BAT Algorithm: A Novel Approach for PSSs Design in Multimachine Power System

E. S. Ali[1,2]

1-Electric Power and Machine Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt,
Email: ehabsalimalisalama@yahoo.com
2-Electrical Department, Faculty of Engineering, Jazan University, Jazan, KSA, esalama@jazanu.edu.sa

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.**

Key-Words: Power System Stabilizers; BAT Search Algorithm; Genetic Algorithm; Multimachine System; Power System Stability; Low Frequency Oscillations.

1. 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. 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 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. 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 and non-adaptive tuning under various 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 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 [33–47]. 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 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 performance for suppressing the low frequency oscillations under various operating conditions and disturbances.

2. Mathematical Problem Formulation
2.1 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:

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

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 a point are usually used in the design of PSS. Therefore, the state equation of a power system with m PSSs can be formed as:

$$\dot{X} = AX + BU \qquad (2)$$

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.

2.2 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 [48]. 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:

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

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. Also, 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 [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 second, the values of time constants T_{2i} and T_{4i} are fixed at a reasonable value of 0.05 second. The stabilizer gain K_i and time constants T_{1i}, and T_{3i} are remained to be determined.
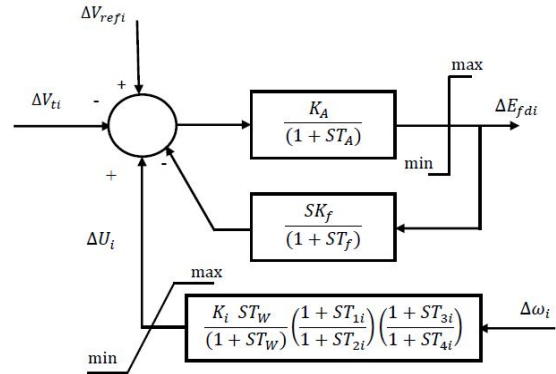

Fig. 1. Block diagram of ith PSS with excitation system

2.3 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 [49]. 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.
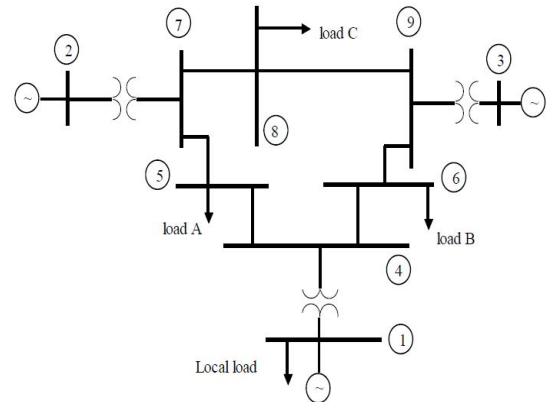

Fig. 2. Multimachine test system.

Table (1) Loading conditions for the system (in p.u.).						
	Light		Normal case		Heavy	
Generator	P	Q	P	Q	P	Q
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	P	Q	P	Q	P	Q
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

3. 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 [50-53] 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 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 [54-57].

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 [58-59]:

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

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

$$x_i^t = x_i^{t-1} + v_i^t \qquad (6)$$

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 [60-62].

$$x_{new} = x_{old} + \varepsilon L^t \qquad (7)$$

Where, $\varepsilon \in [-1, 1]$ is a random number, while L^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:

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

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.
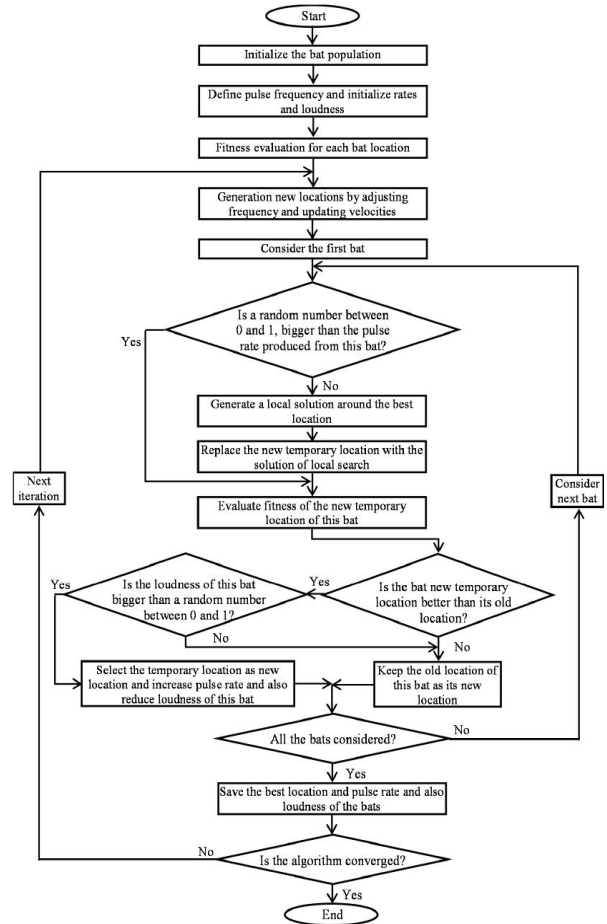

Fig. 3. Flow chart of BAT search algorithm.

4. 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:

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

This will place the system closed loop eigenvalues in the D-shape sector characterized by $\sigma_{ij} \leq \sigma_0$ and $\xi_{ij} \rangle \xi_0$ as shown in Fig. 4.
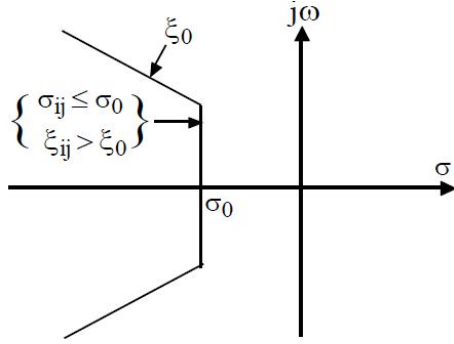
Fig. 4. D-shaped sector in the negative half of s plane.

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 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:

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

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

$$T_{3i}^{min} \leq T_{3i} \leq T_{3i}^{max} \qquad (10)$$

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.

5. Results and Simulations

In this section, the superiority of the proposed BAT algorithm in designing PSS compared with optimized PSS with GA [63-64] 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).
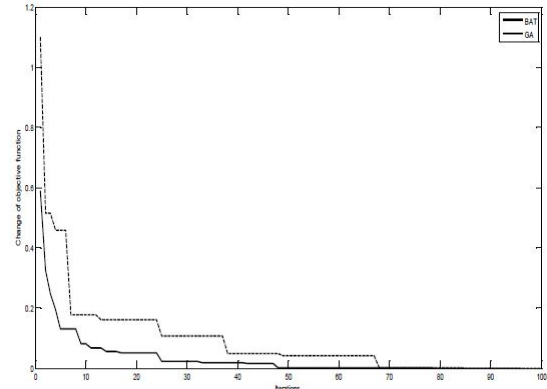

Fig. 5. Variations of objective functions.

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

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

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

5.1 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 second near bus 7. Figs. 6-7, show the response of $\Delta\omega_{12}$ and $\Delta\omega_{13}$ 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 second with BATPSS, 1.8 second for GAPSS, and 2.56 second with CPSS so the designed controller is qualified for supplying adequate damping to the low frequency oscillations.
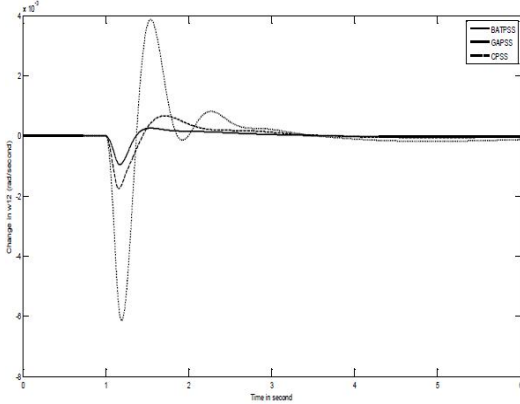

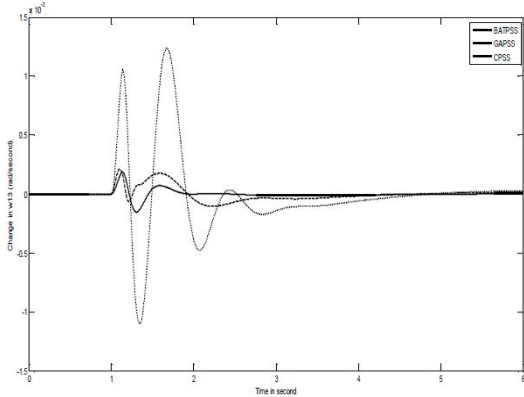Fig. 6. Change in $\Delta\omega_{12}$ for normal load.

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

5.2 Response under light load condition:

Figs. 8-9, 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 second for BATPSS, GAPSS, and CPSS respectively. Hence, 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.
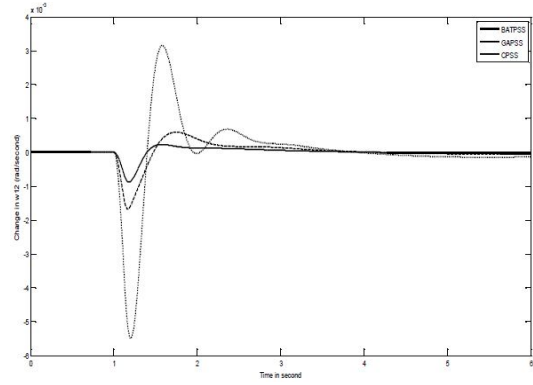

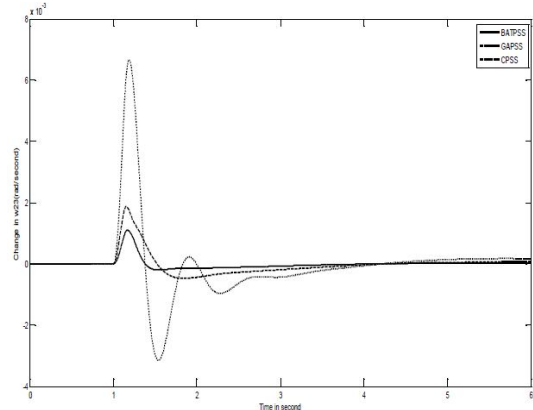Fig. 8. Change in $\Delta\omega_{12}$ for light load.

Fig. 9. Change in $\Delta\omega_{23}$ for light load.

5.3 Response under heavy load condition:

Figs. 10-11, 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 second for BATPSS, GAPSS, and CPSS respectively. Hence, BATPSS controller greatly enhances the damping characteristics of power system. Furthermore, the settling time of the proposed controller is smaller than that in [37, 39].
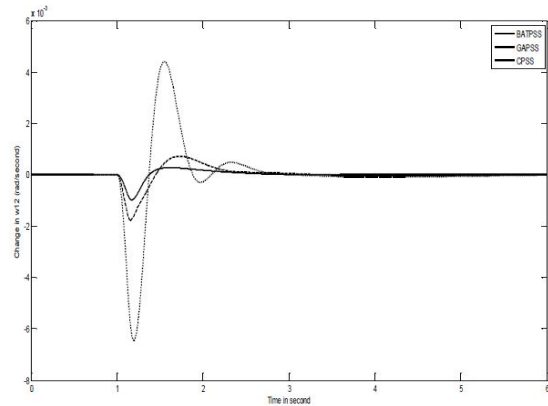

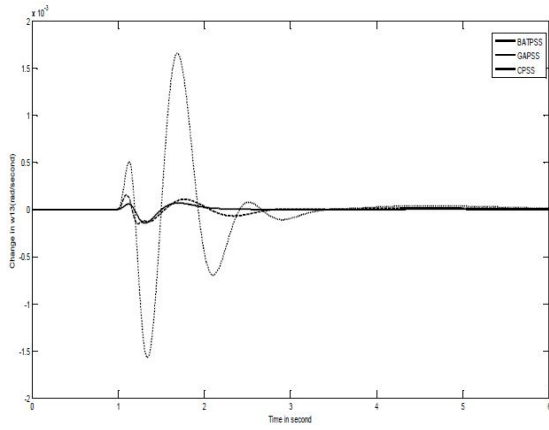Fig. 10. Change in $\Delta\omega_{12}$ for normal load.

Fig. 11. Change in $\Delta\omega_{13}$ for normal load.

5.4 Response under small disturbance:

Figs. 12-13, 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.
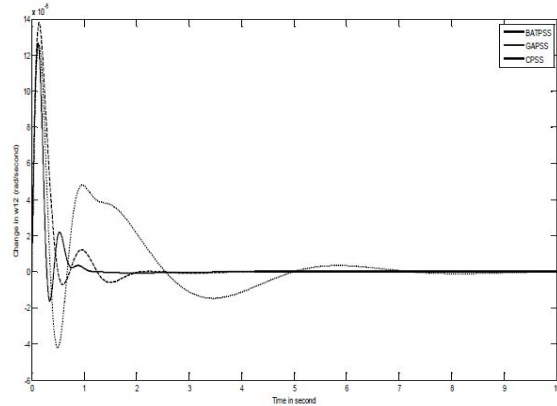

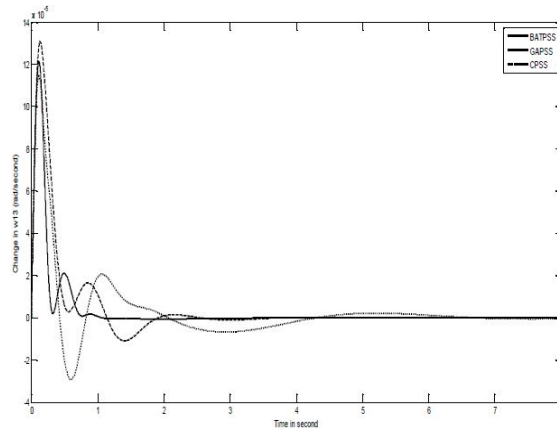Fig. 12. Change in $\Delta\omega_{12}$ for 20% change in Tm.

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

5.5 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:

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

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

It is noteworthy that the lower the value of these indices is, the better the system response in terms of time domain characteristics [65-67]. 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 [68].

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

6. 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.

Appendix
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] G. Rogers, "Power System Oscillations", The Springer International Series in Engineering and Computer Science 2000.

[2] K. R. Padiyar, "Power System Dynamics Stability and Control", Second edition, BS Publications, Hyderabad, India, 2008.

[3] J. Machowski, J. Bialek, and J. Bumby, "Power System Dynamics Stability and Control", Second edition, Wiley, 2009.

[4] X. F. Wang, Y. Song, M. Irving, "Modern Power Systems Analysis", 2008, Springer.

[5] Y. Zhang, G. P. Chen, O. P. Malik and G. S. Hope, "An Artificial Neural Network Based Adaptive Power System Stabilizer", IEEE Transactions on Energy Conversion, Vol. 8, No. 1, 1993, pp. 71-77.

[6] A. Mahabuba, and M.A. Khan, "Small Signal Stability Enhancement of A Multi-Machine Power System Using Robust and Adaptive Fuzzy Neural Network Based Power System Stabilizer", European Transactions on Electrical Power, 2009, Vol.19, No. 7, pp. 978-1001.

[7] R. Segal, A. Sharma, and M. L. Kothari, "A Self-Tuning Power System Stabilizer Based on Artificial Neural Network", Int. J. of Electrical Power and Energy Systems, Vol. 26, No. 3, July 2004, pp. 423-430.

[8] H. Ye, and Y. Liu, "Design of Model Predictive Controllers for Adaptive Damping of Inter-Area Oscillations", Int. J. of Electrical Power and Energy Systems ,Vol. 45, No. 1, February 2013, pp. 509-518.

[9] H. A. Toliyat, J. Sadeh, and R. Ghazi, "Design of Augmented Fuzzy Logic Power System Stabilizers to Enhance Power Systems Stability", IEEE Transactions on Energy conversion, Vol. 11, No. 1 , March 1996, pp. 97-103.

[10] Z. S. El-Razaz, and E. S. Ali, "Design of An Adaptive PSS Using FLC For Multi-Machine Power System", Proceedings of the Universities Power Engineering Conference 36, UPEC 2001, Swansea, September 12-14, 2001 pp. 1833-1838.

[11] S. K. Yee, J. V. Milanovic, "Fuzzy Logic Controller for Decentralized Stabilization of Multimachine Power Systems", IEEE Transactions on Fuzzy Systems, Vol. 16, No. 4, 2008, pp. 971-981.

[12] A. M. El-Zonkoly, A. A. Khalil, N.M. Ahmied, "Optimal Tuning of Lead-Lag and Fuzzy Logic Power System Stabilizers Using Particle Swarm Optimization", Int. J. of Expert Systems with Applications, Vol. 36, 2009, pp. 2097- 2106.

[13] T. Hussein, M.S. Saad, A.L. Elshafei, A. Bahgat, "Robust Adaptive Fuzzy Logic Power System Stabilizer", Int. J. of Expert Systems with Applications, Vol. 36, 2009, pp. 12104-12112.

[14] T. Hussein, M.S. Saad, A.L. Elshafei, and A. Bahgat, "Damping Inter-Area Modes of Oscillation Using an Adaptive Fuzzy Power System Stabilizer", Int. J. of Electric Power Systems Research, Vol. 80, 2010, pp.1428-1436.

[15] B. Yousefpour, M. B. Tabar, M. Nikzad, S. S. S. Farahani, and H. Tourang, "Fuzzy Scaled Power System Stabilizer In Multi Machine Power System", Life Science Journal, Vol. 9, No. 4, December 2012, pp. 5924-5928.

[16] T. C. Yang, "Applying H_∞ Optimization Method to Power System Stabilizer Design Part 1: Single-Machine Infinite-Bus Systems", Int. J. of Electrical Power Energy System, Vol. 19, No. 1, 1997, pp. 29-35.

[17] Z. S. EL-Razaz, M. E-D. Mandour, and E. S. Ali, "Damping Controller Design for Power Systems Using LMI and GA Techniques", 41st International Universities Power Engineering Conference, UPEC, September 6-8, 2006, pp. 500 - 506.

[18] Z. M. M. Ali, and A. I. Malikov, "Robust Techniques for Designing Power System Stabilizer", J. of Theoretical and Applied Information Technology, Vol. 9, No.1, November 2009, pp. 20-28

[19] R. Jayapal, and J. K. Mendiratta, " H_∞ Controller Design for a SMIB Based PSS Model", J. of Theoretical and Applied Information Technology, Vol. 11, No. 1, 2010, pp. 73-82.

[20] A. N. Cuk Supriyadi, H. Takano, J. Murata, T. Goda, "Adaptive Robust PSS to Enhance Stabilization of Interconnected Power Systems with High Renewable Energy Penetration", Renewable Energy, Vol. 63, March 2014, pp. 767-774.

[21] H. Werner, P. Korba, and T. C. Yang, "Robust Tuning of Power System Stabilizers Using LMI Techniques", IEEE Transaction on Control System Technology, Vol. 11, No. 1, 2003, pp. 147-152.

[22] Y. Peng, Q. M. Zhu, and H. Nouri, "Robust H_2 Power System Stabilizer Design Using LMI Techniques", Proceedings of 2011 International Conference on Modeling, Identification and Control (ICMIC), pp. 405 - 410

[23] M. Yue, and R. A. Schlueter, "μ-Synthesis Power System Stabilizer Design Using a Bifurcation Subsystem Based Methodology", IEEE Transaction on Power Systems, Vol. 18, No. 4, Nov. 2003, pp. 1497-1506.

[24] M. Kothari, L. Bhattacharya, and J. Nanda, "Adaptive Power System Stabilizer Based On Pole Shifting Technique", Proceedings of Generation, Transmission and Distribution, Vol. 143, No. 1, 2002, pp. 96-98.

[25] M. K. El-Sherbiny, M. M. Hasan, G. El-Saady, and A. M. Yousef, "Optimal Pole Shifting For Power System Stabilization", Int. J. of Electric Power Systems Research, Vol. 66, No. 3, September 2003, pp. 253-258.

[26] M. A. Abido, "Simulated Annealing Based Approach to PSS and FACTS Based Stabilizer Tuning", Int. J. of Electrical Power and Energy Systems, Vol. 22, No. 4, May 2000, pp. 247-258

[27] M. A. Abido, and Y. L. Abdel-Magid, "A Tabu Search Based Approach to Power System Stability Enhancement via Excitation and Static Phase Shifter Control", Int. J. of Electric Power Systems Research, Vol. 52, No. 2, November 1999, pp. 133-143.

[28] M. A. Abido, "A Novel Approach to Conventional Power System Stabilizer Design Using Tabu Search", Electrical Power and Energy Systems, Vol. 21, 1999, pp. 443- 454.

[29] M. A. Abido, and Y. L. Abdel-Magid, "A Genetic Based Fuzzy Logic Power System Stabilizer for Multimachine Power Systems", In Proceedings of IEEE conference, 1997, pp. 329-334.

[30] L. H. Hassan, M. Moghavvemi, H. A. F. Almurib, K. M. Muttaqi, and V.G. Ganapathy, "Optimization of Power System Stabilizers Using Participation Factor and Genetic Algorithm", Int. J. of Electrical Power and Energy Systems, Vol. 55, 2014, pp. 668-679.

[31] A. Jalilvand, and R. A. E. Khalkhali, "Optimal Design of PID Power System Stabilizer in Multimachine Power System Using PSO and Genetic Algorithm", Int. Review of Electrical Engineering, Vol. 6, No. 2, 2011, pp. 907-912.

[32] K. M. Passino, "Biomimicry of Bacterial Foraging for Distributed Optimization and Control", IEEE Control System Magazine, Vol. 22, No. 3, June 2002, pp. 52-67.

[33] S. P. Ghoshal, A. Chatterjee, and V. Mukherjee, "Bio-Inspired Fuzzy Logic Based Tuning of Power System Stabilizer", Int. J. of Expert Systems with Applications, Vol. 36, 2009, pp. 9281-9292.

[34] E. S. Ali, S. M. Abd-Elazim, "Coordinated Design of PSSs and TCSC via Bacterial Swarm Optimization Algorithm in a Multimachine Power System", Int. J. of Electrical Power and Energy Systems, Vol. 36, No. 1, March 2012, pp. 84-92.

[35] E. S. Ali, S. M. Abd-Elazim, "Coordinated Design of PSSs and SVC via Bacteria Foraging Optimization Algorithm in a Multimachine Power System", Int. J. of Electrical Power and Energy Systems, Vol. 41, No. 1, October 2012, pp. 44-53.

[36] H. I. Abdul-Ghaffar, E. A. Ebrahim, M. Azzam, "Design of PID Controller for Power System Stabilization Using Hybrid Particle Swarm-Bacteria Foraging Optimization", WSEAS Transactions on Power Systems, Vol. 8, No. 1, January 2013, pp. 12-23.

[37] E. S. Ali, and S. M. Abd-Elazim, "Bacteria Foraging Optimization Algorithm Based Load Frequency Controller for Interconnected Power System", Int. J. of Electrical Power and Energy Systems, Vol. 33, No. 3, March 2011, pp. 633-638.

[38] E. S. Ali and S. M. Abd-Elazim, "TCSC Damping Controller Design Based on Bacteria Foraging Optimization Algorithm for a Multimachine Power System", Int. J. of Electrical Power and Energy Systems, Vol. 37, No. 1, May 2012, pp. 23-30.

[39] S. M. Abd-Elazim, and E. S. Ali, "Bacteria Foraging Optimization Algorithm Based SVC Damping Controller Design for Power System Stability Enhancement", Int. J. of Electrical Power and Energy Systems, Vol. 43, No. 1, December 2012, pp. 933-940.

[40] E. S. Ali and S. M. Abd-Elazim, "BFOA based Design of PID Controller for Two Area Load Frequency Control with Nonlinearities", Int. J. of Electrical Power and Energy Systems, Vol. 51, 2013, pp. 224-231.

[41] S. M. Abd-Elazim and E. S. Ali, "A Hybrid Particle Swarm Optimization and Bacterial Foraging for Optimal Power System Stabilizers Design", Int. J. of Electrical Power and Energy Systems, Vol. 46, No. 1, March 2013, pp. 334-341.

[42] E. S. Ali and S. M. Abd-Elazim, "Power System Stability Enhancement via Bacteria Foraging Optimization Algorithm", Int. Arabian J. for Science and Engineering (AJSE), Vol. 38, No. 3, March 2013, pp. 599-611

[43] S. M. Abd-Elazim and E. S. Ali, "Optimal Power System Stabilizers Design for Multimachine Power System Using Hybrid BFOA-PSO Approach", Int. J. of WSEAS Transactions on Power Systems, Vol. 8, No. 2, April 2013, pp. 85-94.

[44] S. M. Abd-Elazim and E. S. Ali, "Synergy of Particle Swarm Optimization and Bacterial Foraging for TCSC Damping Controller Design", Int. J. of WSEAS Transactions on Power Systems, Vol. 8, No. 2, April 2013, pp. 74-84.

[45] E. S. Ali and S. M. Abd-Elazim, "Optimal Power System Stabilizers Design for Multimachine Power System via Hybrid Approach", Int. J. of Electric Engineering (JEE), Vol. 13, No. 3, September 2013, pp. 83-90.

[46] E. S. Ali and S. M. Abd-Elazim, "Optimal SSSC Design for Power Systems via Hybrid Approach", Int. J. of Electric Engineering (JEE), Vol. 14, No. 1, March 2014, pp. 138-147.

[47] A. S. Oshaba and E. S. Ali, "Assessment Study on Speed Control of DC Series Motor Fed by Photovoltaic System via Bacterial Foraging", Int. J. of Electric Engineering (JEE), Vol. 14, No. 3, September 2014, pp. 195-203.

[48] P. Kundur, M. Klein, G. J. Rogers, and M. S. Zywno, "Application of Power System Stabilizers for Enhancement of Overall System Stability", IEEE Transactions on Power Systems, Vol. 4, No. 2, May 1989, pp. 614 -626.

[49] P. M. Anderson and A. A. Fouad, "Power System Control and Stability", Iowa State University Press, Iowa, 1977.

[50] X. S. Yang, "A New Metaheuristic BAT-Inspired Algorithm", Nature Inspired Cooperative Strategies for Optimization (NICSO), Studies in Computational Intelligence, Vol. 284. Springer; 2010, p. 65–74.

[51] X. S. Yang, "BAT Algorithm for Multiobjective Optimization", Int. J. Bio-Inspired Computation", Vol. 3, No. 5, 2011, pp. 267-274.

[52] T. C. Bora, L. S. Coelho, and L. Lebensztajn, "BAT-Inspired Optimization Approach for the Brushless DC Wheel Motor Problem", IEEE Transactions on Magnetics, Vol. 48, No. 2, 2012, pp. 947-950.

[53] X. S. Yang and A. H. Gandomi, "BAT Algorithm: A Novel Approach for Global Engineering Optimization", Engineering Computations, Vol. 29, No. 5, 2012, pp. 464-483.

[54] A. M. Taha, and A. Y. C. Tang, "BAT Algorithm for Rough Set Attribute Reduction", J. of Theoretical and Applied Information Technology, May 2013, Vol. 51, No.1, pp. 1-8.

[55] V. Rakesh, S. B. Aruna, and T. D. Raju, "Combined Economic Load And Emission Dispatch Evaluation Using BAT Algorithm", Int. J. of Engineering Research and Applications, Vol. 3, No.3, May-Jun 2013, pp.1224-1229.

[56] A. S. Oshaba, E. S. Ali and S. M. Abd-Elazim, "BAT Algorithm: A Novel Approach for MPPT Control Design of PV Generator Supplied SRM", International Journal of Electric Engineering (JEE), Vol. 15, No. 1, March 2015, pp. 293-302.

[57] Xin-She Yang, "BAT Algorithm: Literature Review and Applications", Int. J. Bio-Inspired Computation, Vol. 5, No.3, 2013, pp. 141-149.

[58] S. Biswal, A. K.Barisal, A. Behera, and T. Prakash, "Optimal Power Dispatch Using BAT Algorithm", Int. Conference on Energy Efficient Technologies for Sustainability (ICEETS), Nagercoil 10-12 April 2013, pp.1018- 1023.

[59] R. Kheirollahi, and F. Namdari, "Optimal Coordination of Overcurrent Relays Based on Modified BAT Optimization Algorithm", Int. Electrical Engineering Journal (IEEJ), Vol. 5, No. 2, 2014, pp. 1273-1279.

[60] N. N. Islam, M. A. Hannan, H. Shareef, and A. Mohamed, "Power System Stabilizer Design Using BAT Optimization Algorithm in Multimachine Power System", IEEE SCoReD Conference, 16-17 Dec. 2013, 2013, 540-544.

[61] W. Peres, E. J. De Oliveira, J. A. Passos Filho, and I. C. Da Silva Junior, "Coordinated Tuning of Power System Stabilizers Using Bio-Inspired Algorithms", Int. J. of Electrical Power and Energy Systems, 2015, 64, pp. 419-428.

[62] A. S. Oshaba, E. S. Ali, and S. M. Abd-Elazim, "MPPT Control Design of PV System Supplied SRM Using BAT Search Algorithm", Sustainable Energy, Grids and Networks, (SEGAN Elsevier), Vol. 2C, 2015, pp. 51-60.

[63] J. H. Holland, "Adaptation in Natural and Artificial Systems", the University of Michigan Press, 1975.

[64] A. Ashlock, "Evolutionary Computation for Modeling and Optimization", Springer, 2006.

[65] S. M. Abd-Elazim and E. S. Ali, "New Coordinated Design of PSSs and SVC to Improve Power System Stability via BSO", Int. J. of Electric Engineering (JEE), Vol. 15, No. 1, March 2015, pp. 21-30.

[66] A. S. Oshaba, E. S. Ali and S. M. Abd-Elazim, "Speed Control of SRM Fed by Photovoltaic System Using Ant Colony Optimization Algorithm", Int. J. of Electric Engineering (JEE), Vol. 15, No. 1, March 2015, pp. 46-54.

[67] A. S. Oshaba, E. S. Ali and S. M. Abd-Elazim, "MPPT Control Design of PV Generator Powered DC Motor-Pump System based on Artificial Bee Colony Algorithm", Int.J. of Electrical Engineering (JEE), Vol. 14, No. 4, December 2014, pp. 315-324.

[68] H. Shayeghi, H. A. Shayanfar, S. Jalilzadeh, and A. Safari, "Multimachine Power System Stabilizers Design Using Chaotic Optimization Algorithm", Energy Conversion and Management, Vol. 51, 2010, pp. 1572-1580.