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Optimal tuning of PID controller for LFC of two area power system (PV-diesel) using bio-inspired optimization algorithms*

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Abstract. This work presents a methodology for optimal parameter tuning of PID controller for frequency regulation in PV-Diesel two area power system. The gains of PV generator and diesel generator are optimized in a coordinated manner by employing biologically inspired optimized algorithms like Bat Algorithm (BA) and Firefly Algorithm (FA). Transfer function model of the diesel generator is interfaced with the photovoltaic system to create a two area hybrid power system. Load frequency control (LFC) of this two area hybrid power system is achieved by minimization of the objective function at different step load perturbation using optimization algorithms. Finally an analysis is carryout based on the obtained results. The simulation/coding of the entire system is performed in the MATLAB R2010a environment.

Keywords: LFC, PV-Diesel, PID controller, bio-inspired optimization

1 Introduction

Renewable energy sources, such as photovoltaic (PV), wind energy, or small-scale hydro, provide a realistic alternative to engine-driven generators for electricity generation in remote areas. One of the most promising applications of renewable energy technology is the installation of hybrid energy systems in remote areas, where the cost of grid extension is prohibitive and the price for fuel drastically increases with the remoteness of the location[1, 3, 7]. Among various renewable energy systems, photovoltaic power generation systems (PV systems) are expected to play an important role as a clean electricity power source in meeting future electricity demands. However, the power output of PV systems fluctuates depending on weather conditions. In future, when a significant number of PV systems will be connected to the grids of power utilities, power output fluctuations may cause problems like voltage fluctuation and large frequency deviation in electric power system operation[2, 4, 11, 12]. It is observed that after connecting two networks together, the changed and produced disturbance in each of the areas cause to effect on both produced voltage and frequency of other regions. Therefore the employed controllers must be capable of quick and correct responses in each area and also have this capability among the connection path.Hence, such issues need to be addressed before installation of hybrid power systems. Very few authors addressed the LFC by tuning conventional PI and PID controllers in hybrid power systems via either trial and error based parameter selection[6] or fuzzy logic based parameter selection[9] so far. This drives the author LFC in two area PV-Diesel power systems using robust optimization algorithms which have been not explored till now.

In this paper, a diesel power generator and PV solar network have been connected to each other and then dynamic optimal parameter selection of PID controllers during the effect of a step disturbance has been investigated on the output of frequency of each network along with tile-line power. Finally, comparative analyses of obtained results have been presented.

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2 Material and methods

2.1 Two area model of hybrid power system

Changes in the power system load affect mainly the system frequency and real power. The load frequency control mainly deals with the control of the system frequency and real power. Load frequency control is the basis of many advanced concepts of the large scale control of the power system. The reasons for keeping a strict limit on the system frequency variation were

(1) The speed of the alternating current motors depends on the frequency of the power supply.

(2) If the normal frequency is 50 Hz and the system frequency falls below 47.5 Hz or goes up above 52.5 Hz then the blades of the turbine are likely to get damaged so as to prevent the stalling of the generator.

(3) The under frequency operation of the power transformer is not desirable. If we implement the PV panel alone will result in the fluctuation. At night we cannot able to access PV panel. It will also results in the voltage fluctuation. So we will incorporate PV panel with battery or other source generator. Here, PV System is considered along with diesel generator.

In two area model of PV and diesel generator system has been shown in Fig. 1. The step input in the PV system represents the change in radiation and temperature. And a diesel generator model consists of generator, governor, turbine and a reheater along with small power system. In Fig. 1, $B1$ and $B2$ represent the frequency bias parameters; $ACE1$ and $ACE2$ stands for area control errors; $u1$ and $u2$ are the control outputs form the controller; $R1$ and $R2$ represent the governor speed regulation parameters in p.u Hz; $TG1$ and $TG2$ are the speed governor time constants in sec; $\Delta PG1$ and $\Delta PG2$ are the change in governor valve positions (p.u); $TT1$ and $TT2$ are the turbine time constant in sec; $\Delta PT1$ and $\Delta PT2$ are the change in turbine output powers; $\Delta PD1$ and $\Delta PD2$ are the load demand changes; $\Delta PTieis$ the incremental change in tie line power (p.u); $KP1$ and $KP2$ stands for the power system gains; $TP1$ and $TP2$ represent the power system time constant in sec; $T12$ is the synchronizing coefficient and $\Delta F1$ and $\Delta F2$ are the system frequency deviations in Hz. The relevant parameters are given in Appendix A.

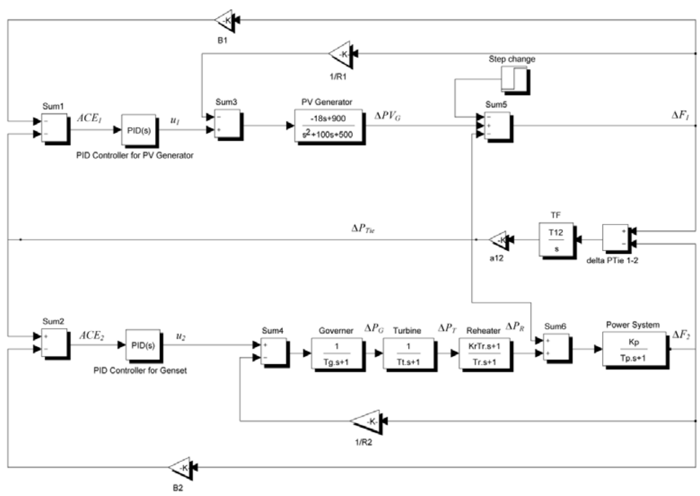

Fig. 1: Transfer function model of a two-area system of PV and diesel generator

2.2 Controller structure

To control the frequency, PID controllers are provided in each area. The structure of PID controller is shown in Fig. 1[8, 10]. The error inputs to the controllers are the respective area control errors (ACE) given by:

$$e_1(t) = ACE_1 = B_1 \Delta F_1 + \Delta P_{\text{Tie}}, \tag{1}$$

$$e_2(t) = ACE_2 = B_2 \Delta F_2 - \Delta P_{\text{Tie}}. \tag{2}$$

The output of the PID controller's $u1$ and $u2$ are the control inputs of the power system i.e. the reference power settings $\Delta Pref1$ and $\Delta Pref2$. The proportional, integral and derivative gains of PID controller are represented by KP, KI and KD respectively.

2.3 Objective function

In the design of a modern heuristic optimization technique based controller, the objective function is first defined based on the desired specifications and constraints. Performance criteria usually considered in the control design are the Integral of Time multiplied Absolute Error (ITAE), Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE) and Integral of Absolute Error (IAE). ITAE criterion reduces the settling time which cannot be achieved with IAE or ISE based tuning. ITAE criterion also reduces the peak overshoot. ITSE based controller provides large controller output for a sudden change in set point which is not advantageous from controller design point of view. It has been reported that ITAE is a better objective function in LFC studies[8]. Therefore in this paper ITAE is used as an objective function to optimize the proportional, integral and derivative gains of PID controller. Expression for the ITAE objective function is depicted in Eq. (3).

$$OF = \text{ITAE} = \int_0^{t_{\text{sim}}} (|\Delta F1| + |\Delta F2| + |\Delta P_{\text{Tie}}|) \cdot t \cdot dt. \tag{3}$$

In the above equation, $\Delta F1$ and $\Delta F2$ are the system frequency deviations; ΔP_{Tie} is the incremental change in tie line power; t_{sim} is the time range of simulation. The problem constraints are the PID controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

$$\min OF \tag{4}$$

Subjected to constraints

$$K_{p\min} \leq K_p \leq K_{p\max}, \tag{5}$$

$$K_{l\min} \leq K_l \leq K_{l\max}, \tag{6}$$

$$K_{D\min} \leq K_D \leq K_{D\max}. \tag{7}$$

3 Optimization algorithms

To search the highly multimodal space, most popular bio inspired optimization algorithms like PSO, Bat and Firefly are employed. In this paper individual PID parameter tuning for each individual area of power system has been carried out.

3.1 Particle swam optimization

Particle Swarm Optimization (PSO) is a population-based continuous optimization technique proposed by Ebherhert and Kennedy[5]. The algorithm simulates a simplified social milieu in a swarm of potential solutions (called "particles"), which means that a single particle bases its search not only on its own experience but also on the information given by its neighbors in the swarm. This paradigm leads to successful results and contributes to the popularity of PSO.

3.1.1 Steps followed in PSO algorithm

IPSO algorithm implementation steps are as follows:
Step 1: Read the data and initialize algorithm parameters and generate the initial solution randomly.

$$X_{\text{pop}} = (x_{\text{pop}}, 1, x_{\text{pop}}, 2, x_{\text{pop}}, 3, \cdots, x_{\text{pop}}, n), \tag{8}$$
$$V_{\text{pop}} = (v_{\text{pop}}, 1, v_{\text{pop}}, 2, v_{\text{pop}}, 3, \cdots, v_{\text{pop}}, n), \tag{9}$$

where, pop is population size and n is dimension of the problem.
Step 2: Calculation of fitness value of the objective function using Eq. (3) and Eq. (4).
Step 3: Calculate $p$best i.e. objective function value of each particle in the population of the current iteration is compared with its previous iteration and the position of the particle having a lower objective function value as $p$best for the current iteration is recorded:

$$p\text{best}_m^{k+1} = \begin{cases} p\text{best}_m^k & \text{if } f_m^{k+1} \geq f_m^k \\ x_m^{k+1} & \text{if } f_m^{k+1} \leq f_m^k, \end{cases} \tag{10}$$

where, k is the number of iterations, and f is objective function evaluated for the particle.
Step 4: Calculation of $g$best i.e. the best objective function associated with the $p$best among all particles in the current iteration is compared with that in the previous iteration and the lower value is selected as the current overall $g$best.

$$g\text{best}_m^{k+1} = \begin{cases} g\text{best}_m^k & \text{if } f_m^{k+1} \geq f_m^k \\ p\text{best}_m^{k+1} = & \text{if } f_m^{k+1} \leq f_m^k. \end{cases} \tag{11}$$

Step 5: Velocity updating, after calculation of the $p$best and $g$best the velocity of particles for the next iteration should be modified by using equation:

$$V_m^{k+1} = V_m^k + C_1\text{rand}(p\text{best}_m^k - X_m^k) + C_2\text{rand}(g\text{best}^k - X_m^k), \tag{12}$$

where, the parameters of the above equation should be determined in advance and is the inertia weight factor, defined as follows:

$$= \max - \frac{\max - \min}{\text{iter}_{\max}} * \text{iter}, \tag{13}$$

$C1$, $C2$ are the acceleration coefficients usually in range[3, 7]. A large inertia weight (w) facilitates a global search while a small inertia weight facilitates a local search.
Step 6: Check the velocity components constraints occurring in the limits from the following conditions,

$$\text{If } Vid > V_{\max}, \text{ then } Vid = V_{\max} \text{ (or) If } Vid < -V_{\max} \text{ then } Vid = -V_{\max}. \tag{14}$$

Step 7: Position updating, the position of each particle at the next iteration (k+1) is modified as follows:

$$X_j^{k+1} = X_j^k + V_j^{k+1}. \tag{15}$$

Step 8: If the number of iterations reaches the maximum i.e. iter $=$ iter$_{\max}$, then go to step 9. Otherwise, go to step 2.
Step 9: The individual that generates the latest $g$best is the optimal PID parameters at minimum objective function.

3.2 Bat algorithm

The majority of heuristic and meta-heuristic algorithms have been derived from the behaviour of biological systems and/or physical systems in nature. The Bat Algorithm (BA) is based on the echolocation behaviour of bats, proposed by Xin-She-Xang for engineering optimization in [13]. If we idealize some of the echolocation characteristics of micro bats, we can develop various bat-inspired algorithms or bat algorithms.

3.2.1 Steps for implementation of bat algorithm

In this section, BAT algorithm is described for solving the optimal placement of capacitors in radial distribution systems.
Step 1: Initialization of problem and algorithm parameters. In the first step, the algorithm parameters such as population size (Pop), dimension of the problem and maximum number of iterations ($\text{iter}_{\max}$), limits of f, β and A are to be initialized. And initialize dimension of the problem.
Step 2: Random generation of PID gains.

$$X = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{d-1}^1 & x_d^1 \\ x_1^2 & x_2^2 & \cdots & x_{d-1}^2 & x_d^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{\text{pop}-1} & x_2^{\text{pop}-1} & \cdots & x_{d-1}^{\text{pop}-1} & x_d^{\text{pop}-1} \\ x_1^{\text{pop}} & x_2^{\text{pop}} & \cdots & x_{d-1}^{\text{pop}} & x_d^{\text{pop}} \end{bmatrix} \tag{16}$$

$$x_i^j = x_{\min,i} + (x_{\max,i} - x_{\min,i}) * \text{rand}(), \tag{17}$$

where, d is the number of decision variables, x_i^j represents PID gains, i.e., j^{th} population of i^{th} parameter, which is generated randomly in between the limits as $x_{\max,i}$ and $x_{\min,i}$ are the i^{th} parameter limits and rand() is a random number in between 0 and 1.

$$Soln = [X]. \tag{18}$$

In Bat algorithm, $Soln$ represents a group of Bats, where Bat is one position in search space. Bat is a solution that contains capacitor locations and sizes.
Step 3: Fitness evaluation. Calculate the fitness value for each initial solution using Eq. (3) and record the best solution.
Step 4: Start evolution procedure of BAT algorithm. Assign frequency for each Bat randomly.

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta, \tag{19}$$

where $\beta \in [0, 1]$ is a random vector drawn from a uniform distribution. Initially each bat is randomly assigned a frequency which is drawn uniformly from $[f_{\min}, f_{\max}]$.
Step 5: Random generation of Bat positions (PID parameters).

$$XV_i^t = V_i^{t-1} + (X_i^t - \text{best}X_*)f_i, \tag{20}$$
$$Xnew_i^t = X_i^{t-1} + XV_i^t. \tag{21}$$

Step 6: Fitness evaluation (Objective function). Calculate the fitness value for each initial solution using Eq. (3).
Step 7: Compare each new bat solution with corresponding initial bat solution and replace better solution new bats to initial bat & find best bat, best solution among initial bats.
Step 8: Stopping criterion. If the maximum number of iterations is reached, computation is terminated. Otherwise, Step 4 to Step 7 is repeated.

3.3 Firefly algorithm

The idealized Flashing characteristics of fireflies are used to develop firefly-inspired algorithm. Firefly Algorithm (FFA)[14] developed by Xin-She Yang at Cambridge University, use the following three idealized

rules:
(1) All the fireflies are unisex so it means that one firefly is attracted to other fireflies irrespective of their sex.
(2) Attractiveness and brightness are proportional to each other, so for any two flashing fireflies, the less bright one will move towards the one which is brighter.
(3) Attractiveness and brightness both decrease as their distance increases. If there is no one brighter than other firefly, it will move randomly.
The brightness of a firefly is determined by the view of the objective function. For a maximization problem, the brightness is simply proportional to the value of the objective function. Other forms of the brightness could be defined in an identical way to the fitness function in genetic algorithms. The distance between any two fireflies i and j at x_i and x_j, is expressed as

$$r_{ij} = \sqrt{(x_i - x_j)^2 - (y_i - y_j)^2}. \tag{22}$$

The movement of the i^{th} firefly is attracted to another more attractive (brighter) firefly j^{th} is expressed as

$$x_i = x_i + \beta_0 e^{-r^{r_{ij}}{}^2}(x_i - x_j) + \alpha e_i. \tag{23}$$

3.3.1 Pseudocode for FFA algorithm

Begin;
Initialize algorithm parameters:
$MaxGen$: the maximal number of generations
γ: the light absorption coefficient
r: the particular distance from the light source
d: the domain space or dimension of the problem
Define the objective function of $f(x)$, where $x = (x_1, \cdots, x_d)^T$
Generate the initial population of fireflies or $x_i (i = 1, 2, \cdots, n)$
Determine the light intensity of Ii at x_i via $f(x_i)$
While ($t < MaxGen$)
  For $i = 1$ to n (all n fireflies);
    For $j = 1$ to n (n fireflies)
      If ($Ij > Ii$), move firefly i towards j by using Eq. (22);
      End if
      Attractiveness varies with distance r (Eq. (21)) via e $[-\gamma r2]$
      Evaluate new solutions and update light intensity;
    End for j;
  End for i;
  Rank the fireflies and find the current best;
End while.
The problem specific implementation flow chart of FFA has been given in Fig. 2.

4 Implementation results and discussions

The model of the system under study shown in Fig. 1 is developed in MATLAB/SIMULINK environment and PSO, BA and FFA algorithms are implemented via MATLAB script (.m file). The objective function ITAE is simulated in the SIMULINK block so that when during the execution the SIMULINK block will obtain the PID data from MATLAB script and return the objective function value to the MATLAB program. A number of trails on the performance of the applied algorithms have been carried out on the system under study to determine the most suitable parameters. The data regarding the PSO, BA and FFA algorithms has been provided in Tab. 1. Initially all three optimization algorithms are implemented on the system under study

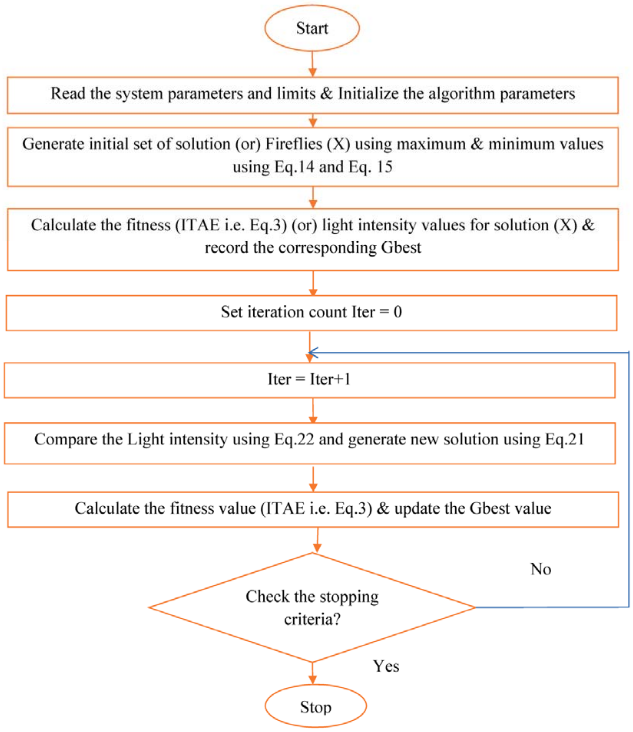

Fig. 2: Implementation flow chart of Firefly Algorithm

for PID tuning of LFC for 1% change in irradiation of the PV system. Later, the same procedure has been repeated for 2% change. Finally, an algorithm comparison has been presented for the along with performance index, settling time, simulation execution time etc. All Simulations wereconducted on an Intel core i-5-2400 CPU of 3.10GHz 4 GB RAM computer in the MATLAB 7.10.0.499 (R2010a) environment.

Table 1: Parameter description for PSO, BA and FFA algorithms

Type	Parameter	Description	Assigned value
PSO	P	Population size	20
	npar	Number of particles	6
	$W_{\max}$	Maximum inertia weight factor	0.9
	$W_{\min}$	Minimum inertia weight factor	0.4
	$C1$,$C2$	Cognitive parameters	2, 2
	$\text{iter}_{\max}$	Maximum no of iterations	50
BA	pop	Population of Bats	20
	n	Dimensional search space of a bats	6
	A	Loudness	0.50
	r	Pulse rate	0.50
	$f_{\min}$	Minimum frequency	0.00
	$f_{\max}$	Maximum frequency	2.00
	$\text{iter}_{\max}$	Maximum no of iterations	50
FFA	N	Population of fireflies	20
	n	Search space dimension of a firefly	6
	β_O	Initial attractiveness	1
		Randomness	0.25
	Γ	Absorption	1
	$\text{iter}_{\max}$	Maximum no of iterations	50

4.1 Case 1: PID tuning of LFC of two area power system using PSO, BA and FFA for 1% change in irradiation of PV system

The system under study is a two area power system consisting of PV and Diesel generators. Where, the output of PV system is more fluctuated in reality due to partial shaded conditions and change in irradiation. If the system is grid connected it would have an impact on the grid frequency hence it leads to grid failure. So in Case 1 change in irradiation of PV system has been considered as 1% and then optimal PID tuning via optimization algorithms has been carried out. The results obtained in Case 1 are presented in Tab. 2. Tab. 2 contains the information about optimal gains of PID controllers of individual areas of the power system, method of optimization, objective function value i.e. ITAE and simulation execution time. Form Tab. 2 it is observed that Bat algorithm has been performed well in obtaining the minimized ITAE value than PSO and FFA. The objective function values of PSO, BA and FFA are 0.0245, 0.0233 and 0.0452 respectively. And simulation run time for PSO, BA and FFA are 104.6s, 65.42s and 87.92s respectively. In fact, the ITAE values of PSO and BA are nearly close, but the execution time has large variation between three algorithms. The convergence characteristics of PSO, BA and FFA are shown in Fig. 3. Form Fig. 3, it is observed that BA reached the best solution at 29th iteration, whereas PSO and FFA at 25th and 15th iterations respectively.

Table 2: Tuned PID parameters for 1% change in irradiation

Parameter	Optimization Method		
	PSO	BA	FFA
K_{P1}	1.3235	1.5852	1.2292
K_{P2}	0.4331	1.5641	0.6375
K_{I1}	2.0000	1.6511	1.0681
K_{I2}	1.2864	0.7112	0.7882
K_{D1}	0.0050	0.0052	0.0090
K_{D2}	0.0008	0.0003	0.0090
$ITAE$	0.0245	0.0233	0.0452
Comp. Time (s)	104.61	95.72	87.92

Table 3: Tuned PID parameters for 2% change in irradiation

Parameter	Optimization Method		
	PSO	BA	FFA
K_{P1}	1.3235	1.6060	1.4497
K_{P2}	0.4331	0.1843	1.4495
K_{I1}	2.0000	1.8573	1.7596
K_{I2}	1.2864	1.5043	0.6163
K_{D1}	0.0055	0.0006	0.0090
K_{D2}	0.0008	0.0041	0.0090
$ITAE$	0.0491	0.0450	0.0612
Comp. Time (s)	103.71	60.82	102.47

4.2 Case 2: PID tuning of LFC of two area power system using PSO, BA and FFA for 1% change in irradiation of PV system

In Case 2, the change in irradiation of the PV system has been considered as 2% and then optimal PID tuning via optimization algorithms has been carried out. The results obtained in Case 2 are presented in Tab. 3. Tab. 3 contains the information about optimal gains of PID controllers of individual areas of the power system, method of optimization, objective function value i.e. ITAE and simulation execution time. Form Tab. 3 it is observed that Bat algorithm has been performed well in obtaining the minimized ITAE value than PSO

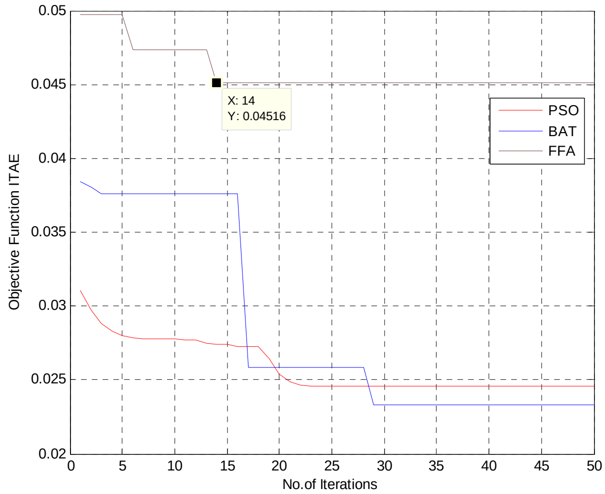

Fig. 3: Convergence of PSO, BA and FFA approaches at 1% change in irradiation

and FFA. The objective function values of PSO, BA and FFA are 0.0491, 0.0450 and 0.0612 respectively. And simulation run time for PSO, BA and FFA are 103.71s, 60.82s and 98.92s respectively. In fact, the ITAE values of PSO and BA are nearly close, but the execution time has large variation between three algorithms. The convergence characteristics of PSO, BA and FFA are shown in Fig. 4.

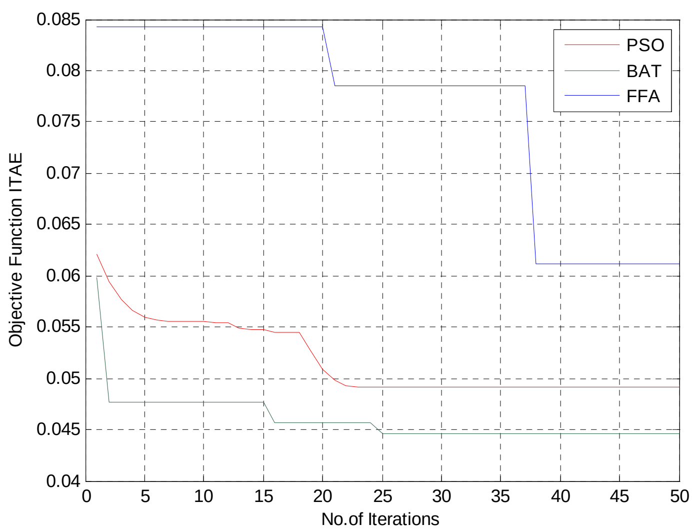

Fig. 4: Convergence of PSO, BA and FFA approaches at 2% change in irradiation

Fig. 4 Convergence of PSO, BA and FFA approaches at 2% change in irradiation Form Fig. 4, it is observed that BA reached the best solution at 25th iteration, whereas PSO and FFA at 22nd and 33rd iterations respectively.

4.3 Performance analysis of results

In this section performance of each algorithm on optimal PID tuning of two area power system consisting of PV and diesel generators has been evaluated. The settling times for area 1, area 2 and tie line with respect to PSO, BA and FFA approaches for 1% and 2% change in irradiation of the PV system has been furnished in Table 4. Form Table 4 it is noticed that BA optimized PID controller outperforms PSO and FFA. The settling time in frequency and tie-line power deviations following 1% step change in irradiation in area 1 obtained by

BA are 14.28s, 14.84s and 16.2s and for PSO and FFA are 13.53s, 21.59s, 21.03s and 18.98s, 23.43s, 23.7s respectively. Similarly for 2% step change in irradiation the settling time in frequency and tie-line power are 10.89s, 15.37s, and 15.04s for BA, 16.99s, 16.93s, 16.1s for PSO and 11.45s, 20.11s, 23.13s for FFA respectively. For 1% step change in irradiation in area 1 the system dynamic response is shown in Fig. 5-7. Similarly for 2% step change in irradiation in area 1 the system dynamic response is shown in Fig. 8-10. So, it can be concluded that BA approach provides a robust control under changes in PV system irradiation. The reason may be BA has simple and strong evolution procedure to generate new solution and it is proved from aforementioned results. Simulation time mainly depends on evolution procedure, if complex calculations involve in the evolution procedure then it consumes lot of time to converge. So in this point of view BA has very simple and strong evolution strategy than PSO and FFA algorithms.

Table 4: Performance analysis of two area PV-Diesel power system

Irradiation variation	Performance index with PSO optimized PID controller settling time (s)			Performance index with BA optimized PID controller settling time (s)			Performance index with FFA optimized PID controller settling time (s)		
	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}	ΔF_1	ΔF_2	ΔP_{Tie}
1%	13.53	21.59	18.98	14.28	14.84	16.2	18.98	23.43	23.7
2%	16.99	16.93	16.1	10.89	15.37	15.04	11.45	20.11	23.13

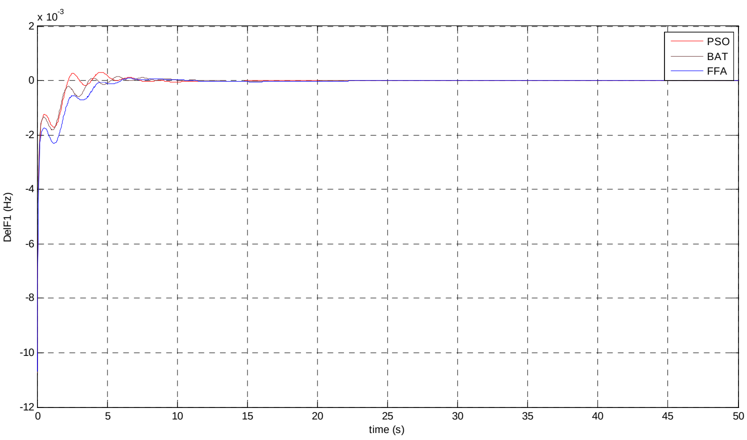

Fig. 5: Change in frequency of area 1 for 1% change in irradiation in loaded condition

5 Conclusions

In this paper, optimization approach has been proposed for PID controller tuning of two area power system consisting PV and diesel generators. Initially the SIMULINK block of power system has been prepared along with ITAE as an objective function. Later, MATLAB code has been developed and interfaced to SIMULINK to optimize the PID controller gains for better power system frequency control. Three optimization approaches PSO, BA and FFA were discussed for optimal PID controller gains. In which Bat algorithm has been outperformed. The results obtained with BA are shown efficiency of the algorithm in achieving the desire objective. However, the other algorithms are also performed well at their level best. So, it can be concluded that the overall dynamic response of the controllers are optimized with BA has shown better results comparatively with those results obtained by PSO and FFA. From this study, it is revealed that the implementation of BA to optimal PID controller tuning of LIC of multi area power system may yield promising results.

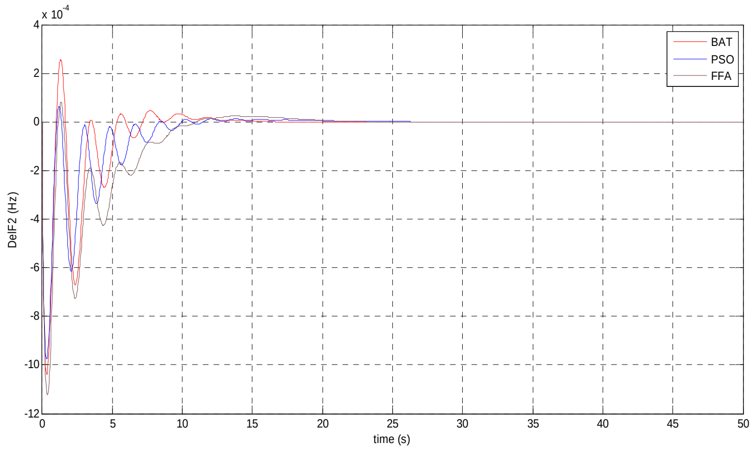

Fig. 6: Change in frequency of area 2 for 1% change in irradiation in loaded condition

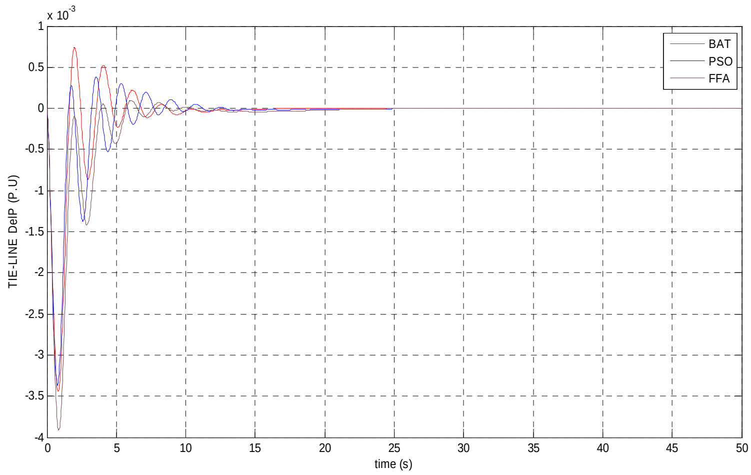

Fig. 7: Change in tie line power for 1% change in irradiation in loaded condition

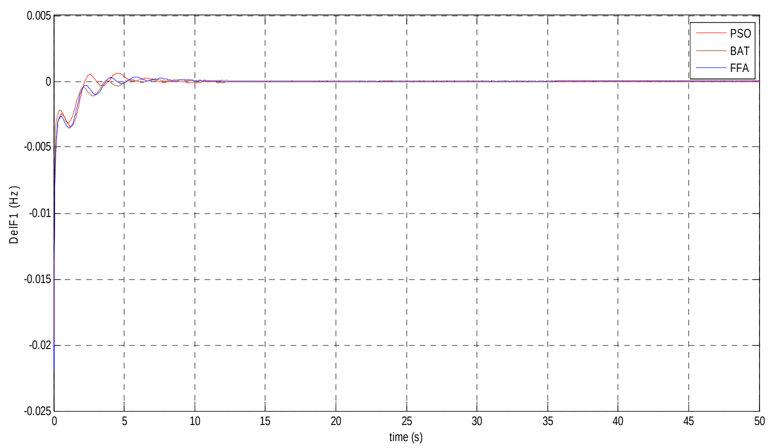

Fig. 8: Change in frequency of area 1 for 2% change in irradiation in loaded condition

6 Appendix a: two area (PV-Diesel) power system[6]

$R1 = R2 = 0.425$; $B1 = B2 = 0.817$; $T12 = 1$; $Tg = 0.08$; $Kg = 1$; $Tt = 0.3$; $Kt = 1$; $Tr = 10$; $Kr = 0.33$; $Kp = 120$; $Tp = 20$.

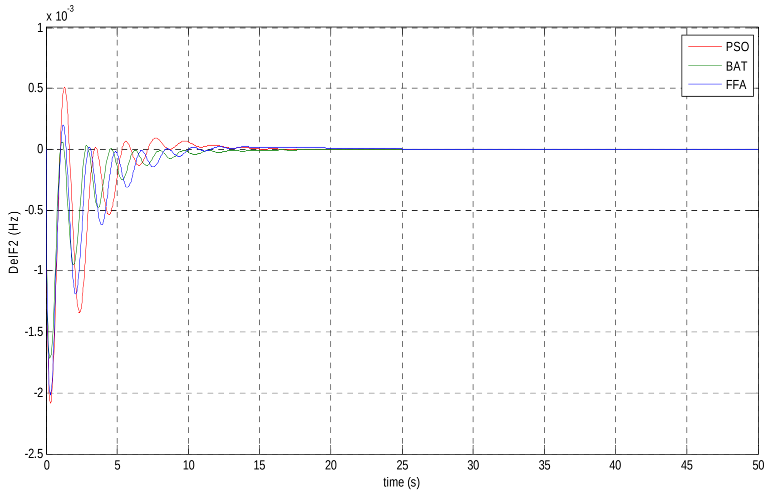

Fig. 9: Change in frequency of area 2 for 2% change in irradiation in loaded condition

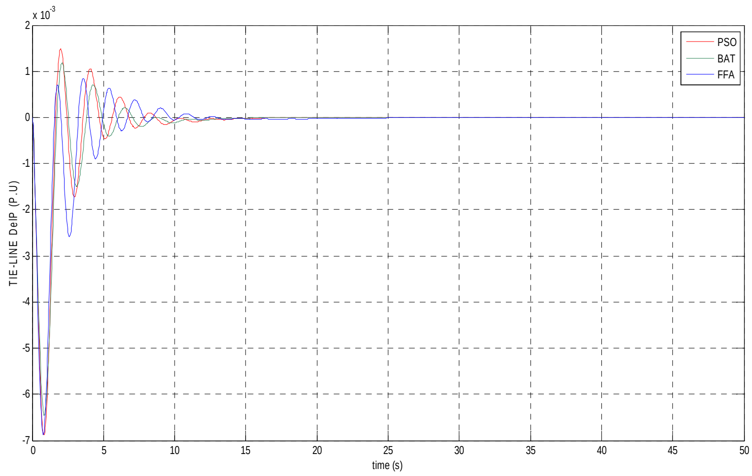

Fig. 10: Change in tie line power for 2% change in irradiation in loaded condition

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