Optimization of Power System Stabilizers using BAT search algorithm

E.S. Ali *

Electric Power and Machine Department, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt

ABSTRACT

A new metaheuristic method, the BAT search algorithm based on the echolocation behavior of bats is proposed in this paper for optimal design of Power System Stabilizers (PSSs) in a multimachine environment. The PSSs parameter tuning problem is converted to an optimization problem which is solved by BAT search algorithm. An eigenvalues based objective function involving the damping factor, and the damping ratio of the lightly damped electromechanical modes is considered for the PSSs design problem. The performance of the proposed BAT based PSSs (BATPSS) has been compared with Genetic Algorithm (GA) based PSSs (GAPSS) and the Conventional PSSs (CPSS) under various operating conditions and disturbances. The results of the proposed BATPSS are demonstrated through time domain analysis, eigenvalues and performance indices. Moreover, the results are presented to demonstrate the robustness of the proposed algorithm over the GA and conventional one.

© 2014 Elsevier Ltd. All rights reserved.

Introduction

One problem that faces power systems is the low frequency oscillations arising due to disturbances. These oscillations may sustain and grow to cause system separation if no adequate damping is providing [1]. In analyzing and controlling the power system's stability, two distinct types of system oscillations are recognized. One is referred to inter-area modes resulted from swinging one generation area with respect to other areas. The second one is associated with swinging of generators existed in one area against each other and is known as local mode [2,3]. Power System Stabilizer (PSS) is used to generate supplementary control signals for the excitation system in order to mitigate both types of oscillations [4].

In last few years, Artificial Intelligence (AI) techniques have been discussed in literatures to solve problems related to PSS design. Artificial Neural Network (ANN) for designing PSS is addressed in [5–8]. The ANN approach has its own merits and demerits. The performance of the system is improved by ANN based controller but, the main problem of this controller is the long training time, the selecting number of layers and the number of neurons in each layer. Another AI approach likes Fuzzy Logic Control (FLC) has received much attention in control applications. In contrast with the conventional techniques, FLC formulates the control action of a plant in terms of linguistic rules drawn from the behavior of a human operator rather than in terms of an algorithm synthesized from a model of the plant [9–15]. It offers the

following merits: it does not require an accurate model of the plant; it can be designed on the basis of linguistic information obtained from the previous knowledge of the control system and gives better performance results than the conventional controllers. However, a hard work is inevitable to get the effective signals when designing FLC. Also, it requires more fine tuning and simulation before operational. Robust techniques such as H_∞ [16–20], H_2 [21,22] and μ-synthesis [23] have been also used for PSS design. However, these methods are iterative, sophisticated and, the system uncertainties should be carried out in a special format. On the other hand, the order of the stabilizers is as high as that of the plant. This gives rise to complex structure of such stabilizers and reduces their applicability. Another technique like pole shifting is illustrated in [24,25] to design PSS. However, this technique suffers from complexity of computational algorithm, heavy computational burden, memory storage problem and non-adaptive tuning under various system operating conditions and configurations. Also, this design approach assumes full state availability.

Recently, global optimization techniques have been applied to PSS design problem. Simulated Annealing (SA) is presented in [26] for optimal tuning of PSS but this technique might fail by getting trapped in one of the local optimal. Another heuristic technique like Tabu Search (TS) is introduced in [27–28] to design PSS. Despite this optimization method seems to be effective for the design problem, the efficiency is reduced by the use of highly epistatic objective functions, and the large number of parameters to be optimized. Also, it is time consuming method. Genetic Algorithm (GA) is developed in [29,30] for optimal design of PSS. Despite this optimization technique requires a very long run time

* Tel.: +201112669781; fax: +20552321407.
E-mail address: ehabsalimalisalama@yahoo.com

depending on the size of the system under study. Also, it suffers from settings of algorithm parameters and gives rise to repeat revisiting of the same suboptimal solutions. A Particle Swarm Optimization (PSO) for the design of the PSS parameters is illustrated in [31]. However, PSO pains from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Moreover, the algorithm cannot work out the problems of scattering and optimization. Furthermore, the algorithm suffers from slow convergence in refined search stage, weak local search ability and algorithm may lead to possible entrapment in local minimum solutions. A relatively newer evolutionary computation algorithm, called Bacteria Foraging (BF) scheme has been developed by [32] and further established recently by [33–39]. The BF algorithm depends on random search directions which may lead to delay in reaching the global solution. In order to overcome these drawbacks, a BAT search optimization algorithm is proposed in this paper.

A new metaheuristic algorithm known as BAT search algorithm, based on the echolocation behavior of bats, is proposed in this paper for the optimal design of PSS parameters. The problem of a robust PSS design is formulated as an objective optimization problem and BAT algorithm is used to handle it. The stabilizers are tuned to shift all electromechanical modes to a prescribed zone in the S-plane in such a way that the relative stability is confirmed. The effectiveness of the proposed BATPSS is tested on a multimachine power system under various operating conditions in comparison with GAPSS and CPSS through time domain analysis, eigenvalues and performance indices. Results evaluation show that the proposed algorithm attains good robust performance for suppressing the low frequency oscillations under various operating conditions and disturbances.

Mathematical problem formulation

Power system model

The complex nonlinear model related to n machines interconnected power system, can be formalized by a set of nonlinear differential equations as:

$$\dot{X} = f(X, U) \tag{1}$$

where X is the vector of the state variables and U is the vector of input variables. $X = [\delta, \omega, E'_q, E_{fd}, V_f]^T$ and U is the output signals of PSSs in this paper. δ and ω are the rotor angle and speed, respectively. Also, E'_q, E_{fd} and V_f are the internal, the field, and excitation voltages respectively.

The linearized incremental models around an equilibrium point are usually used in the design of PSS. Therefore, the state equation of a power system with m PSSs can be formed as:

$$\dot{X} = AX + BU \tag{2}$$

where A is a $5n \times 5n$ matrix and equals $\partial f / \partial X$ while B is a $5n \times m$ matrix and equals $\partial f / \partial U$. Both A and B are estimated at a certain operating point. X is a $5n \times 1$ state vector and U is a $m \times 1$ input vector.

PSS controller structure

Power system utilities still prefer CPSS structure due to the ease of online tuning and the lack of assurance of the stability related to some adaptive or variable structure techniques. On the other hand, a comprehensive analysis of the effects of different CPSS parameters on the overall dynamic performance of the power system is investigated in [40]. It is shown that the appropriate selection of the CPSS parameters results in satisfactory performance during the system disturbances. The structure of the ith PSS is given by:
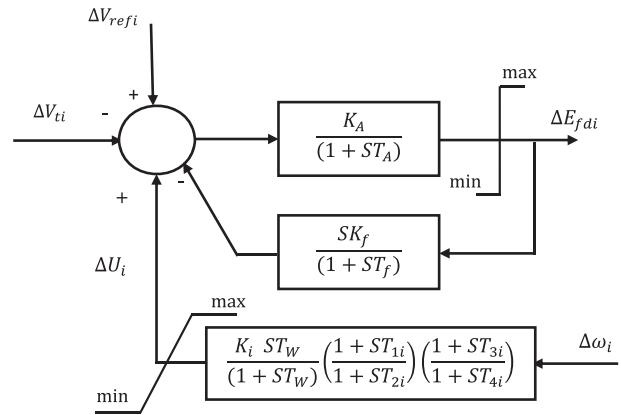

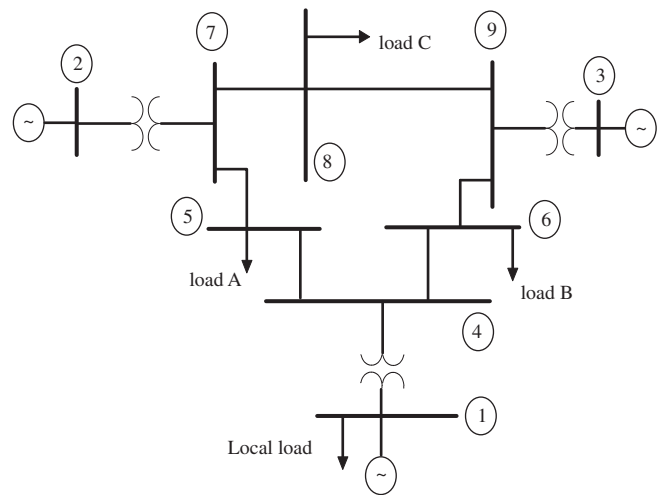**Fig. 1.** Block diagram of ith PSS with excitation system.

Fig. 2. Multimachine test system.

Table 1
Loading conditions for the system (in p.u.).

	Light		Normal case		Heavy	
	P	Q	P	Q	P	Q
Generator						
G1	0.9649	0.223	1.7164	0.6205	3.5730	1.8143
G2	1.00	−0.1933	1.630	0.0665	2.20	0.7127
G3	0.45	−0.2668	0.85	−0.1086	1.35	0.4313
Load						
A	0.7	0.35	1.25	0.5	2.0	0.9
B	0.5	0.3	0.9	0.3	1.8	0.6
C	0.6	0.2	1.0	0.35	1.6	0.65
Local load at G1	0.6	0.2	1.0	0.35	1.6	0.65

$$\Delta U_i = K_i \frac{ST_W}{(1 + ST_W)} \left[\frac{(1 + ST_{1i})}{(1 + ST_{2i})} \frac{(1 + ST_{3i})}{(1 + ST_{4i})} \right] \Delta\omega_i \tag{3}$$

This structure consists of a gain, washout filter, a dynamic compensator and a limiter as it is shown in Fig. 1. The output signal is fed as a supplementary input signal, ΔU_i to the regulator of the excitation system. The input signal $\Delta\omega_i$ is the deviation in speed from the synchronous speed. The stabilizer gain K_i is used to determine the amount of damping to be injected. Then, a washout filter makes it just act against oscillations in the input signal to avoid steady state error in the terminal voltage. In addition, two lead–lag circuits are included to eliminate any delay between the excitation and the electric torque. The limiter is included to prevent the output signal of the PSS from driving the excitation system into heavy saturation
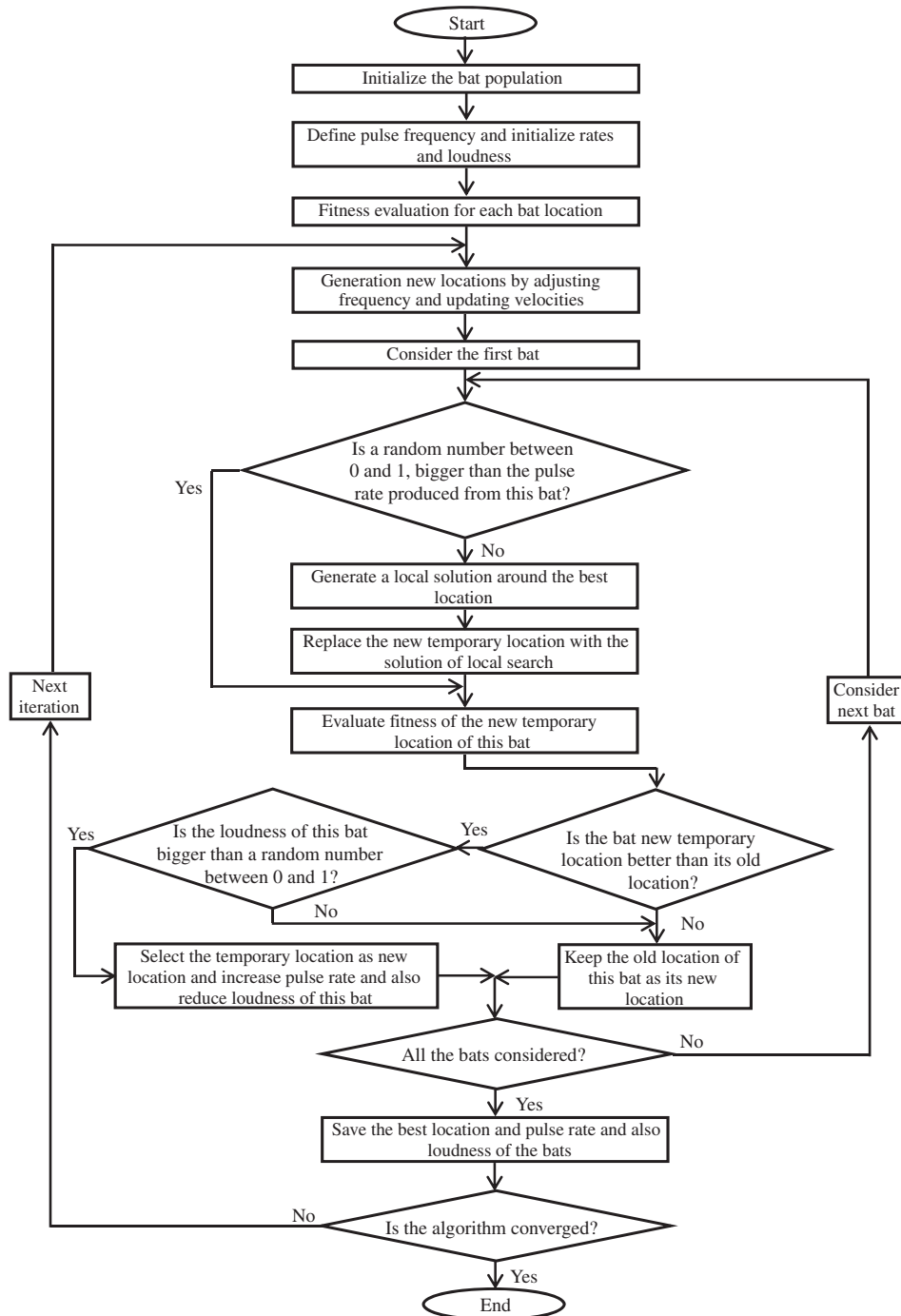
Fig. 3. BAT search algorithm flow chart.

[2]. Moreover, the block diagram of excitation system and PSS is shown in Fig. 1.

In this paper, the value of the washout time constant T_W is kept at 10 s, the values of time constants T_{2i} and T_{4i} are fixed at a reasonable value of 0.05 s. The stabilizer gain K_i and time constants T_{1i}, and T_{3i} are remained to be determined.

Test system

In this paper, the three machine nine bus power system shown in Fig. 2 is considered. The system data in detail is given in [41]. Three different operating conditions are taken in consideration and named as light, normal, and heavy load to show the superiority

of the proposed algorithm in designing robust PSS. The generator and loading level are given in Table 1 for these loading conditions.

Overview of BAT search algorithm

BAT search algorithm is an optimization algorithm inspired by the echolocation behavior of natural bats in locating their foods. It is introduced by Yang [42–45] and is used for solving various optimization problems. Each virtual bat in the initial population employs a homologous manner by performing echolocation way for updating its position. Bat echolocation is a perceptual system in which a series of loud ultrasound waves are released to create echoes. These waves are returned with delays and various sound
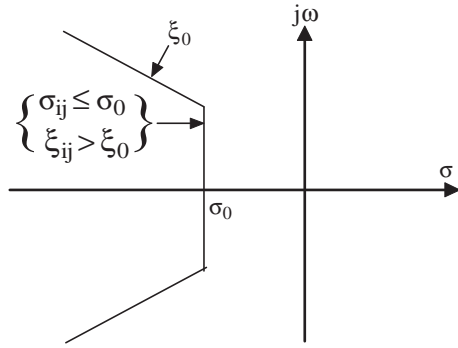
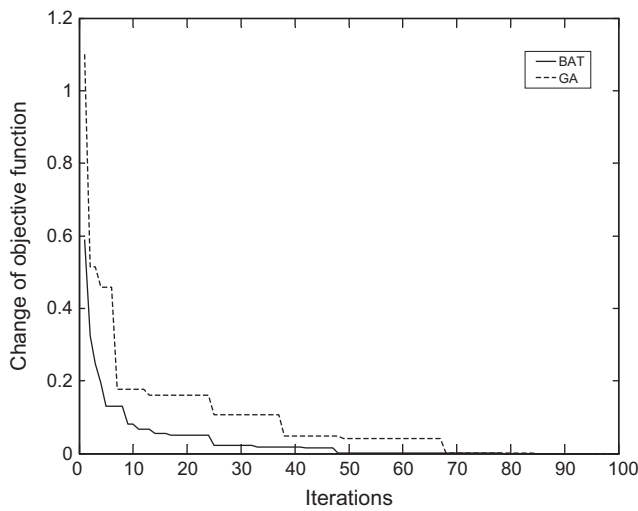**Fig. 4.** D-shaped sector in the negative half of S-plane.

Fig. 5. Variations of objective functions.

levels which qualify bats to discover a specific prey. Some rules are investigated to extend the structure of BAT algorithm and use the echolocation characteristics of bats [46–49].
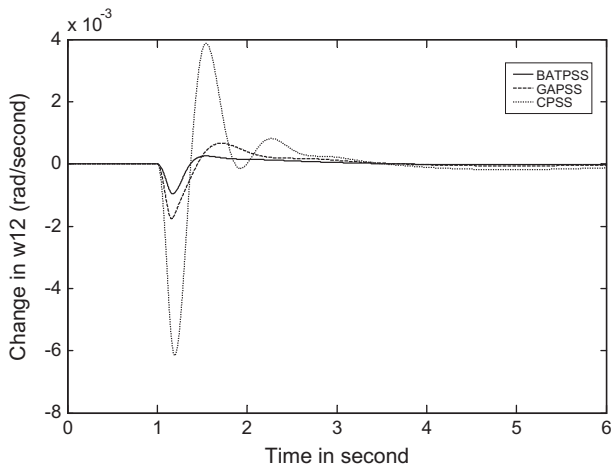
(a) Each bat utilizes echolocation characteristics to classify between prey and barrier.
(b) Each bat flies randomly with velocity v_i at position x_i with a fixed frequency f_{min}, varying wavelength λ and loudness L_0 to seek for prey. It regulates the frequency of its released pulse and adjust the rate of pulse release r in the range of [0,1], relying on the closeness of its aim.
(c) Frequency, loudness and pulse released rate of each bat are varied.

(d) The loudness L_m^{iter} changes from a large value L_0 to a minimum constant value L_{min}.

The position x_i and velocity v_i of each bat should be defined and updated during the optimization process. The new solutions x_i^t and velocities v_i^t at time step t are performed by the following equations [50,51]:

$$f_i = f_{min} + (f_{max} - f_{min})\alpha \tag{4}$$

$$v_i^t = v_i^{t-1} + (x_i^t - x^*)f_i \tag{5}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{6}$$

where α in the range of [0,1] is a random vector drawn from a uniform distribution. x^* is the current global best location, which is achieved after comparing all the locations among all the n bats. As the product $\lambda_i f_i$ is the velocity increment, one can consider either f_i (or λ_i) to set the velocity change while fixing the other factor. For implementation, every bat is randomly assigned a frequency which is drawn uniformly from (f_{min}, f_{max}). For the local search, once a solution is chosen among the current best solutions, a new solution for each bat is generated locally using random walk.

$$x_{new} = x_{old} + \varepsilon L^t \tag{7}$$

where $\varepsilon \in [-1, 1]$ is a random number, while t is the mean loudness of all bats at this time step. As the loudness usually decreases once a bat has found its prey, while the rate of pulse emission increases, the loudness can be selected as any value of convenience. Assuming $L_{min} = 0$ means that a bat has just found the prey and temporarily stop emitting any sound, one has:

$$L_i^{t+1} = \beta L_i^t, \quad r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \tag{8}$$

where β is constant in the range of [0, 1] and γ is positive constant. As time reach infinity, the loudness tend to be zero, and γ_i^t equal to γ_i^0. The flow chart of BAT algorithm is shown in Fig. 3, and the parameters are given in appendix.

Objective function

To guarantee stability and attain greater damping to low frequency of oscillations, the parameters of the PSSs may be picked to minimize the following objective function:

$$J_t = \sum_{j=1}^{np} \sum_{\sigma_{ij} \geqslant \sigma_0} (\sigma_0 - \sigma_{ij})^2 + \sum_{j=1}^{np} \sum_{\xi_{ij} \geqslant \xi_0} (\xi_0 - \xi_{ij})^2 \tag{9}$$

This will place the system closed loop eigenvalues in the D-shape sector characterized by $\sigma_{ij} \leqslant \sigma_0$ and $\xi_{ij} \geqslant \xi_0$ as shown in Fig. 4.

Where, np is the number of operating points investigated in the design operation, σ and ξ are the real part and the damping ratio of the eigenvalue of the operating point. In this paper, σ_0 and ξ_0 are

Table 2
Mechanical modes and ζ under different loading conditions and controllers.

	No stabilizers	CPSS	GAPSS	BATPSS
Light load	$+0.01 \pm 0.8j$, -0.12	$-0.19 \pm 0.69j$, 0.26	$-1.06 \pm 0.7j$, 0.83	$-1.09 \pm 0.63j$, 0.87
	$-0.58 \pm 6.04j$, 0.09	$-2.35 \pm 4.15j$, 0.49	$-3.73 \pm 6.3j$, 0.51	$-6.27 \pm 6.51j$, 0.69
	$-0.96 \pm 7.77j$, 0.12	$-3.24 \pm 5.2j$, 0.52	$-3.49 \pm 8.1j$, 0.4	$-3.64 \pm 6.01j$, 0.52
Normal load	$+0.15 \pm 1.49j$, -0.1	$-0.24 \pm 0.75j$, 0.3	$-1.13 \pm 0.69j$, 0.85	$-1.16 \pm 0.68j$, 0.86
	$-0.35 \pm 8.14j$, 0.04	$-2.41 \pm 4.42j$, 0.47	$-4.27 \pm 7.02j$, 0.52	$-6.84 \pm 6.97j$, 0.70
	$-0.67 \pm 11.6j$, 0.06	$-3.32 \pm 5.34j$, 0.47	$-3.61 \pm 8.72j$, 0.38	$-4.17 \pm 8.06j$, 0.46
Heavy load	$+0.32 \pm 1.6j$, -0.19	$-0.33 \pm 0.89j$, 0.34	$-1.17 \pm 0.72j$, 0.85	$-1.32 \pm 0.75j$, 0.87
	$+0.15 \pm 7.8j$, -0.02	$-1.96 \pm 4.32j$, 0.41	$-3.51 \pm 6.72j$, 0.46	$-7.98 \pm 5.44j$, 0.83
	$-0.36 \pm 12.2j$, 0.03	$-3.09 \pm 5.25j$, 0.5	$-3.79 \pm 8.91j$, 0.39	$-4.62 \pm 7.34j$, 0.53

Table 3
Parameters of PSSs for different algorithms.

	BAT	GA	CPSS
PSS$_1$	$K = 46.6588$	$K = 25.3696$	$K = 14.4386$
	$T_1 = 0.4153$	$T_1 = 0.4684$	$T_1 = 0.2652$
	$T_3 = 0.2698$	$T_3 = 0.7428$	$T_3 = 0.8952$
PSS$_2$	$K = 8.4751$	$K = 7.8187$	$K = 5.1659$
	$T_1 = 0.4756$	$T_1 = 0.2918$	$T_1 = 0.5242$
	$T_3 = 0.1642$	$T_3 = 0.1429$	$T_3 = 0.2032$
PSS$_3$	$K = 4.2331$	$K = 3.5314$	$K = 8.3287$
	$T_1 = 0.2513$	$T_1 = 0.5121$	$T_1 = 0.5817$
	$T_3 = 0.1853$	$T_3 = 0.3731$	$T_3 = 0.4268$

Fig. 8. Change in $\Delta\omega_{23}$ for normal load.

Fig. 6. Change in $\Delta\omega_{12}$ for normal load.
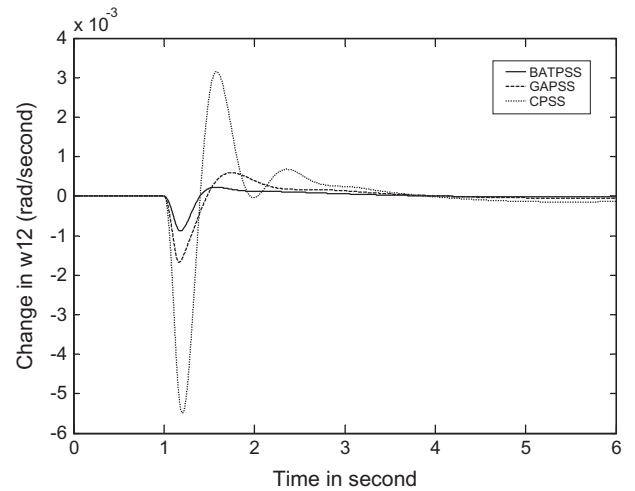
Fig. 9. Change in $\Delta\omega_{12}$ for light load.

$$T_{3i}^{min} \leqslant T_{3i} \leqslant T_{3i}^{max} \tag{10}$$

This paper focuses on optimal tuning of PSSs using BAT search algorithm. The aim of the optimization is to minimize the objective function in order to improve the system performance in terms of settling time and overshoots under different operating conditions and finally designing a low order controller for easy implementation.

Results and simulations

In this section, the superiority of the proposed BAT algorithm in designing PSS compared with optimized PSS with GA [52,53] and CPSS is illustrated. Fig. 5. shows the change of objective functions with two optimization algorithms. The objective functions decrease over iterations of BAT, and GA. The final value of the objective function is $J_t = 0$ for both algorithms, indicating that all modes have been shifted to the specified D-shape sector in the S-plane and the proposed objective function is achieved. Moreover, BAT converges at a faster rate (48 generations) compared with that for GA (68 generations).

Table 2, shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear

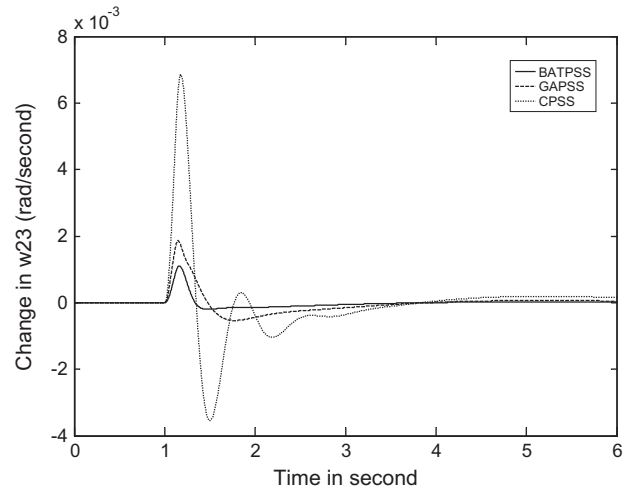**Fig. 7.** Change in $\Delta\omega_{13}$ for normal load.

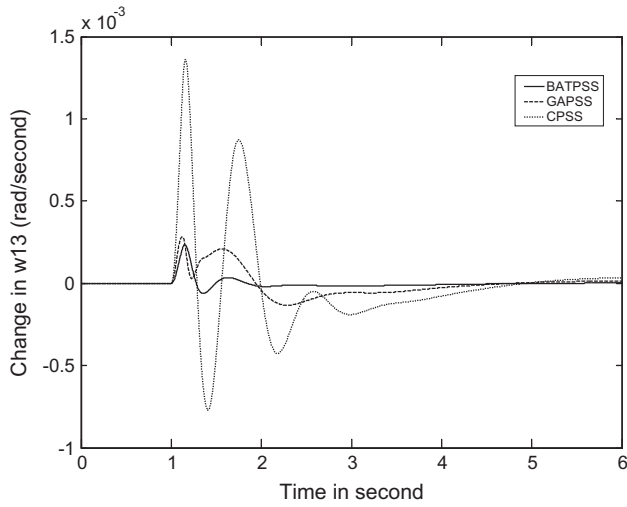selected to be −0.5 and 0.1 respectively [39]. Typical ranges of the optimized parameters are [1–100] for K and [0.06–1.0] for T_{1i} and T_{3i}. Optimization problem based on the objective function J_t can be stated as: minimize J_t subjected to:

$$K_i^{min} \leqslant K_i \leqslant K_i^{max}$$

$$T_{1i}^{min} \leqslant T_{1i} \leqslant T_{1i}^{max}$$

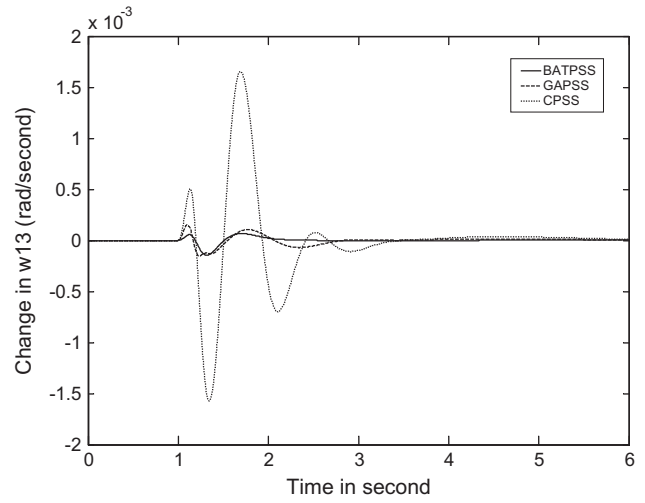**Fig. 10.** Change in $\Delta\omega_{13}$ for light load.

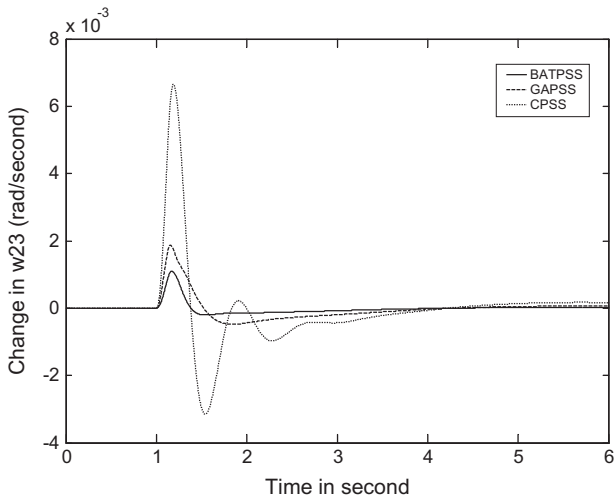**Fig. 13.** Change $\Delta\omega_{13}$ for heavy load.

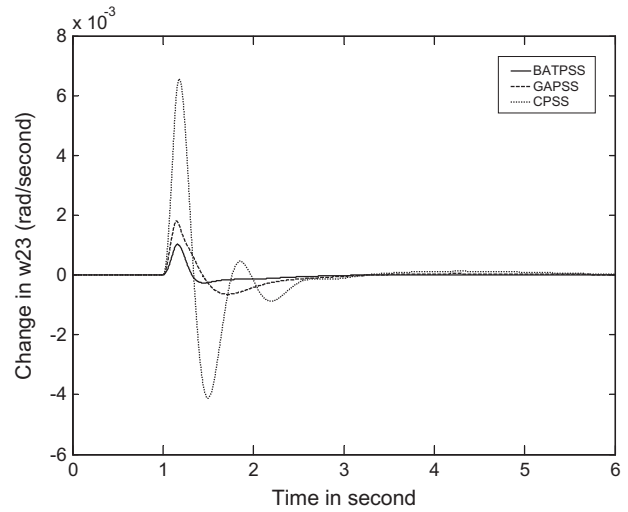**Fig. 11.** Change in $\Delta\omega_{23}$ for light load.

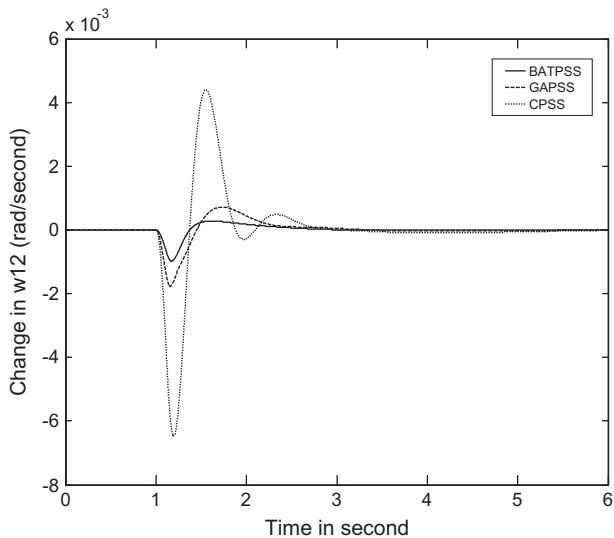**Fig. 14.** Change in $\Delta\omega_{23}$ for heavy load.

Fig. 12. Change in $\Delta\omega_{12}$ for heavy load.

that the BATPSS shift the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed BATPSS are significantly enhanced to be ($\sigma = -1.09$, -1.16, -1.32) for light, normal, and heavy loading respectively. Also, the damping ratios corresponding to BATPSS controllers are larger than those corresponding to GAPSS and CPSS. Hence, compared with GAPSS and CPSS, BATPSS provides good robust performance and achieves superior damping characteristics of electromechanical modes. Results of PSSs parameters set values based on the proposed objective function using BAT, GA and conventional method are given in Table 3.

Response under normal load condition

The validation of the performance under severe disturbance is confirmed by applying a three phase fault of 6 cycle duration at 1.0 s near bus 7. Figs. 6–8, show the response of $\Delta\omega_{12}$, $\Delta\omega_{13}$ and $\Delta\omega_{23}$ due to this disturbance under normal loading condition. It can be seen that the system with the proposed BATPSS is more stabilized than GAPSS and CPSS. In addition, the required mean settling time to mitigate system oscillations is approximately 1.1 s
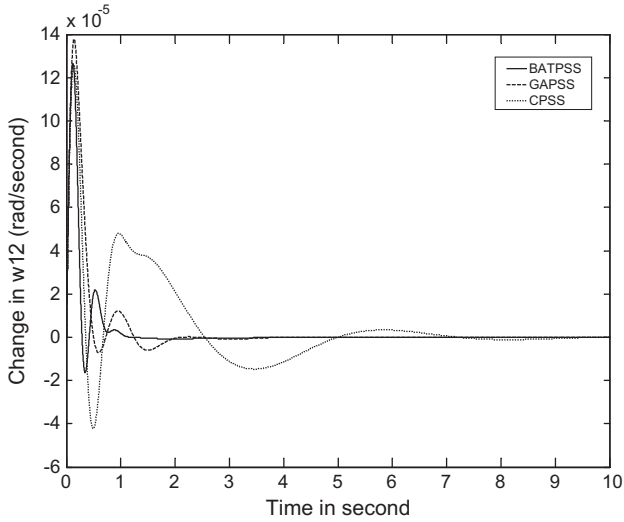
the proposed BATPSS outlasts GAPSS and CPSS controller in attenuating oscillations effectively and minifying settling time. Consequently, the proposed BATPSS extend the power system stability limit.

Response under heavy load condition

Figs. 12–14, show the system response under heavy loading condition. These figures indicate the superiority of the BATPSS in reducing the settling time and suppressing power system oscillations. Moreover, the mean settling time of these oscillation is T_s = 1.1, 1.37, and 1.97 s for BATPSS, GAPSS, and CPSS respectively. Hence, BATPSS controller greatly improves the system stability and enhances the damping characteristics of power system. Furthermore, the settling time of the proposed controller is smaller than that in [37,39].

Response under small disturbance

Figs. 15 and 16, show the response of $\Delta\omega_{12}$ and $\Delta\omega_{13}$ under heavy loading condition due to 20% increase of mechanical torque of generator 1 as a small disturbance. From these figures, it is can be seen that the BAT based PSSs using the proposed objective function introduces superior damping and attains better robust performance in comparison with the other methods.

Robustness and performance indices

To demonstrate the robustness of the proposed controller, some performance indices: the Integral of Absolute value of the Error (IAE), and the Integral of the Time multiplied Absolute value of the Error (ITAE), are being used as:

$$IAE = \int_0^\infty (|\Delta w_{12}| + |\Delta w_{23}| + |\Delta w_{13}|)dt \qquad (11)$$

$$ITAE = \int_0^\infty t(|\Delta w_{12}| + |\Delta w_{23}| + |\Delta w_{13}|)dt \qquad (12)$$

It is noteworthy that the lower the value of these indices is, the better the system response in terms of time domain characteristics. Numerical results of performance robustness for all cases are listed in Table 4. It can be seen that the values of these system performance with the BATPSS are smaller compared with those of GAPSS and CPSS. This demonstrates that the overshoot, settling time and speed deviations of all units are greatly decreased by applying the proposed BAT based tuned PSSs. Eventually; values of these indices are smaller than those obtained in [54].

Conclusions

A new optimization technique known as BAT search algorithm, for optimal designing of PSSs parameters is proposed in this paper. The PSSs parameters tuning problem is formulated as an optimization problem and BAT search algorithm is employed to seek for optimal parameters. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio is optimized for various operating conditions. Simulation results confirm the robustness and superiority of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions. Moreover, the system performance characteristics in terms of 'IAE' and 'ITAE' indices reveal that the proposed BATPSS demonstrates its effectiveness than GAPSS and CPSS.

Application of the proposed algorithm and the most recent optimization algorithms to large scale power system is the future scope of this work.

Fig. 15. Change in $\Delta\omega_{12}$ for 20% change in Tm.

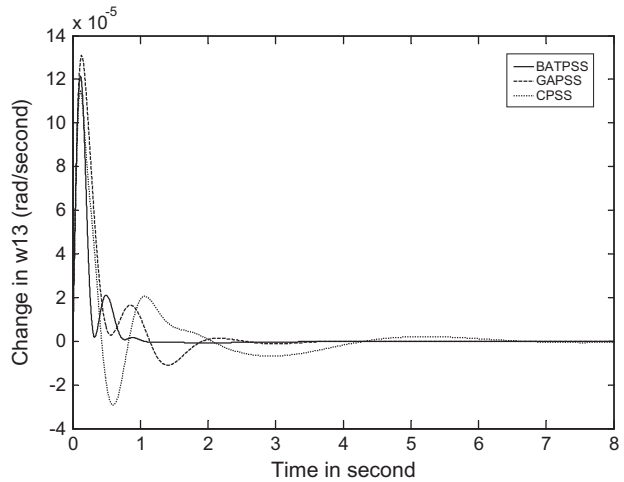**Fig. 16.** Change in $\Delta\omega_{13}$ for 20% change in Tm.

Table 4
Performance indices for different algorithms.

	IAE$*10^{-4}$			ITAE$*10^{-4}$		
	CPSS	GAPSS	BATPSS	CPSS	GAPSS	BATPSS
Light load	7.93	0.4264	0.0544	24.2	1.5148	0.2949
Normal load	16.3	0.6028	0.0676	35.56	1.845	0.7026
Heavy load	25.76	1.1736	0.1009	47.9	3.5067	0.9498

with BATPSS, 1.8 s for GAPSS, and 2.56 s with CPSS so the designed controller is qualified for supplying adequate damping to the low frequency oscillations.

Response under light load condition

Figs. 9–11, show the system response under light loading condition with fixing the controller parameters. It is clear from these figures, that the proposed BATPSS has good damping characteristics to system oscillatory modes and stabilizes the system rapidly. Also, the mean settling time of oscillations is T_s = 1.0, 1.84, and 2.47 s for BATPSS, GAPSS, and CPSS respectively. Hence,

Appendix A

(a) The parameters of BAT search algorithm are as follows: Max generation = 100; Population size = 50; $\beta = \gamma = 0.9$, $L_{\min} = 0$; $L_0 = 1$, $f_{\min} = 0$; $f_{max} = 100$.

(b) The parameters of GA are as follows: Max generation = 100; Population size = 50; Crossover probabilities = 0.75; Mutation probabilities = 0.1.

References

[1] Rogers G. Power System Oscillations. The Springer International Series in Engineering and Computer Science; 2000.
[2] Padiyar KR. Power system dynamics stability and control. 2nd ed. Hyderabad, India: BS Publications; 2008.
[3] Machowski J, Bialek J, Bumby J. Power system dynamics stability and control. 2nd ed. Wiley; 2009.
[4] Wang XF, Song Y, Irving M. Modern power systems analysis. Springer; 2008.
[5] Zhang Y, Chen GP, Malik OP, Hope GS. An artificial neural network based adaptive power system stabilizer. IEEE Trans Energy Conversion 1993;8(1):71–7.
[6] Mahabuba A, Khan MA. Small signal stability enhancement of a multi-machine power system using robust and adaptive fuzzy neural network based power system stabilizer. Eur Trans Electr Power 2009;19(7):978–1001.
[7] Segal R, Sharma A, Kothari ML. A self-tuning power system stabilizer based on artificial neural network. Int J Electr Power Energy Syst 2004;26(3):423–30.
[8] Ye H, Liu Y. Design of model predictive controllers for adaptive damping of inter-area oscillations. Int J Electr Power Energy Syst 2013;45(1):509–18.
[9] Toliyat HA, Sadeh J, Ghazi R. Design of augmented fuzzy logic power system stabilizers to enhance power systems stability. IEEE Trans Energy Conversion 1996;11(1):97–103.
[10] El-Razaz ZS, Ali ES. Design of an adaptive PSS using FLC for multi-machine power system. In: Proceedings of the Universities Power Engineering Conference 36, UPEC 2001, Swansea, September 12–14; 2001. p. 1833–8.
[11] Yee SK, Milanovic JV. Fuzzy logic controller for decentralized stabilization of multimachine power systems. IEEE Trans. Fuzzy Syst. 2008;16(4):971–81.
[12] El-Zonkoly AM, Khalil AA, Ahmied NM. Optimal tuning of lead-lag and fuzzy logic power system stabilizers using particle swarm optimization. Int J Exp Syst Appl 2009;36:2097–106.
[13] Hussein T, Saad MS, Elshafei AL, Bahgat A. Robust adaptive fuzzy logic power system stabilizer. Int J Exp Syst Appl 2009;36:12104–12.
[14] Hussein T, Saad MS, Elshafei AL, Bahgat A. Damping inter-area modes of oscillation using an adaptive fuzzy power system stabilizer. Int J Electr Power Syst Res 2010;80:1428–36.
[15] Yousefpour B, Tabar MB, Nikzad M, Farahani SSS, Tourang H. Fuzzy scaled power system stabilizer in multi machine power system. Life Sci J 2012;9(4):5924–8.
[16] Yang TC. Applying H_∞ optimization method to power system stabilizer design Part 1: Single-machine infinite-bus systems. Int J Electr Power Energy Syst 1997;19(1):29–35.
[17] EL-Razaz ZS, Mandour ME-D, Ali ES. Damping controller design for power systems using LMI and GA techniques. In: 41st International Universities Power Engineering Conference, UPEC, September 6–8; 2006. p. 500–6.
[18] Ali ZMM, Malikov AI. Robust techniques for designing power system stabilizer. J Theor Appl Information Technol 2009;9(1):20–8.
[19] Jayapal R, Mendiratta JK. H_∞ controller design for a smib based pss model. J Theor Appl Information Technol 2010;11(1):73–82.
[20] Cuk Supriyadi AN, Takano H, Murata J, Goda T. Adaptive robust PSS to enhance stabilization of interconnected power systems with high renewable energy penetration. Renew Energy 2014;63(1):767–74.
[21] Werner H, Korba P, Yang TC. Robust tuning of power system stabilizers using LMI techniques. IEEE Trans Control Syst Technol 2003;11(1):147–52.
[22] Peng Y, Zhu QM, Nouri H. Robust H2 power system stabilizer design using LMI techniques. In: Proceedings of 2011 international conference on modeling, identification and control (ICMIC); p. 405–10.
[23] Yue M, Schlueter RA. μ-Synthesis power system stabilizer design using a bifurcation subsystem based methodology. IEEE Trans Power Syst Nov. 2003;18(4):1497–506.
[24] Kothari M, Bhattacharya L, Nanda J. Adaptive power system stabilizer based on pole shifting technique. Proc Generation Trans Distribution 2002;143(1):96–8.
[25] El-Sherbiny MK, Hasan MM, El-Saady G, Yousef AM. Optimal pole shifting for power system stabilization. Int J Electr Power Syst Res 2003;66(3):253–8.
[26] Abido MA. Simulated annealing based approach to PSS and FACTS based stabilizer tuning. Int J Electr Power Energy Syst 2000;22(4):247–58.
[27] Abido MA, Abdel-Magid YL. A tabu search based approach to power system stability enhancement via excitation and static phase shifter control. Int J Electr Power Syst Res 1999;52(2):133–43.
[28] Abido MA. A novel approach to conventional power system stabilizer design using tabu search. Electr Power Energy Syst 1999;21:443–54.
[29] Abido MA, Abdel-Magid YL. A genetic based fuzzy logic power system stabilizer for multimachine power systems. Proc IEEE Conf 1997;329–34.
[30] Hassan LH, Moghavvemi M, Almurib HAF, Muttaqi KM, Ganapathy VG. Optimization of power system stabilizers using participation factor and genetic algorithm. Int J Electr Power Energy Syst 2014;55:668–79.
[31] Jalilvand A, Khalkhali RAE. Optimal design of PID power system stabilizer in multimachine power system using PSO and genetic algorithm. Int Rev Electr Eng 2011;6(2):907–12.
[32] Passino KM. Biomimicry of bacterial foraging for distributed optimization and control. IEEE Cont Syst Mag 2002;22(3):52–67.
[33] Ghoshal SP, Chatterjee A, Mukherjee V. Bio-inspired fuzzy logic based tuning of power system stabilizer. Int J Exp Syst Appl 2009;36:9281–92.
[34] Ali ES, Abd-Elazim SM. TCSC damping controller design based on bacteria foraging optimization algorithm for a multimachine power system. Int J Electr Power Energy Syst 2012;37(1):23–30.
[35] Abd-Elazim SM, Ali ES. Bacteria foraging optimization algorithm based SVC damping controller design for power system stability enhancement. Int J Electr Power Energy Syst 2012;43(1):933–40.
[36] Abdul-Ghaffar HI, Ebrahim EA, Azzam M. Design of PID controller for power system stabilization using hybrid particle Swarm-Bacteria foraging optimization. WSEAS Trans Power Syst 2013;8(1):12–23.
[37] Ali ES, Abd-Elazim SM. Power system stability enhancement via bacteria foraging optimization algorithm. Int Arab J Sci Eng 2013;38(3):599–611.
[38] Ali ES, Abd-Elazim SM. BFOA based design of PID controller for two area load frequency control with nonlinearities. Int J Electr Power Energy Syst 2013;51:224–31.
[39] Abd-Elazim SM, Ali ES. A hybrid particle swarm optimization and bacterial foraging for optimal power system stabilizers design. Int J Electr Power Energy Syst 2013;46(1):334–41.
[40] Kundur P, Klein M, Rogers GJ, Zywno MS. Application of power system stabilizers for enhancement of overall system stability. IEEE Trans Power Syst 1989;4(2):614–26.
[41] Anderson PM, Fouad AA. Power System Control and Stability. Iowa: Iowa State University Press; 1977.
[42] Yang XS. A New Metaheuristic BAT-Inspired Algorithm. Nature inspired cooperative strategies for optimization (NICSO), studies in computational intelligence, vol. 284. Springer; 2010. p. 65–74.
[43] Yang XS. BAT Algorithm for Multiobjective Optimization. Int J Bio-Inspired Comput 2011;3(5):267–74.
[44] Bora TC, Coelho LS, Lebensztajn L. BAT-inspired optimization approach for the brushless DC wheel motor problem. IEEE Trans Magn 2012;48(2):947–50.
[45] Yang XS, Gandomi AH. BAT algorithm: a novel approach for global engineering optimization. Eng Comput 2012;29(5):464–83.
[46] Taha AM, Tang AYC. BAT algorithm for rough set attribute reduction. J Theor Appl Inf Technol 2013;51(1):1–8.
[47] Rakesh V, Aruna SB, Raju TD. Combined economic load and emission dispatch evaluation using BAT algorithm. Int J Eng Res Appl 2013;3(3):1224–9.
[48] Ramesh B, Mohan VCJ, Reddy VCV. Application of BAT algorithm for combined economic load and emission dispatch. Int J Electr Electron Eng Telecommun 2013;2(1):1–9.
[49] Yang Xin-She. BAT algorithm: literature review and applications. Int J Bio-Inspired Comput 2013;5(3):141–9.
[50] Biswal S, Barisal AK, Behera A, Prakash T. Optimal power dispatch using BAT algorithm. In: Int conference on energy efficient technologies for sustainability (ICEETS), Nagercoil; 10–12 April 2013. p. 1018–23.
[51] Kheirollahi R, Namdari F. Optimal coordination of overcurrent relays based on modified BAT optimization algorithm. Int Electr Eng J (IEEJ) 2014;5(2):1273–9.
[52] Holland JH. Adaptation in Natural and Artificial Systems. The University of Michigan Press; 1975.
[53] Ashlock A. Evolutionary Computation for Modeling and Optimization. Springer; 2006.
[54] Shayeghi H, Shayanfar HA, Jalilzadeh S, Safari A. Multimachine power system stabilizers design using chaotic optimization algorithm. Energy Conversion Manage 2010;51:1572–80.