuit with the same set of parameters. The proposed hardware system is designed with the Cyclone-IV EP4CE30F484 FPGA controller and the gain value for this proposed controller is fed from the simulation results tested with ABC and EABC algorithm. The results obtained from the hardware setup is compared with simulation results. The experimental result enhanced the performance of THD of source current, settling time and percentage peak overshoot of DC Link voltage.

Keywords Single phase Shunt Active Power Filter · Artificial Bee Colony algorithm · Harmonics · Power quality · Total harmonic distortion

1 Introduction

In recent power electronic industries, current harmonics are highly occurred due to the automatic switching sequence using power electronics elements. Harmonics are major constraints in power electronics systems, causes from loads such as UPS, microwave oven and conversion equipment in drives based industries. These types' problems in switching elements affect the voltage and current waveforms of any designed system. This leads to less power quality, poor power factor, induces thermal effect in equipment, malfunctioning of protective equipment's also it cause much interference in the telecommunication system. Many researchers were focused on harmonic reduction and the response of the designed system with power electronic equipment with their electrical parameters such as voltage, current and power factor disturbance [1–3].

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Researchers contributed their work in the field of Active and passive filter to overcome the problems of harmonics and power electronic system. Among these passive filters based harmonic control are assessed by the least number of researchers due to selective Traditionally, SAPFs are controlled using the standard DC-link PI control approach in that proportional-integral (PI) controllers are preferred due to their simple design and fast response. The design of the PI controller relates to tuning proportional and integral gains which are needed to tune properly to obtain better performance. The major challenge in Control design is that there exists no well-established systematic approach for tuning the controller PI gains and hence an optimal gain value is difficult to obtain. This is quite an interesting and ill-defined research problem.

The active power filter concept is initially proposed in [4]. The filter can be designed for single-phase or three phases. The three-phase loads are used in industries whereas single-phase loads are normally used in household appliances.

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To get suitable PI gain values Trial and error search or mathematical approaches were used [7, 9]. However, the approaches present poor response in addition to being complex and time-consuming work.

So researchers have a focus on using a global optimization algorithm for PI tuning. In the contest, various global optimization techniques were used to optimize the PI controller gains. Which includes ACO technique [11–13], particle swarm optimization (PSO) [14–17] ABC Algorithm [18–21], Bacterial Foraging (BF) technique [22, 23], Genetic Algorithm (GA) [24], Gravitational search [25] Adaptive Tabu search and Genetic Algorithm [26], Enhanced Bacterial foraging approach [27], are employed.

Among them, the ABC optimization algorithm believed to excellent global optimization algorithm developed by Karaboga [17]. When compared to other algorithms (e.g., GA, ACO and ABC). Because it runs faster at the searching speed, wider exploration and in-depth exploitation searching ability [12]. The main elements of the ABC algorithm are honey bees foraging which consist of three main groups of bees namely employed, onlooker and scout bees. The number of employee bees makes half of the population size of the bee colony, and the reaming includes onlooker bees.

In [17, 18] authors proposed an ABC optimization algorithm for unconstrained optimization in 2005. The ABC algorithm has captured more attention among the researchers due to its simplicity, fewer parameters, low computational cost and easier to implement.

In [29], an ABC algorithm based PMSM drive has been proposed. Author proposes the Optimal Reactive Power Dispatch (ORPD) for real power loss minimization and voltage stability enhancement using Artificial Bee Colony (ABC) Algorithm [30]. Enhanced ABC based PID Controller for Nonlinear Control Systems is proposed by Kaliappan [31]. Haluk Gozde presents the Automatic Generation Control in two area system using Artificial Bee Colony (ABC) algorithm [32]. In [33] author proposes a novel controller design method based on using artificial bee colony (ABC) algorithms for an unstable nonlinear continuously stirred tank reactor (CSTR) chemical system. Bagis [34] presented a PID controller design method for Higher Order Oscillatory Systems by using an ABC approach.

In [20] ABC based optimal-controlled SAPF to provide reactive power and harmonic compensation. The ABC based SAPF is proposed for harmonic compensation and results were compared with conventional and Genetic Algorithm (GA) based SAPF [21].

However, the classical ABC algorithms exhibit a slow convergence rate and poor exploration because the abandoned food source is replaced randomly.

So in order to improve the exploration rate and speed up the convergence, the Enhanced ABC algorithm is proposed. In the EABC algorithm, the replacement of the food source is carried out through the Adaptive Real coded Genetic Algorithm (A-RGA) which will improve the exploration rate.

This combines the advantages of the GA algorithm in the global search and the artificial bee colony (ABC) algorithm in fine search, is presented to optimize the gain values of the PI controller in the SAPF system.

The proposed work of shunt active filter configuration developed with the EABC algorithm to set the parameters for the gain values of the control system. The proposed algorithm having the ability to tune the gain values with least number of parameters, the memory space allotted for the control algorithm is low when compared with the conventional schemes controlling algorithm, the performance indices used in the PI controller is decided by the performance of different indices such as ISE, IAE, ITAE, ITSE Among these indices ISE is providing better performance with SAPF, the benefits of ISE based optimization brings out the better performance with a dynamic response [41].

Some positive aspects of proposed EABC namely it is easy to implement to tune the gain values with fewer parameters and the memory capability of the proposed method is more effective than the other methods.

The common performance indices used by the PI controller for DC link voltage regulation are the Integral of Absolute Error (IAE), Integral of Squared Error (ISE), Integral of Time Multiplied Absolute Error (ITAE) and Integral of Time Squared Error (ITSE) [10]. The authors in [14] investigated the application of GA in optimizing the PI controller by using the ITAE cost function.

In [13] the Artificial Bee Colony (ABC) algorithm to tune PI and PID controller by investigating the controller's performance on each criterion—IAE, ISE, ITAE and ITSE [13]. In [12] authors presented the implementation of ACO to optimize the parameters of the PI controller based on the ISE cost function. So in this manuscript, ISE is considered as cost function to improve the dynamic performance of SAPF. This manuscript consists of five parts.

Initial starting with an introduction, the discussion about harmonic current extraction technique and current control technique are also presented in Sects. 2. The detailed description of ABC, Enhanced ABC are described in Sect. 3. In Sects. 4 and 5, discussion on simulation and Experimental results are present. At last, the concluding observations are drawn.

The main contribution of this manuscript over previous research work are presented as follows:

- A single objective technique based on ISE is taken into account as a cost function for the minimization of THD and improves the dynamic performance of SAPF.
- A Enhanced ABC algorithm is proposed and convergence characteristics are improved by integrating real coded genetic algorithm (RGA) with Artificial Bee Colony (ABC) algorithm.
- A detailed analysis of the proposed EABC PI, ABC PI and Conventional PI controller based SAPF is done in MATLAB/Simulink system environment and real-time experimentation with Cyclone-IV EP4CE30F484 FPGA controller-based SAPF setup.
- The proposed method finally will recognize and find an optimal solutions for minimizing dynamic objective functions like THD, Percentage peak overshoot (% M_p), and improve the DC link voltage settling time (V_{dc}_T_s).

2 Reference Current Extraction and Current Control

The complete Single-phase SAPF model is illustrated in Fig. 1. The SAPF control strategy mainly depends on two control approaches such as reference current extraction and current control. The extraction algorithm consists of V_{dc} of voltage source inverter, source voltage, source current and loads current. Initially by comparing V_{dc} with its reference value ($V_{dc,\ ref}$) then the voltage error is fed to a PI voltage controller. The controller output is considered as reference supply current peak value ($I_{sp,\ ref}$). Subsequently, a unit amplitude of source voltage ($I_{s,\ ref}$) is multiplied by a controller output.

$$i_{s,ref} = k * u = k * \sin \omega t \tag{1}$$

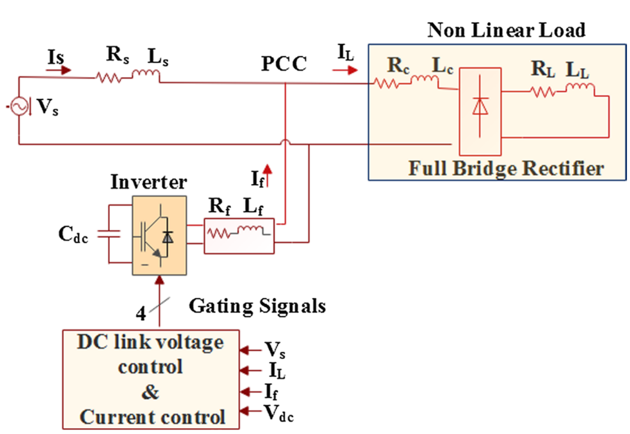


Fig. 1 Configuration of single phase SAPF system

The value of k is obtained by PI controller which can be expressed ass follows

$$k = k_p(V_{dc,\ ref} - V_{dc}) + k_i \int_0^t (V_{dc,ref} - V_{dc})dt \tag{2}$$

where V_{dc} is the DC is link voltage, K_p and K_i are controller gain values. Then the load current added with the supply current reference which gives filter reference current. Finally, the filter reference current and VSI output current signal are fed to the model predictive current controller to generate gating signals for SAPF [28].

3 Hybrid ARGA–ABC Algorithm

In order to find out the optimal solution (PI gain values) of the SAPF system with some system constraints, many evolutionary algorithms has been used in the literature. In this section, ABC and Adaptive Real coded Genetic Algorithm based ABC algorithms are used for minimizing the cost function ISE.

3.1 Implementation Of Artificial Bee Colony Algorithm For Optimal PI Gain Selection

Artificial Bee Colony (ABC) optimization is a metaheuristic algorithm based on swarm intelligence which is developed by the author in (2012) to solve multidimensional optimization problems. By comparing the algorithm with other well-known techniques such as the ACO, GA, and DE, the ABC algorithm has many advantages, which include simple structure, require fewer control parameters, computational efficiency, and inherent convergence agility.

The main elements of the ABC algorithm are honey bees foraging which consist of three main groups of bees namely employed, onlooker and scout bees. The number of employee bees makes half of the population size of the bee colony, and the reaming includes onlooker bees. Initially, the Employee bee examines the availability of food around the food source in their memory, in the meantime employee bee send their information about the food to onlooker bees. The onlooker bees tend to choose worthy food sources which are founded by the employed bees, then additional search the foods about the selected food source. Scout bees are translated from a few employed bees, which abandon their food sources and search for new ones.

Similar to the other population-based algorithms, ABC is an iterative process. The detailed steps of the ABC algorithm for optimal PI gain selection is described as follows:

Steps for ABC PI Tuning method to SAPF.

Step 1: All PI Tuning parameters are initialized
Choose the upper and lower bound for PI controller parameters (K_p, K_i)
Employed bees + onlooker bees= 20
Number of food sources=10
Maximum Iteration =1000
Trail limit=100
Calculate the objective function value and fitness value.

Step 2: Initially reset trial counters
If the value is high reset the food source into the bounds of tuning parameters
Calculate the objective and fitness value Finalize the PI parameters

Step 3: EMPLOYED BEE PHASE
Produce mutant solutions based on following relationship

$$x_{i,j} = x_{\min,j} + rand\,(0,1)\,(x_{\max,j} - x_{\min,j})$$

Measures the distance hive and food source (ISE)using equation

$$ISE = \int_0^t \left(e_r^2 * t\right) dt$$

A greedy search is applied between current solution "i" and with its variant
If the mutant solution is better than the current solution i, replace the solution with the mutant and reset the trial counter of solution i
if the solution i can not be improved, increase its trial counter
A food source is chosen with the probability which is proportional to its quality. The value of the probability is given by

$$\rho_i = \left(\left(\frac{\alpha(fit_i)}{\max\,(fit_{overall})}\right) + \beta\right).$$

Step 4: ONLOOKER BEE PHASE
Calculate the new solutions

$$v_{i,j} = x_{i,j} + \Phi_{i,j}(x_{i,j} - x_{k,j})$$

If the controller parameters are out of margin, shifted to the margin
if the mutant result is better than the current result, update the solution and initialization iteration and generate new PI parameter using following equation
Find out minimum ISE objective function
if the solution "I" cannot be improved, increase its trial counter
A food source is chosen with the probability which is proportional to its quality. The probability is defined as follows

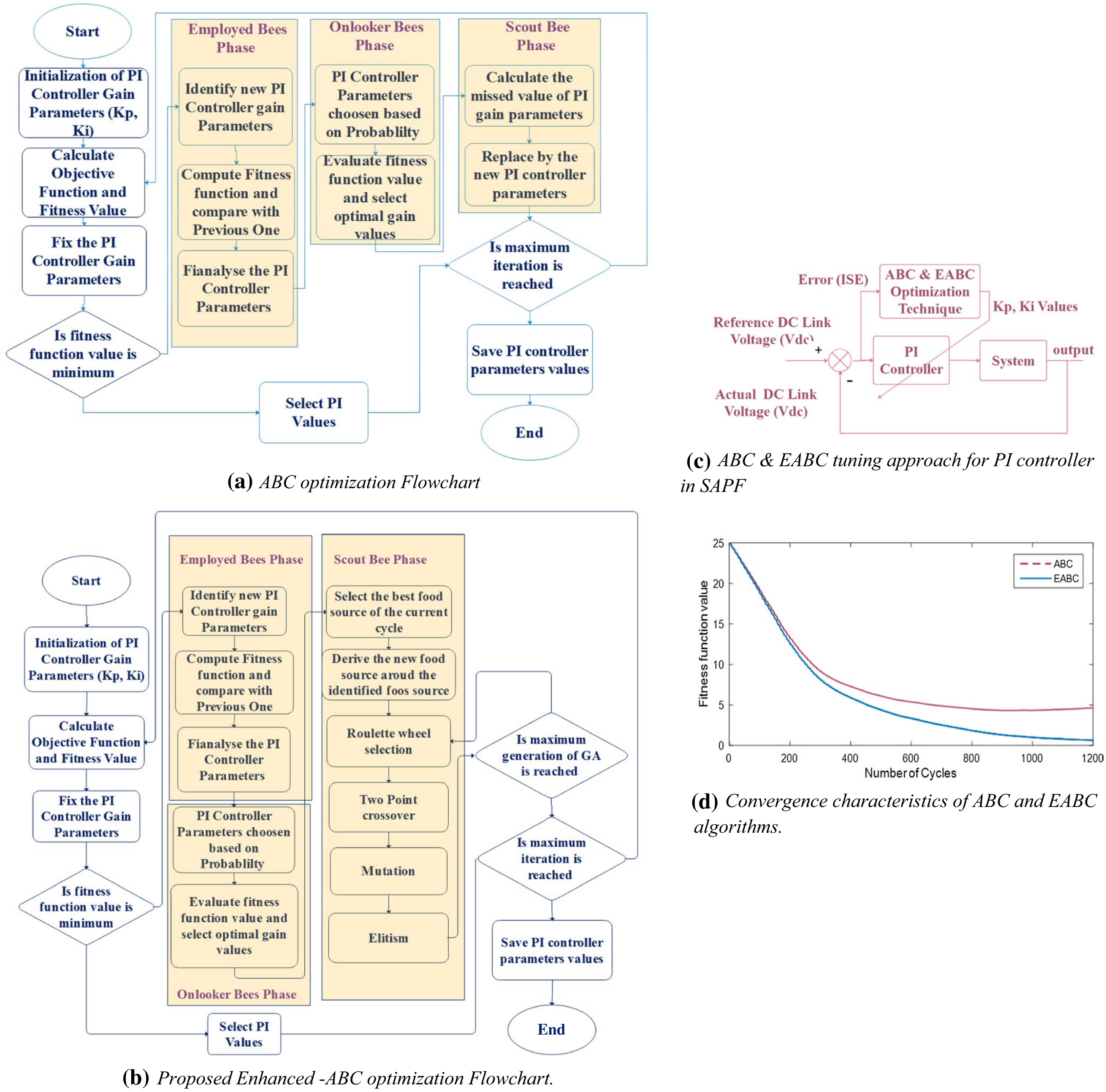
$$\rho_i = \left(\left(\frac{\alpha(fit_i)}{\max\,(fit_{overall})}\right) + \beta\right)$$

Step 5: SCOUT BEE PHASE
If employed bee is not able to attain best PI parameter, shift the employed bee to new region and then iteration is carried out as shown in Equation (1).

Step 6: Repeat Steps 2, 3 and 4 until get the best solution of controller parameters and Terminate the iterative process, when there is no any further execution of iteration.

3.2 Implementation of Enhanced Artificial Bee Colony Algorithm For Optimal PI Gain Selection

The detailed explanation of the Adaptive Real coded Genetic Algorithm based ABC algorithm is presented in this section. In conventional ABC the abandoned food source is replaced randomly. The random food source may not yield a good nectar value. To improve the food source quality the modified ABC utilizes a novel guided approach to find



(a) *ABC optimization Flowchart*

(b) *Proposed Enhanced -ABC optimization Flowchart.*

(c) *ABC & EABC tuning approach for PI controller in SAPF*

(d) *Convergence characteristics of ABC and EABC algorithms.*

Fig. 2 **a** ABC optimization flowchart. **b** proposed enhanced-ABC optimization flowchart. **c** ABC and EABC tuning approach for PI controller in SAPF. **d** Convergence characteristics of ABC and EABC algorithms

Table 1 ARGA parameters

	Initial values
Population size P_s	10
Mutation rate M_r	0.2
Number of generations N_g	20
Crossover rate C_r	0.8
Elite count E_c	1

new food sources to replace the abandoned food sources. The replacement of the food source is carried out through a Bio-inspired optimization technique. The new food source is identified from a group of food sources that are derived near the best food source of the current cycle. The Adaptive Real coded Genetic Algorithm (A-RGA) is employed on the derived food source group and through the genetic operators, the optimized food source is identified. And the identified food source is used to replace the abandoned food source. In normal GA the crossover rate and mutation rate is fixed at a constant value [0.8, 0.2] throughout all generation, we propose adaptive A-RGA method in which the GA adjust its crossover and mutation rate iteratively in each generation cycle. The proposed algorithm starts with a very minimum crossover rate which is increases it gradually and the mutation rate started with a high rate which is decreased gradually there by the convergence towards finding the scout bee food sources is increased.

The pseudo-code of conventional ABC and algorithm are shown in below. The flowchart illustration of ABC and EABC algorithm with optimal PI gain value selection of SAPF are shown in Fig. 2a and b. The parameter's value chosen for the ABC has been given in Table 1.

The Hybrid ABC has the following steps:

Steps for EABC PI Tuning method to SAPF

The steps 1-4 are similar to conventional ABC algorithm

Step 1: All PI Tuning parameters are initialized

Step 2: Reset trial counters

Step 3: Employed Bee Phase

Step 4: Onlooker Bee Phase

Step 5: Scout Bee Phase

If employed bee is not able to attain best PI parameter, shift the employed Bee to new region by using the following steps.

The genetic algorithm parameters are initialized to parameters listed in the Table.

Random initial population is created within the bounds of the PI parameters.

Initially the Mutation rate is kept at Mr=0.8 and Crossover rate $C_r = 0.2$

Step 6: Calculate the fitness value of each chromosomes and select the parent Chromosomes based on the roulette wheel selection. Number of Mutation kids $M_n = M_r * P_s$ and create M_n number of mutation kits

Number of crossover kits $C_n = C_r * C_s$ and perform two point

New population = {crossover kits, mutation kits, Elite kits}

Step 7: Update the crossover and mutation rate

$$C_n = C_r + ((1 - C_r) * \frac{1}{N_a})$$

$$M_r = M_r - \frac{1}{N_a}$$

Step 8: Repeat Steps 2, 3 and 4 until get the best solution of controller parameters and Terminate the iterative process, when there is no any further execution of iteration.

This novel modification increases the convergence rate and the quality of the food source identified by the scout bee.

Table 2 Performance assessment of single phase SAPF for conventional PI, ABC-PI, ACO-PI, BF-PI and EABC-PI

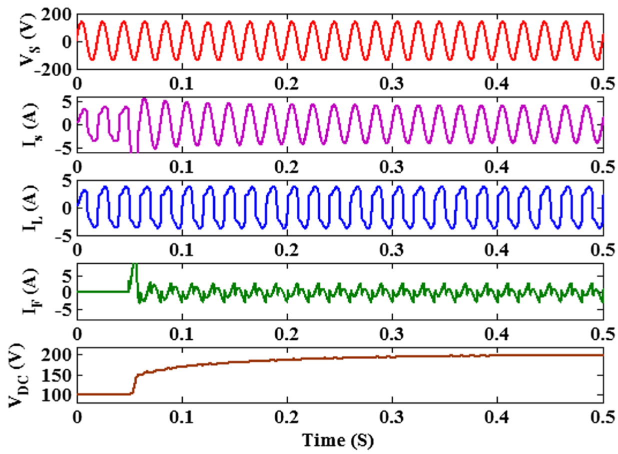
Performance indices	Type of controller				
	Conv. PI	ABC-PI	EABC-PI	ACO-PI	BF-PI
Kp	0.105	0.25	0.32	0.24	0.21
Ki	0.65	6.9	4.3	5.6	6.1
Vdc_Ts (ms)	670	122	105	128	132
%THD	3.8	3.56	3.53	3.58	3.6
%Mp	0	4.857	1.1859	5.213	5.84
ISE	154.2	61.98	60.42	62.93	62.59
IAE	6.144	1.8800	1.616	1.796	1.869
ITAE	0.9433	0.3488	0.3342	0.3580	0.3615
ITSE	8.248	0.6152	0.5265	0.5896	0.6216

Table 3 Single-phase SAPF characteristics

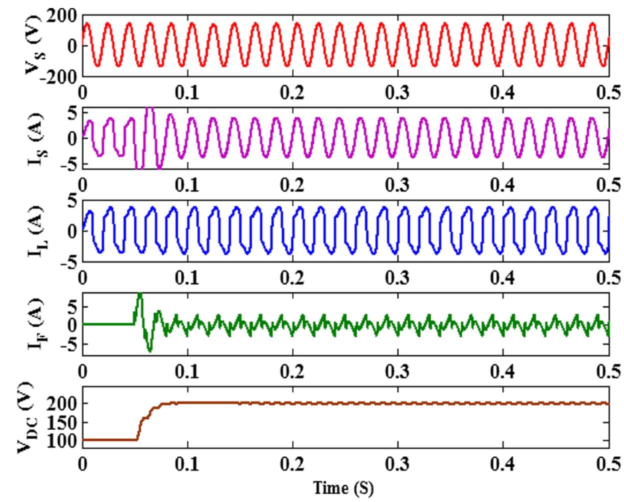
Parameters	Symbol	Value
Supply voltage	V_s	100 V (rms)
Source resistance and inductance	R_s and L_s	0.1Ω & 1mH
Supply frequency	F	50 Hz
DC link voltage	V_{dc}	200 V
DC link capacitance	C_{dc}	800 µF
Filter resistance and inductance	R_f & L_f	0.01Ω & 5 mH
Average switching frequency	F_{sw}	10 kHz
AC side resistance	R_c	0.01Ω
AC side inductance	L_c	1 mH
DC side resistance	RL_{dc}	28 Ω
DC side inductance	LL_{dc}	160 mH

Table 4 Statistical analysis of the convergence curve

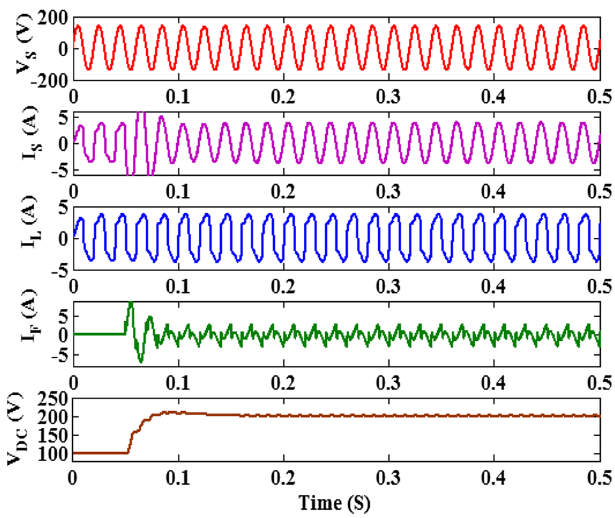
Parameter	ABC	EABC
Mean	8.108	6.086
Median	5.371	3.339
Standard deviation	5.492	6.475
Minimum value	4.316	0.651
Maximum value	24.99	24.99



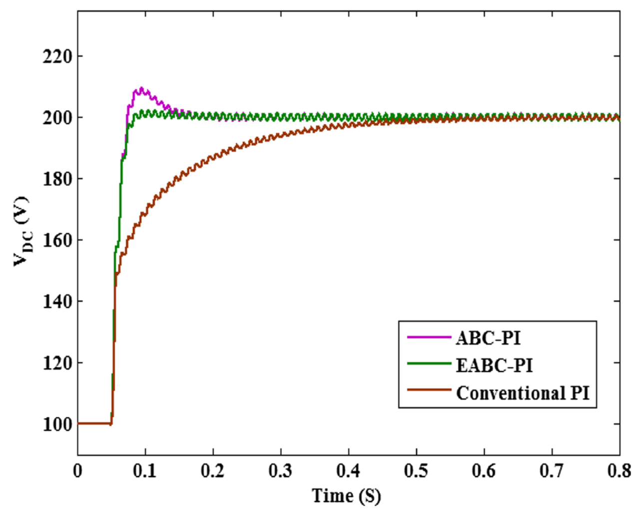
(a) *V_s, I_s, I_L, I_f, and V_{dc} of conventional PI controller*



(c) *V_s, I_s, I_L, I_f and V_{dc} of EABC Controller*



(b) *V_s, I_s, I_L, I_f and V_{dc} of ABC PI controller*



(d) *V_{dc} during Switch on response conventional PI, ABC-PI and EABC- PI.*

Fig.3 **a** V_s, I_s, I_L, I_f, and V_{dc} of conventional PI controller. **b** V_s, I_s, I_L, I_f and V_{dc} of ABC PI controller. **c** V_s, I_s, I_L, I_f, and V_{dc} of EABC Controller. **d** V_{dc} during Switch on response conventional PI, ABC-PI and EABC- PI

3.3 Formulation Of Objective Function

The difference between references DC-Link voltage and actual DC link voltage is used as an input signal for the PI controller. The tuned PI controller gains are used in single-phase SAPF as shown in Fig. 2c. The gain values of the PI controller states the voltage response and damping factor, the minimum value of gains for the PI controller is verified in Ref. [10].

SAPF is a highly nonlinear system and mainly depends on system parameters and load conditions. Hence calculated PI controller parameters don't meet the system requirement in all conditions. So in this proposed work ABC optimization is used to optimize the gain values of PI Controller. The ISE error criterion function exhibits less overshoot and faster settling time when compare to IAE, ITAE, and ITSE.

The ISE error criterion is used as the objective function "J" for optimization is represented by the following equation

$$J = ISE = \int_{o}^{t} \left(e_r^2 * t\right) dt \tag{3}$$

$$e_r = V_{dc,ref} - V_{dc}$$

Table 5 Summarises the simulation and practical test results for conventional PI, ABC PI and EABC-PI based SAPF including THD, settling time and peak over-shoot

Controllers	Source current THD before and after compensation (%)		Settling time (T_s) and peak overshoot			
			Switch on response		Transient response	
	Before compensation	After compensation	T_s	M_p	T_s	M_p
Simulation results						
Con PI	28.47	3.8	670	0	600	4
ABC-PI	28.47	3.56	122	4.857	185	2.032
EABC-PI	28.47	3.53	105	1.186	113	2.225
Hardware results						
Con PI	24.9	3.9	1250	0	1200	17.5
ABC-PI	24.9	3.8	310	22.5	320	12.5
EABC-PI	24.9	3.8	240	12.5	215	10.5

where e_r is the difference between reference DC link voltage $V_{dc,ref}$ and actual DC link voltage V_{dc} and t is the time.

4 Simulation Results and Discussions

The modeling and optimization of the SAPF system is carried out using MATLAB software. The MATLAB simulink model of single-phase SAPF is developed and executed to compensate for the reactive power and harmonic compensation. This section presents the performance analysis of single-phase SAPF using conventional PI, ABC PI, and Enhanced ABC PI controllers. The proposed and conventional algorithms have been coded in the Matlab programming environment. Off line tuning technique has been used to find the optimal gain of the controller.

The lowest value of the objective function is estimated and convergence characteristics are representing the best ISE at each iteration during the optimization process. The proposed Enhanced ABC algorithm is compared with ABC algorithm as shown in Fig. 2d. From the convergence characteristics, it is clear that the proposed method converges very quickly. The low mean value indicates the good quality of the food source produced in each iteration. All statistical parameters of EABC are better than that of EABC.

The proposed EABC based optimum controller outperforms the conventional tuning such as ABC [11], BF and ACO [12] algorithms and from Table 2 it is clear that the very minimum value of THD and ISE is achieved by the proposed design. The corresponding optimized PI gain values found to be 0.32 and 4.3 respectively. A design specification of single-phase SAPF is given in Table 3.

The statistical analysis of the convergence curve is shown in Table 4.

Before compensation, the THD for the source current is 28.47%. After connecting single-phase SAPF to the Point of Common Coupling (PCC) the harmonics are eliminated from supply current. The performance of conventional PI, ABC PI, and EABC PI are evaluated in terms of its dynamic performance analysis for the two different scenarios such as switch on response and transient response.

Scenario 1—Switch on Response The single-phase SAPF is switched on at 0.05 s. The supply voltage (V_s), supply current (I_s), load current (I_L), filter current (I_f), and V_{dc} for Conventional-PI and ABC-PI and EABC-PI are shown in Fig. 3a–d. From the results, the V_{dc} under conventional PI controller shows that the performance suffers from a relatively long settling time of 670 ms. Whereas the maximum overshoot and the settling time were improved using the ABC (ISE)-PI to 4.857 and, 122 ms, EABC(ISE) –PI to 1.1859 and, 105 ms, respectively.

The peak overshoot and settling time were minimum using ABC (ISE) PI and EABC (ISE)-PI. In all the three controllers % THD is within the IEEE limit. Comparing the performance of three controllers EABC PI gives better results in terms of minimum peak overshoot and less settling time (Table 5).

Scenario 2—Transient response The single-phase SAPF is switched on at 1.2 s during the transient response. During the transient response, the load changed from 28 ohms to 40ohm. Figure 4a–d depicts simulation results of the supply voltage (V_s), supply current (Is), load current (IL), filter current (If), and V_{dc} for Conventional-PI, ABC-PI, and EABC-PI respectively. In a conventional PI controller, longer settling time of 600 ms and critical overshoot 4 V of V_{dc} were obtained due to a sudden variation of the load as shown in Fig. 6. The ISE objective function based ABC-PI and EABC–PI controller's performance shows superior performance in terms of compensating the load variations and V_{dc} remains equal to its V_{dc} set value. The settling time of V_{dc} by the ABC PI is 185 ms and EABC PI is 113 ms.

Also, it is confirmed that the EABC-PI controller gives better harmonics and reactive power compensation and with a fast transient response. The source current THD is nearly

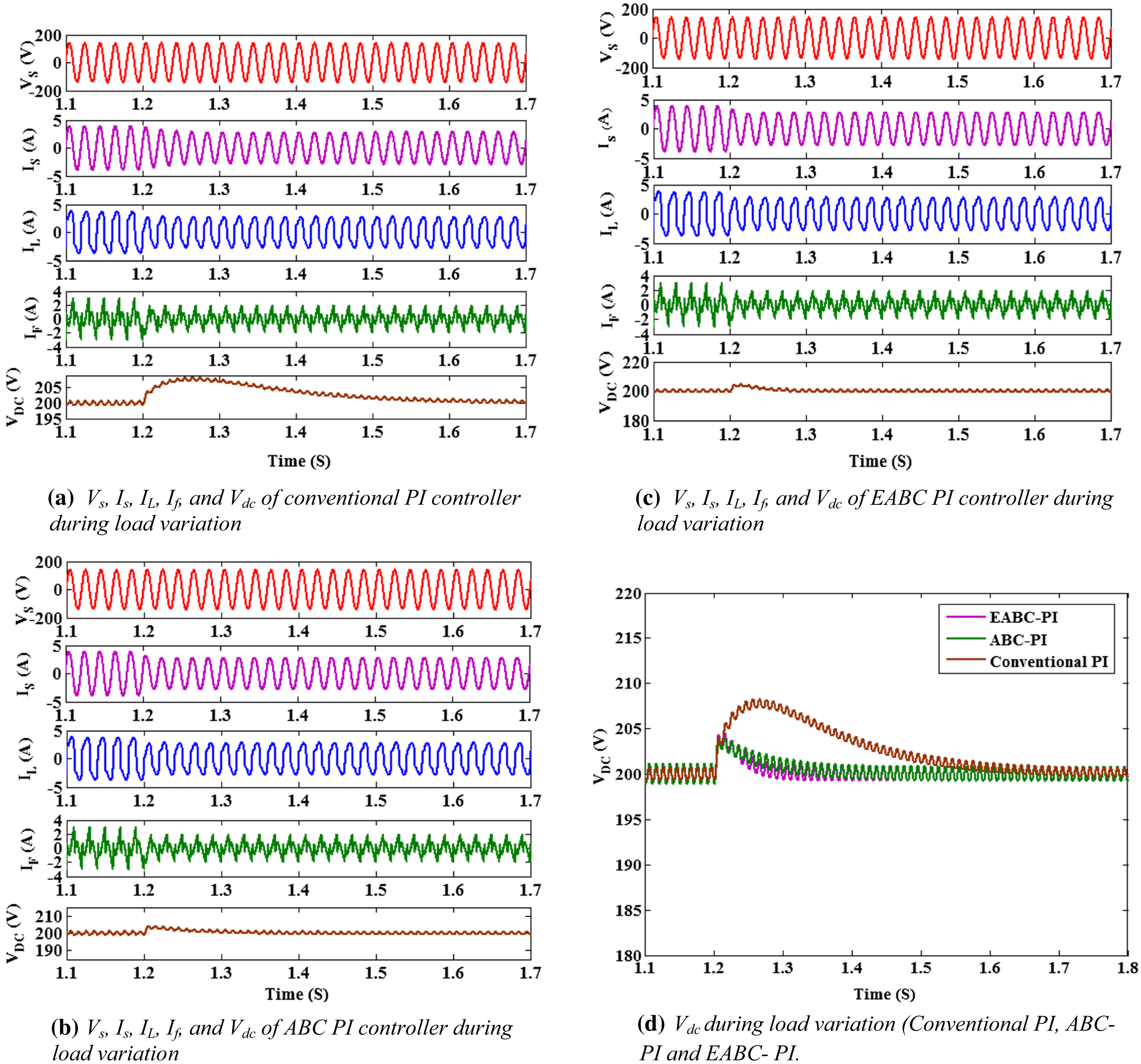


Fig. 4 **a** V_s, I_s, I_L, I_f, and V_{dc} of conventional PI controller during load variation. **b** V_s, I_s, I_L, I_f, and V_{dc} of ABC PI controller during load variation. **c** V_s, I_s, I_L, I_f, and V_{dc} of EABC PI controller during load variation. **d** V_{dc} during load variation (conventional PI, ABC-PI and EABC- PI

3.8% for conventional PI, 3.56% in the case of ABC (ISE) optimized PI controller and 3.53% for EABC based PI controller. The detailed comparative analysis of three controllers is shown in Table 2.

The proposed technique outperforms the conventional PI and ABC PI by considering all performance indexes:

Settling time (T_s) is improved, T_s is found to be 105 ms (122 ms for ABC PI and 670 ms for conventional PI).

The peak overshoot is reduced to 1.1859 V (4.852 V for ABC PI). Source current THD is reduced from 28.47% (Without SAPF) to 3.8% (Conventional PI), 3.56% (ABC-PI) and 3.53% (EABC-PI). From Table 4 and Figs. 5, 6, the main contribution of this manuscript as follows: (1) improved settling time; (2) reduced peak overshoot; (3) better source current THD.

5 Experimental results and Discussions

To validate the work in various cases similar to those effectuated in the simulation a prototype model (1.5 kW) is used the same load configurations as in the simulation work with a supply voltage of 100 V (141 V_{peak}),50 Hz. Which

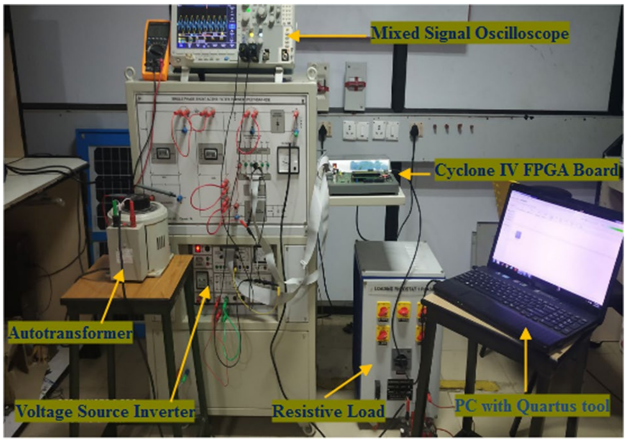
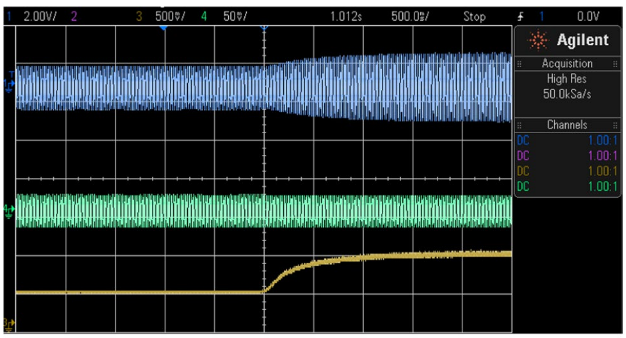
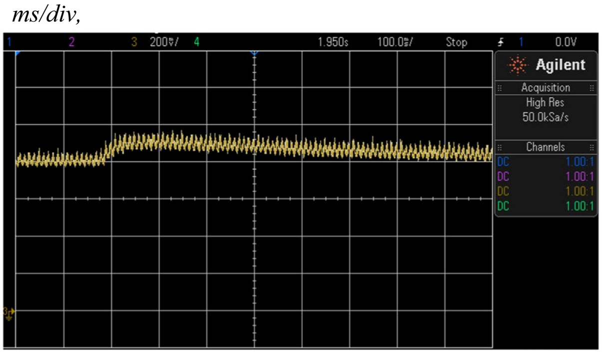


Fig. 5 Photograph of the developed single-phase SAPF prototype

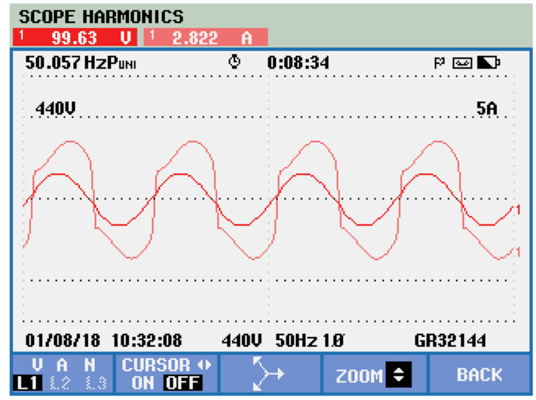


(a) *Conventional –PI Switch on response (I_s, I_L, V_{dc}) with I_s= 5A/div, I_L= 10A /div, V_{dc} = 200 V/div, time 500 ms/div,*

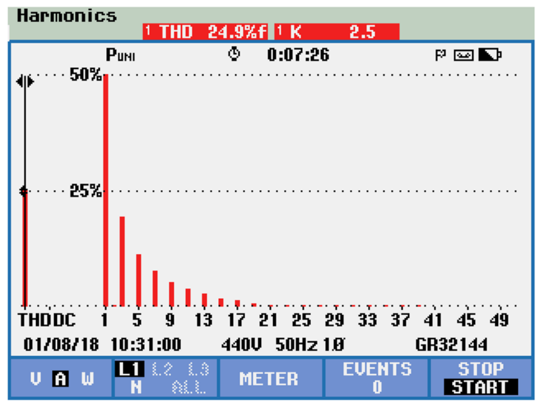


(b) *Conventional –PI Transient response (V_{dc}) with V_{dc}= 50 V/div, time 500 ms/div.*

Fig. 6 **a** Conventional-PI Switch on response (I_s, I_L, V_{dc}) with I_s = 5A/div, I_L = 10A /div, V_{dc} = 200 V/div, time 500 ms/div, **b** conventional-PI Transient response (V_{dc}) with V_{dc} = 50 V/div, time 500 ms/div



(a)

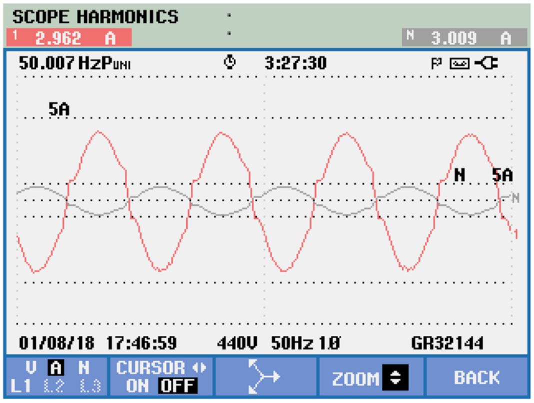


(b)

Fig. 7 Power quality analyser measurements before filtering: **a** supply voltage and current waveform, **b** THD of source current

is developed by using a single-phase autotransformer and the DC link capacitor voltage was set to 200 V_{dc}. Figure 5 illustrates the real photo of the laboratory setup. A Cyclone-IV EP4CE30F484 FPGA controller was used to implement all the algorithms such as a PI algorithm for reference current extraction and MPC algorithm for generating proper gating signals to the VSI of SAPF. VSI was built using four IGBT switches from a Mitsubishi Intelligent Power Modules (IPMs), with protection and gate drive circuits. And also it consisting of a full-wave diode rectifier feeding a resistor series with an inductor.

The load changes are obtained by connecting or disconnecting a parallel load. The source current, load current and filter current are sensed using a current transformer (CTs), Supply voltage and DC-link capacitor voltage are sensed using LEM voltage transducer (LV25-P). The sensed signals are given to A/D converters of the DSP card of the FPGA board. For Hardware realization the complete control algorithm is run at every 10 µs and hence an average switching frequency of VSI of SAPF is 15 kHz is obtained. Before compensation, the supply current is distorted. It shows that the source current waveform with high harmonics. After connecting SAPF to the PCC source current should be nearly sinusoidal and THD for the source current is reduced from 24.9 to 3.8%. The harmonic spectrum of the source current before and after compensation obtained from the Fluke 434 power quality analyzer, are shown in Figs. 7, 8, 9, 10.



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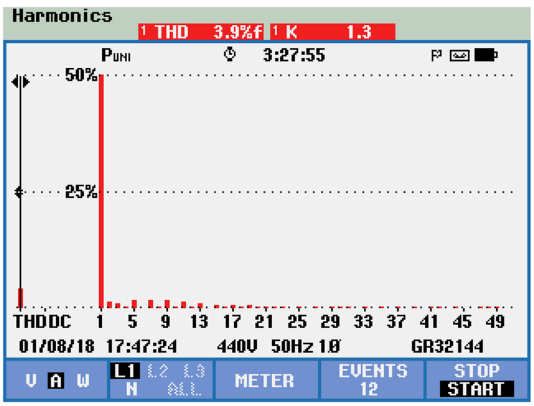
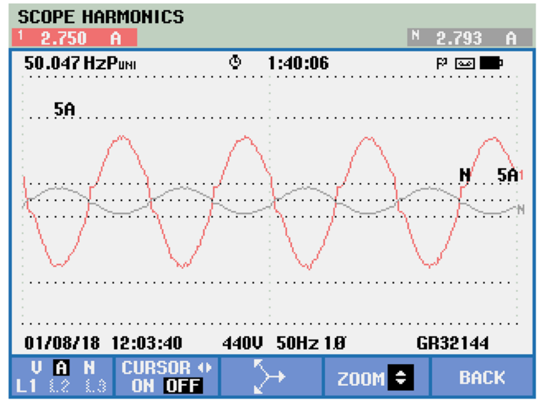


(b)

Fig. 8 Power quality analyser measurements after filtering using Conventional PI: **a** Source current waveform **b** THD of source current



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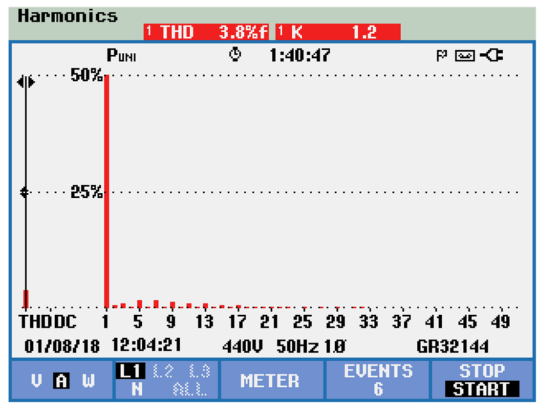


(b)

Fig. 9 Power quality analyser measurements after filtering using ABC PI: **a** Source current waveform **b** THD of source current

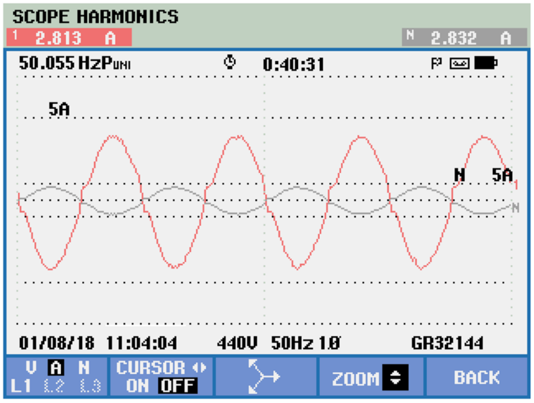
Measured currents and DC link voltage waveforms during steady and transient state conditions are shown in Figs. 6, 11, 12. All of these waveforms were captured using an Agilent DSO-X 3014A Digital oscilloscope.

The supply voltage, supply current and harmonic spectrum of supply current are shown in Fig. 9. The THD before SAPF connected to PCC is found to be 24.9%. It shows that the source current waveform as the same as load current with high harmonics.

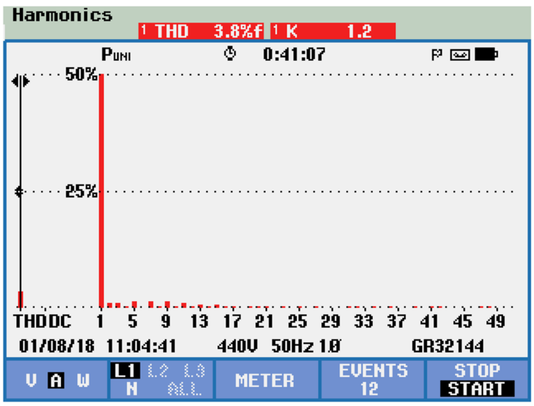
Figure 6a and b illustrate the dynamic response such as switch on response and transient response of conventional PI gain values. During switch response, the DC link voltage reaches its steady-state value of 200 V within 1250 ms as shown in Fig. 6a. The transient response (Increasing load) has been obtained and shown in Fig. 6b. This illustrates that high transition of source current, filter current and DC link voltage from the lower value to higher value and vice versa. The Source current waveform and harmonic spectrum of source current are shown in Fig. 8a and b. The switch on the response of ABC-PI is SAPF shown in Fig. 11a. The DC link voltage to reach its steady-state value of approximately 310 ms. The THD and Peak overshoot is found to be 3.8% and 22.5 V respectively. The THD spectrum of source current as shown in Fig. 9a and b. During transient response conditions, the settling time and peak overshoot are found to be 320 ms and 12.5 V for increasing load as shown in Fig. 11b.

Figure 12a and b illustrate the performance of single-phase SAPF for EABC optimized PI. During the switch on response, the THD and Peak overshoot is found to be 3.8% and 12.5 V respectively. The DC link voltage to reach its steady-state value of approximately 240 ms. The THD spectrum of source current as shown in Fig. 10a and b. During transient response condition the settling time and peak overshoot are found to be 215 ms and 10.5 V for increasing load as shown in Fig. 12b.

From the implementation results, it is seen that by using conventional PI the settling time of DC link voltage is 1250 ms respectively; it was reduced to 310 ms when using ABC- PI, But when integrating RGA with ABC-PI Controller, the settling time is reduced to 240 ms, which is satisfactory. The EABC-PI shows faster, low overshoot and reaches

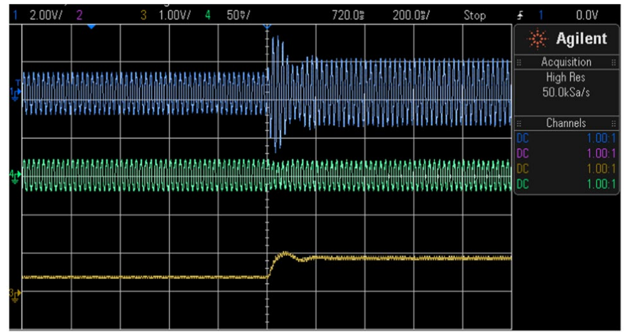


(a)

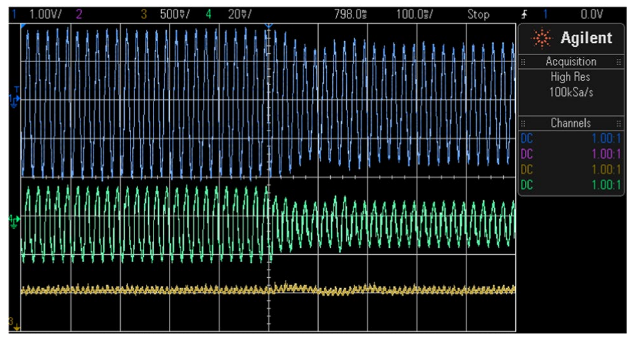


(b)

Fig. 10 Power quality analyser measurements after filtering using EABC PI: **a** Source current waveform **b** THD of source current



(a) *ABC-PI Switch on response (I_s, I_L, V_{dc}) with I_s= 5A/div, I_L= 10A /div, V_{dc} = 200 V/div, time 200 ms/div.*



(b) *ABC –PI Transient response (Increased load) (I_s, I_L, V_{dc}) with I_s= 2.5 A/div, I_L= 5A /div, V_{dc} = 100 V/div, time 200 ms/div.*

Fig. 11 **a** ABC-PI Switch on response (I_s, I_L, V_{dc}) with I_s = 5A/div, I_L = 10A /div, V_{dc} = 200 V/div, time 200 ms/div. **b** ABC –PI Transient response (Increased load) (I_s, I_L, V_{dc}) with I_s = 2.5 A/div, I_L = 5A /div, V_{dc} = 100 V/div, time 200 ms/div

its reference value within short response time and the low overshoot.

6 Conclusion

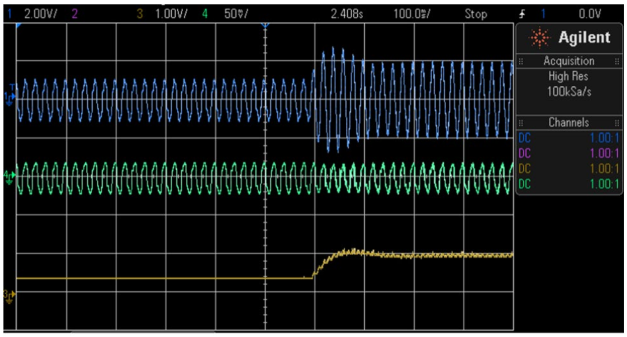
In this proposed system a novel Hybrid ABC optimization algorithm is applied to optimize the gain values of the PI controller and tested with simulation and hardware unit.

The simulation and experimental results of ABC and EABC are compared and validated with the conventional PI control scheme. The proposed EABC algorithm provides better performance in generating cost with the least number of iteration and population when compared with other optimization algorithms. The designed system provides a better accuracy due to the optimized ABC and EABC based SAPH tested with output parameters like THD of source current, Settling time and peak overshoot of DC-link voltage.

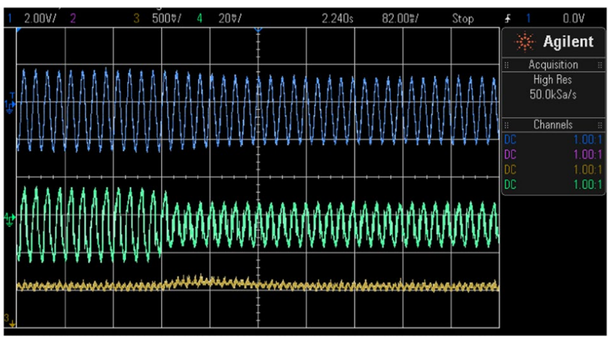
The dynamic performance of the EABC based single phase SAPF is confirmed and highlighted using the following inference made from the simulation and hardware results.

The succeeding conclusions have been ended from the experimental study.

1. Effectively compensate for the current harmonics and reactive power generated by the NLL.
2. Under load changing condition the source current becomes sinusoidal and in phase with source voltage.
3. DC link capacitor voltage returns its reference value under all operating conditions. In addition, the proposed control technique reduces the supply current THD well below 5%.
4. The performance of the SAPF with the EABC optimized controller is found to be superior to ABC optimized PI controller and conventional PI controller for all conditions.
5. By considering the ISE as an objective function, the value of THD, settling time and peak overshoot were accumulated without any deviation.



(a) *EABC–PI Switch on response (I_s, I_L, V_{dc}) with I_s= 5A/div, I_L= 10A /div, V_{dc} = 200 V/div , time 200 ms/div.*



(b) *EABC PI Transient response (Increased load) (I_s, I_L, V_{dc}) with I_s= 2.5 A/div, I_L= 5A /div, V_{dc} = 100 V/div , time 200 ms/div.*

Fig. 12 **a** EABC–PI Switch on response (I_s, I_L, V_{dc}) with I_s = 5A/div, I_L = 10A /div, V_{dc} = 200 V/div, time 200 ms/div. **b** EABC PI Transient response (Increased load) (I_s, I_L, V_{dc}) with I_s = 2.5 A/div, I_L = 5A /div, V_{dc} = 100 V/div, time 200 ms/div

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