Stability Enhancement of Multimachine Power System via New Coordinated Design of PSSs and SVC

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Abstract- In this paper, the assessment of new coordinated design of Power System Stabilizers (PSSs) and Static Var Compensator (SVC) in a multimachine power system via statistical method is proposed. The coordinated design problem of PSSs and SVC over a wide range of loading conditions is handled as an optimization problem. The Bacterial Swarming Optimization (BSO), which synergistically couples the Bacterial Foraging (BF) with the Particle Swarm Optimization (PSO), is employed to seek for optimal controllers parameters. By minimizing the proposed objective function, in which the speed deviations between generators are involved; stability performance of the system is enhanced. To compare the capability of PSS and SVC, both are designed independently, and then in a coordinated manner. Simultaneous tuning of the BSO based coordinated controller gives robust damping performance over wide range of operating conditions and large disturbance in compare to optimized PSS controller based on BSO (BSOPSS) and optimized SVC controller based on BSO (BSOSVC). Moreover, a statistical T test is executed to validate the robustness of coordinated controller versus uncoordinated one.

Key-Words: SVC; PSSs; Multimachine Power System; Coordinated design; Bacteria Swarm Optimization; Statistical Assessment.

1. Introduction

The power transfer in an integrated power system is forced by transient stability, voltage stability and small signal stability. These factors limit a full utilization of available transmission corridors. Flexible AC Transmission System (FACTS) is the technology that supplies the needed corrections of the transmission functionality in order to use the existing transmission facilities and hence, reducing the gap between the stability limit and thermal limit [1].

Recently, there has been a surge of interest in the use and development of FACTS controllers in power transmission systems [2-6]. These controllers utilize power electronics devices to provide more flexibility to AC power systems. The most popular type of FACTS devices in terms of application is the SVC. This device is well known to improve power system properties such as steady state stability limits, voltage regulation and var compensation, dynamic over voltage and under voltage control, and mitigate power system oscillations. The SVC is an electronic generator that dynamically controls the flow of power through a variable reactive admittance to the transmission network.

In last few years, many researchers have introduced techniques for designing SVC to improve the damping of electromechanical oscillations of power systems and enhance power

systems stability. A robust control theory in designing SVC controller to damp out power system swing modes is discussed in [7]. An adaptive network based fuzzy inference system (ANFIS) for SVC is illustrated in [8] to alleviate the damping of power systems. A multi input, single output fuzzy neural network is developed in [9] for voltage stability evaluation of the power systems with SVC. A method of determining the location of a SVC to enhance the stability of power system is suggested in [10]. A systematic approach for designing SVC controller, based on wide area signals, to increase the damping of power system oscillations is introduced in [11]. Genetic Algorithm (GA) optimization technique is employed for the simultaneous tuning of a PSS and a SVC based controller in [12]. A state estimation problem of power systems incorporating various FACTS devices is addressed in [13]. A novel hybrid method for simulation of power systems equipped with SVC is suggested in [14]. The design of SVC with delayed input signal using a state space model based on Pade approximation method is presented in [15]. A new optimization algorithm known as Bacterial Foraging (BF) for designing SVC to damp power system electromechanical oscillations for single machine infinite bus system and multimachine system are introduced in [16-17]. An application of probabilistic theory to the coordinated design of PSSs and SVC is employed in [18]. The application

of the decentralized modal control method for pole placement in multimachine power system utilizing FACTS devices is developed in [19]. The parameter tuning of a PID controller for a FACTS based stabilizer employing multi-objective evolutionary algorithm is illustrated in [20]. A comprehensive assessment of the effects of the PSS and FACT device when applied independently and also through coordinated application is carried out in [21]. other works related to dynamical systems, computational techniques, collaborative systems, time delay systems, recent methods on physical polluting agents and environment modelling and simulation, interactive multimedia systems, on advanced control of energy systems, defence systems, modelling, simulation and optimization in electrical systems are given in [22-36].

Different optimization techniques have been adopted to solve a variety of engineering problems in the past decade. GA has attracted the attention in the field of controller parameter optimization. Although GA is very satisfactory in finding global or near global optimal result of the problem; it needs a very long run time that may be several minutes or even several hours depending on the size of the system under study. Moreover swarming strategies in bird flocking and fish schooling are used in the PSO and introduced in [37]. However, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Also, the algorithm cannot work out the problems of scattering and optimization [38-41]. In addition, the algorithm pains 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 BF scheme has been addressed by [42-44] and further established recently by [45-52]. The BF algorithm depends on random search directions which may lead to delay in reaching the global solution. A new algorithm BF oriented by PSO is developed that combine the above mentioned optimization algorithms [53-54]. This combination aims to make use of PSO ability to exchange social information and BF ability in finding a new solution by elimination and dispersal. This new hybrid algorithm called Bacterial Swarm Optimization (BSO) is adopted in this paper to solve the above mentioned problems and drawbacks.

In this paper, a comprehensive assessment of the effects of the PSSs and SVC based control when applied independently and also through coordinated application has been carried out. The design problem of PSS and SVC based controller to improve power system stability is transformed into an optimization problem. The design objective is to improve the stability of a multimachine power system, subjected to a disturbance. BSO technique is employed to search for the optimal PSS and SVC controller parameters. BSO based SVC controller (BSOSVC) and BSO based PSS (BSOPSS) are presented and their performances are compared with the coordinated design of BSOPSS and BSOSVC. Simulation results are presented to demonstrate the effectiveness of the proposed controller to improve the power system dynamic stability. Furthermore, a statistical T test is performed to prove the robustness of coordinated controller versus uncoordinated one.

2. Problem Statement
A. Power System Model
A power system can be modelled 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. In this study $X = [\delta, \omega, E'_q, E_{fd}, V_f]^T$ and U is the PSS and SVC output signals. Here, 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.

In the design of PSS and SVC, the linearized incremental models around an equilibrium point are usually employed. Therefore, the state equation of a power system with n machines and m PSS and SVC can be written 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 evaluated at a certain operating point. X is a $5n \times 1$ state vector and U is an $m \times 1$ input vector.

B. PSS Modelling and Damping Controller Design
The operating function of a PSS is to produce a proper torque on the rotor of the machine involved in such a way that the phase lag between the exciter input and the machine electrical torque is compensated. The supplementary stabilizing signal considered is one proportional to speed. A widely speed based used conventional PSS is considered

throughout the study [55]. The block diagram of the ith PSS with excitation system is shown in Fig. 1. Where $\Delta\omega_i$ is the deviation in speed from the synchronous speed. This type of stabilizer consists of a washout filter, a dynamic compensator. The output signal is fed as a supplementary input signal, U_i to the regulator of the excitation system. The washout filter, which essentially is a high pass filter, is used to reset the steady state offset in the output of the PSS. The value of the time constant T_W is usually not critical and it can range from 0.5 to 20 s. The dynamic compensator is made up to two lead lag circuits and an additional gain. The adjustable PSS parameters are the gain of the PSS, K_i and the time constants, $T_{1i}-T_{4i}$. The lead lag block present in the system provides phase lead compensation for the phase lag that is introduced in the circuit between the exciter input and the electrical torque. The required phase lead can be derived from the lead lag circuit even if the denominator portion consisting of T_{2i} and T_{4i} gives a fixed lag angle [56].
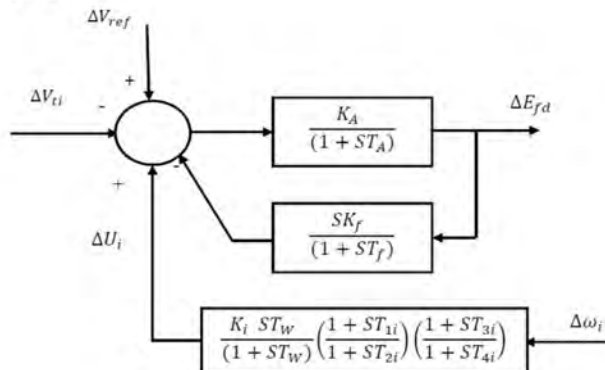

Fig. 1. Block diagram of ith PSS with excitation system.

C. SVC Modelling and Damping Controller Design

The thyristor controlled reactor (TCR) in parallel with a fixed capacitor bank shown in Fig. 2, is used in this paper to develop the desired SVC model. The system is then shunt connected to the AC system through a set up transformer to bring the voltages up to the required transmission levels [8].

It is obvious from (3) and Fig. 3, if the firing angle α of the thyristors is controlled; SVC is able to control the bus voltage magnitude. Time constant (T_r) and gain (K_r) represent the thyristors firing control system. The SVC parameters are given in Appendix.

$$\dot{B}_e = \frac{1}{T_r}\left[-B_e + K_r(V_{ref} - V_t + V_s)\right] \qquad (3)$$

The variable effective susceptance of the TCR is given by

$$B_V = -\frac{(2\pi - 2\alpha + \sin 2\alpha)}{\pi X_L} \quad \pi/2 \le \alpha \le \pi \qquad (4)$$

Where X_L is the reactance of the fixed inductor of SVC. The effective reactance is

$$X_e = X_C \frac{\pi/r_x}{\sin 2\alpha - 2\alpha + \pi(2 - 1/r_x)} \qquad (5)$$

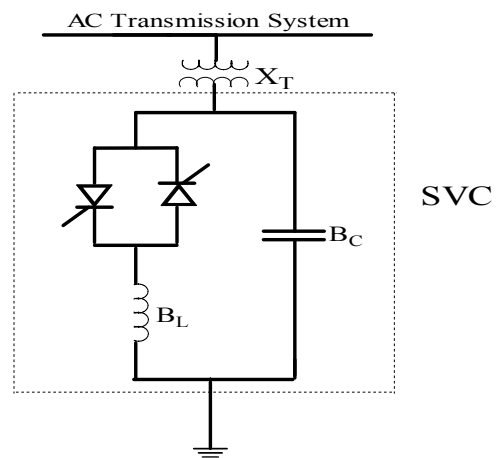Where $X_e = -1/B_e$ and $r_x = X_e/X_L$.
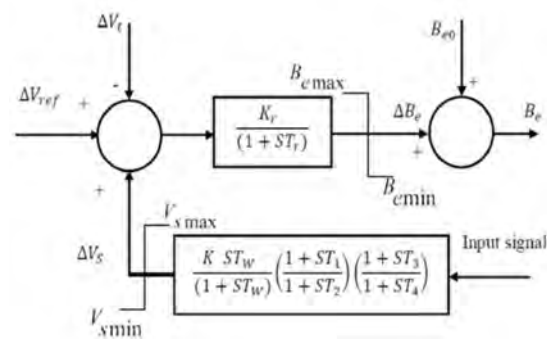

Fig. 2. SVC equivalent circuit.

Fig. 3. Block diagram of SVC.

An auxiliary stabilizing signal from speed can be imposed on the SVC control loop. The block diagram of a SVC with auxiliary stabilizing signal is shown in Fig. 3. This controller may be considered as a lead lag compensator. It comprises gain block, limiter, signal washout block and two stages of lead lag compensator. The parameters of the damping controllers for the purpose of simultaneous coordinated design are obtained using the BSO algorithm.

D. System under Study and SVC Position

Fig. 4 shows the single line diagram of the test system used. Details of system data are given in [57]. The participation matrix can be used in mode identification. Table (1) shows the eigenvalues, and frequencies associated with the rotor oscillation modes of the system. Examining Table (1) shows that the 0.2371 Hz mode is the interarea mode with G1 swinging against G2 and G3. The 1.2955 Hz mode is the intermachine oscillation local to G2. Also, the 1.8493 Hz mode is the intermachine mode local to G3. The positive real part of eigenvalue of G1 indicates instability of the system. The system and generator loading levels are given in Table (2).

In order to determine the suitable position of the SVC in the system, two strategies will be shown below. The first one is based on studying the effect of load percentage while the second is concerned with the line outage on system voltages [58]. Tables (3 and 4) show the effect of load percentage and line outage on bus voltages of the system. It can be noticed that the voltages are affected significantly at buses numbered 5 and 6, respectively which are load buses. The reasons that cause the significant voltage change are the connection of these buses with the longest lines in the system which has greater resistances and reactances than the others. Consequently, the choice of buses number 5 or 6 for placing the SVC controller is expected to be the more suitable choice. Because both of them are close to machine number 1 which causes the system instability due to its unstable mechanical mode. Moreover, bus number 5 is the worst one and will be considered in this paper as the best position for installing the SVC controller.
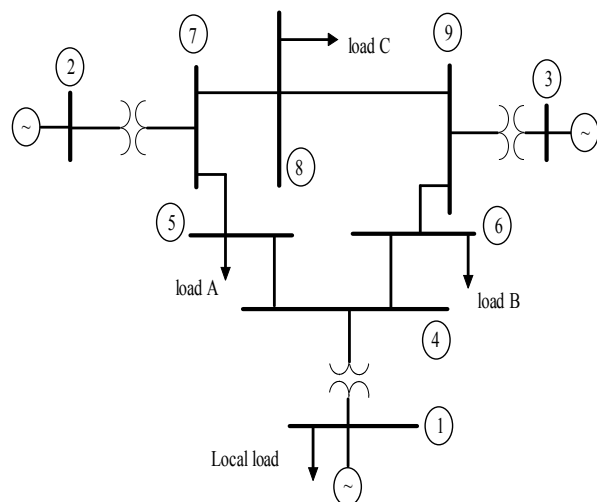

Fig. 4. System under study.

Table (1) The eigenvalues, and frequencies of the rotor oscillation modes of the system.

Generator	Eigenvalues	Frequencies	Damping ratio ξ
G1	**+0.15 $\pm$ 1.49j**	0.2371	**-0.1002**
G2	-0.35 $\pm$ 8.14j	1.2295	0.0430
G3	-0.67 $\pm$ 11.62j	1.8493	0.0576

Table (2) Loading of the system (in p.u).

	Light		Normal case		Heavy	
Generator	P	Q	P	Q	P	Q
G1	0.965	0.22	1.716	0.6205	3.57	1.81
G2	1.0	-0.193	1.63	0.0665	2.2	0.713
G3	0.45	-.267	0.85	-1086	1.35	0.43
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	1.00	0.35	1.6	0.65
at G1	0.6	0.2	1.00	0.35	1.6	0.65

Table (3) Effect of load percentage on load bus voltages.

% Load	0.25	0.50	0.75	1.00	1.25	1.50	1.75
Bus 4	1.06	1.05	1.04	1.03	1.01	0.99	0.98
Bus 5	1.06	1.04	1.02	0.99	0.96	**0.94**	**0.90**
Bus 6	1.06	1.05	1.03	1.01	0.99	0.97	**0.94**
Bus 7	1.05	1.04	1.04	1.03	1.01	1.00	0.98
Bus 8	1.05	1.04	1.03	1.02	0.99	0.98	0.96
Bus 9	1.05	1.05	1.04	1.03	1.02	1.01	1.00

Table (4) Effect of line outage on load bus voltages.

line	4-5	4-6	5-7	6-9	7-8	8-9
Bus 4	1.039	1.028	0.996	1.005	1.016	1.022
Bus 5	**0.839**	0.998	**0.938**	0.968	0.974	0.989
Bus 6	1.020	**0.942**	0.975	0.964	0.999	1.009
Bus 7	0.988	1.022	1.017	1.016	1.019	1.010
Bus 8	0.989	1.006	1.001	1.005	0.969	0.978
Bus 9	1.024	1.017	1.019	1.023	1.013	1.034

3. Objective function

The parameters of the PSSs and SVC may be elected to reduce the following objective function:

$$J = \int_{0}^{\infty} t \left(\left| \Delta w_{12} \right| + \left| \Delta w_{23} \right| + \left| \Delta w_{13} \right| \right) dt \qquad (6)$$

Where $\Delta w_{12} = \Delta w_1 - \Delta w_2$, $\Delta w_{23} = \Delta w_2 - \Delta w_3$, and $\Delta w_{13} = \Delta w_1 - \Delta w_3$.

This index is based on the Integral of Time multiple Absolute Error (ITAE). The merit of this selected performance index is that minimal dynamic plant information is needed. To reduce the computational burden, the value of the wash out time constant T_W is fixed to 10 second, the values of T_{2i} and T_{4i} are kept constant at a reasonable value of 0.05 second and tuning of T_{1i} and T_{3i} are undertaken to reach the net phase lead required by

the system. Based on the objective function J optimization problem can be stated as: Minimize J subjected to:

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

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

$$T_{3i}^{\min} \le T_{3i} \le T_{3i}^{max} \qquad (7)$$

Typical ranges of the optimized parameters are [1-100] for K_i and [0.06-1.0] for T_{1i} and T_{3i}.

This paper focuses on coordinated design of PSSs and SVC via BSO algorithm. The object of the optimization is to search for the optimum controller parameters setting that improve the damping characteristics of the system. Moreover, all controllers are designed simultaneously, taking into consideration the interaction among them.

4. Hybrid BF-PSO Optimization Algorithm

PSO is a stochastic optimization technique that draws inspiration from the behaviour of a flock of birds or the collective intelligence of a group of social insects with limited individual capabilities. In PSO a population of particles is initialized with random positions $\overrightarrow{X}_i$ and velocities $\overrightarrow{V}_i$, and a fitness function using the particle's positional coordinates as input values. Positions and velocities are adjusted, and the function is evaluated with the new coordinates at each time step [37-38]. The velocity and position update equations for the d-th dimension of the i-th particle in the swarm may be given as follows:

$$V_{id}(t+1) = \omega.V_{id}(t) + C_1.\varphi_1.(X_{lid} - X_{id}(t)) +$$

$$C_2.\varphi_2.(X_{gd} - X_{id}(t)) \qquad (8)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \qquad (9)$$

Where X_{lid} is the best position of each bacterial and X_{gd} is the global best bacterial.

On the other hand, the BF is based upon search and optimal foraging decision making capabilities of the Escherichia coli bacteria [53]. The coordinates of a bacterium here represent an individual solution of the optimization problem. Such a set of trial solutions converges towards the optimal solution following the foraging group dynamics of the bacteria population. Chemotactic movement is continued until a bacterium goes in the direction of positive nutrient gradient. After a certain number of

complete swims the best half of the population undergoes reproduction, eliminating the rest of the population. In order to escape local optima, an elimination dispersion event is carried out where, some bacteria are liquidated at random with a very small probability and the new replacements are initialized at random locations of the search space. A detailed description of the complete algorithm can be traced in [53-54]. Also, the flow chart of BSO is shown in Fig. 5.
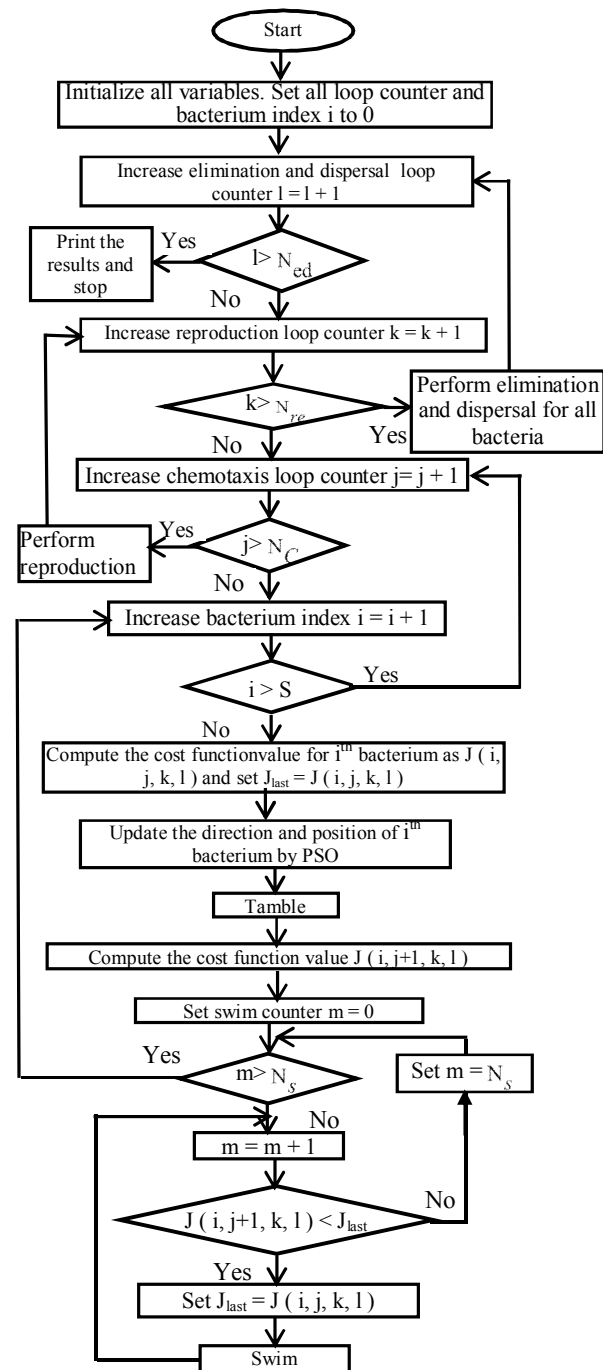

Fig. 5. Flow chart of BSO algorithm.

[Step 1] Initialize parameters n, S, N_C, N_S, N_{re}, N_{ed}, P_{ed}, $C(i)(i = 1,2,.......,N), \phi^i$.

Where,

n : Dimension of the search space,

S : The number of bacteria in population,

N_{re} : The number of reproduction steps,

N_C : The number of chemotactic steps,

N_S : Swimming length after which tumbling of bacteria is performed in a chemotaxis loop,

N_{ed} : The number of elimination-dispersal events to be imposed over the bacteria,

P_{ed} : The probability with which the elimination and dispersal will continue,

$C(i)$: The size of the step taken in the random direction specified by the tumble,

ω : The inertia weight,

C_1, C_2 : The swarm confidence,

$\overrightarrow{\theta}(i, j, k)$: Position vector of the i-th bacterium, in j-th chemotactic step and k-th reproduction,

$\overrightarrow{V_i}$: Velocity vector of the i-th bacterium.

[Step 2] Update the following

$J(i, j, k)$: Cost or fitness value of the i-th bacterium in the j-th chemotaxis, and the k-th reproduction loop.

$\overrightarrow{\theta}\ g\_best$: Position vector of the best position found by all bacteria.

$J_{best}(i, j, k)$: Fitness value of the best position found so far.

[Step 3] Reproduction loop: $k = k + 1$

[Step 4] Chemotaxis loop: $j = j + 1$

[Sub step a] For i=1, 2,…, S, take a chemotaxis step for bacterium i as follows.

[Sub step b] Compute fitness function, $J(i, j, k)$.

[Sub step c] Let $J_{last} = J(i, j, k)$ to save this value since one may find a better cost via a run.

[Sub step d] Tumble: generate a random vector $\Delta(i) \in R^n$ with each element $\Delta_m(i), m = 1,2,.......,n,$ a random number on $[-1, 1]$

[Sub step e] Move: Let

$$\theta(i, j+1, k) = \theta(i, j, k) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}.$$

[Sub step f] Compute $J(i, j + 1, k)$.

[Sub step g] Swim: one considers only the i-th bacterium is swimming while the others are not moving then

i) Let $m = 0$ (counter for swim length).

ii) While $m < N_S$ (have not climbed down too long)

- Let $m = m + 1$

- If $J(i, j+1, k) < J_{last}$ (if doing better),

  Let $J_{last} = J(i, j+1, k)$ and let

  $$\theta(i, j+1, k) = \theta(i, j, k) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \text{ and}$$

  use this $\theta(i, j+1, k)$ to compute the new $J(i, j+1, k)$ as shown in new [sub step f]

- Else, let $m = N_S$. This is the end of the while statement.

[Step 5] Mutation with PSO operator

For i=1, 2,……,S

- Update the $\overrightarrow{\theta}\ g\_best$ and $J_{best}(i, j, k)$

- Update the position and velocity of the d-th coordinate of the i-th bacterium according to the following rule:

$$V_{id}^{new} = \omega V_{id}^{new} + C_1.\varphi_1\left(\theta_{g\_best_d} - \theta_d^{old}(i, j+1, k)\right)$$

$$\theta_d^{new}(i, j+1, k) = \theta_d^{old}(i, j+1, k) + V_{id}^{new}$$

[Step 6] Let $S\_r = S / 2$

The S_r bacteria with highest cost function (J) values die and other half bacteria population with the best values split.

[Step 7] If $k < N_{re}$, go to [step 3]. One has not reached the number of specified reproduction steps, so one starts the next generation in the chemotaxis loop.

More details of BF and PSO parameters are presented in Appendix.

5. Results and Simulations

The overall system has been simulated on the digital computer via Simulink tool box in Matlab [60] software package. Fig. 6. shows the variations of objective function with various optimization techniques. The algorithm is run keeping limiting value of cost function at 10^{-6}. It was found that the BSO gives faster convergence than PSO and BF. Moreover, BSO converges at a faster rate (44 generations) compared to that for PSO (68

generations) and BFOA (88 generations). Moreover, computational time (CPU) of both algorithms is compared based on the average CPU time taken to converge the solution. The average CPU for BSO is 43.4 second while it is 68.3 and 79.2 second for PSO and BF respectively.

Table (5), shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear that the system with BSOSVC has small damping factors (σ =-0.65,-0.69,-1.06) for light, normal, and heavy loading respectively. Moreover, the proposed coordinated controller shifts substantially the electromechanical eigenvalues to the left of the S-plane and the values of the damping factors with the proposed coordinated controller are improved to be (σ =-1.13,-1.17,-1.57) for light, normal, and heavy loading respectively. Also, the damping ratios corresponding to coordinated controller are almost greater than that corresponding to individual ones. Hence compared to the BSOSVC and BSOPSS, the proposed coordinated controller greatly improves the damping characteristics of electromechanical modes. Results of different controllers parameters set values based on the time domain objective function using BF are given in Table (6).
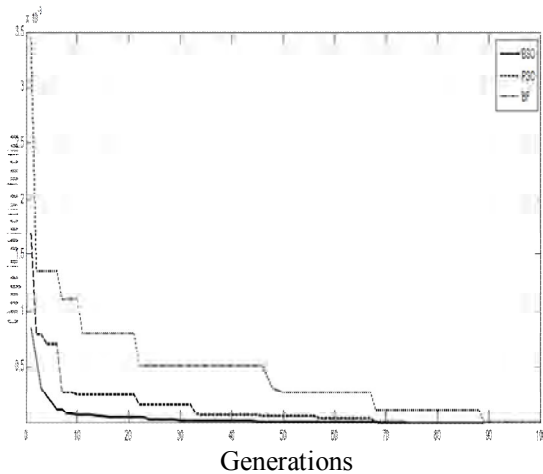

Fig. 6. Change in objective function.

Table (5) Mechanical modes and ζ under different loading conditions and controllers.

	BSOSVC	BSOPSS	Coordinated	Uncoordinated
Light load	-3.1 ± 9.87j, 0.2997	-3.76 ± 6.1j, 0.5247	-4.74 ± 7.39j, 0.54	-3.32 ± 9.42j, 0.332
	-3.83 ± 7.45j, 0.4572	-4.88 ± 6.37j, 0.6081	-4.98 ± 6.09j, 0.633	-1.13 ± 6.72j, 0.1658
	-0.65 ± 0.79j, 0.6354	-0.97 ± 0.67j, 0.8228	-1.13 ± 0.72j, 0.8434	-0.44 ± 0.75j, 0.50
Norma load	-3.27 ± 11.3j, 0.277	-3.95 ± 8.29j, 0.4301	-3.98 ± 8.14j, 0.4392	-3.01 ± 8.85j, 0.322
	-2.76 ± 9.0j, 0.2932	-4.24 ± 6.32j, 0.5571	-4.51 ± 6.34j, 0.5797	-1.21 ± 6.63j, 0.1795
	-0.69 ± 0.78j, 0.6626	-0.95 ± 0.74j, 0.7889	-1.17 ± 0.63j, 0.8805	-0.38 ± 0.74j, 0.456
Heavy load	-2.9 ± 11.38j, 0.2461	-3.67 ± 8.42j, 0.398	-3.93 ± 8.27j, 0.4292	-3.04 ± 8.96j, 0.321
	-1.97 ± 8.78j, 0.2189	-3.97 ± 6.55j, 0.5183	-4.13 ± 5.9j, 0.5735	-1.24 ± 6.76j, 0.18
	-1.06 ± .83j, 0.7873	-1.08 ± 0.83j, 0.7929	-1.57 ± 0.73j, 0.9068	-0.45 ± 0.87j, 0.459

Table (6) Optimal PSSs and SVC parameters.

	Coordinated Design				Uncoordinated Design			
	PSS1	PSS2	PSS3	SVC	PSS1	PSS2	PSS 3	SVC
K	49.51	1.493	1.743	0.915	31.24	8.437	6.38	63.72
T_1	0.465	0.582	0.371	0.371	0.683	0.346	0.25	0.742
T_3	0.268	0.211	0.105	0.288	0.516	0.138	0.33	0.597

A. Response under normal load condition

Figs. 7-8, show the response of $\Delta\omega_{12}, and \ \Delta\omega_{13}$ due to severe disturbance is verified by applying a three phase fault of 6 cycle duration at 1.0 second near bus 7. The results of these studies show that the proposed coordinated controller has an excellent capability in damping oscillations and improves the dynamic stability of the power system. Moreover, the settling time of these oscillations is T_S =1.7, 2.0, and 2.2 second for coordinated controller, BSOPSS, and BSOSVC respectively so the designed controller is capable of providing sufficient damping to the system oscillatory modes. Hence, the proposed coordinated controller extends the power system stability limit.
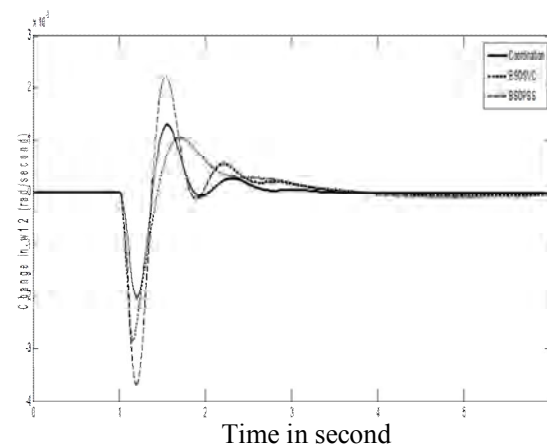

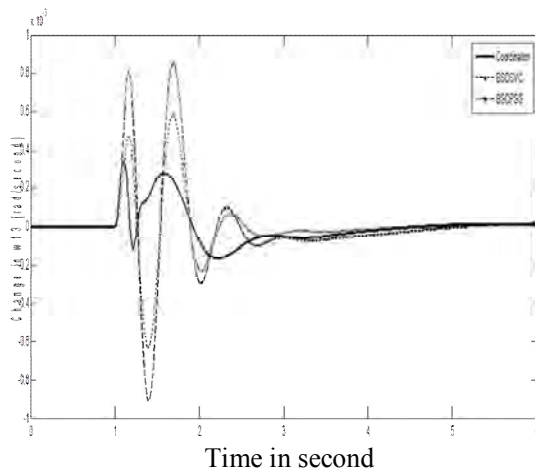Fig. 7. Change of $\Delta\omega_{12}$ under normal load condition.

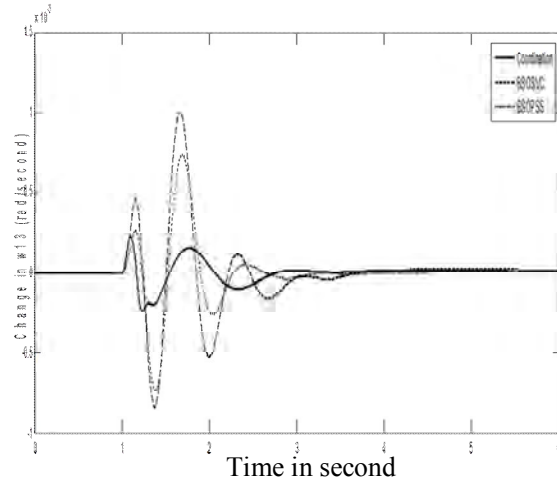Fig. 8. Change of $\Delta\omega_{13}$ under normal load condition.

Fig. 10. Change of $\Delta\omega_{13}$ under heavy load condition.

B. Response under heavy load condition

Figs. 9-10, show the system response at heavy loading condition with fixing the controllers parameters. From these Figures, it can be seen that the response with the proposed coordinated controller shows good damping characteristics to low frequency oscillations and the system is more quickly stabilized than BSOPSS and BSOSVC. Moreover, the settling time of these oscillations is T_s =1.7, 2.0, and 2.2 second for coordinated controller, BSOPSS, and BSOSVC respectively. Hence, the simulations results reveal that the simultaneous coordinated designing of the BSOSVC damping controller and the BSOPSS demonstrates its superiority to both the uncoordinated designed controller of the BSOSVC and the BSOPSS. Also, this controller has a simple architecture and the potentiality of implementation in real time environment.
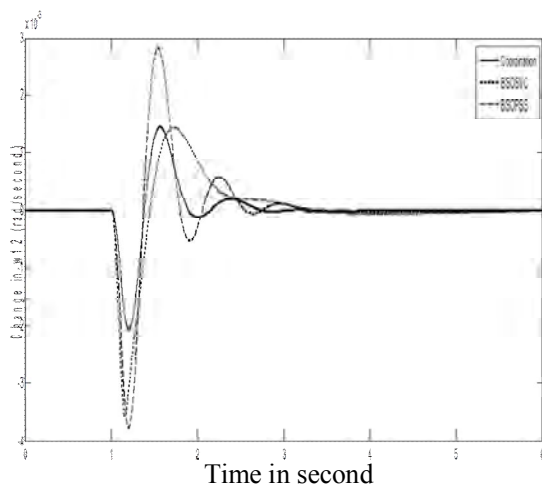
C. Statistical T test

To evaluate the robustness and effectiveness of the proposed coordinated controller, the performance of the system with the proposed coordinated controller is compared to uncoordinated one. A statistical T test is carried out between the coordinated controller and uncoordinated one. The damping ratios of mechanical modes for the coordinated and uncoordinated controller under different loading conditions are selected as input to statistical T test. This test decides that, is there a specific different between two controllers or not?

Let the null hypothesis: $H_0 = \mu_1 - \mu_2 = 0$

Let the alternative hypothesis: $H_1 = \mu_1 - \mu_2 \succ 0$

Where μ_1, μ_2 are the mean values of damping ratios of coordinated and uncoordinated controller respectively. The significance level $\alpha = 0.05$ is established [61-62]. Table (7) shows the output parameters of the statistical T test. The input to the T test is the damping ratios of the mechanical modes for different controllers and operating conditions. The result decides to reject H_0. Also, one can conclude from this test that there is a significant moral difference between the two controllers. Moreover, the response of $\Delta\omega_{12}$ for coordinated and uncoordinated controller is shown in Fig. 11. This Figure indicates the superiority of the proposed coordinated controller in reducing the settling time and damping power system oscillations versus uncoordinated one.

Fig. 9. Change of $\Delta\omega_{12}$ under heavy load condition.

Table (7) Output parameters of statistics T-test.

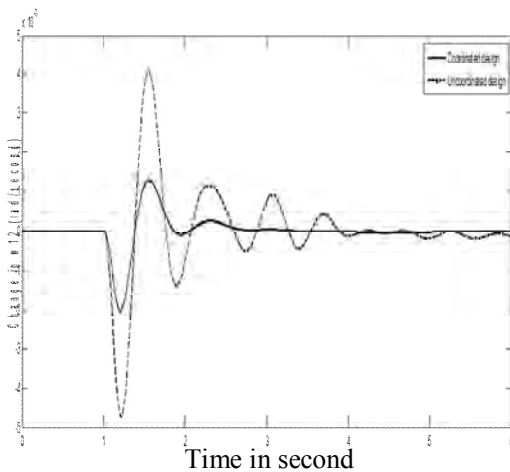| t-Test: Paired Two Sample for Means		
	Coordinated	Uncoordinated
Mean	0.647255556	0.324177778
Variance	0.03409811	0.016694377
Observations	9	9
Pearson Correlation	0.646251843	
Hypothesized Mean Difference	0	
df	8	
t Stat	6.861275353	
P(T<=t) one-tail	6.47503E-05	
t Critical one-tail	1.859548033	
P(T<=t) two-tail	0.000129501	
t Critical two-tail	2.306004133	

Time in second

Fig. 11. Comparison between coordinated and uncoordinated design.

6. Conclusions

The statistical assessment of the robust coordinated design of PSSs and SVC damping controller in a multimachine power system is proposed in this paper. The design problem of the proposed controller is formulated as an optimization problem and BSO is employed to search for optimal controller parameters. By minimizing the time domain objective function, in which the deviations in speed are involved; stability performance of the system is improved. Simulations results assure the effectiveness of the proposed coordinated controller in providing good damping characteristic to system oscillations over a wide range of loading conditions and large disturbance. Moreover, it is superior to uncoordinated controller through the statistical assessment.

7. References

[1] P. Kundur, "*Power System Stability and Control*", McGraw-Hill, 1994.

[2] Y. S. Lee, and S. Y. Sun, "*STATCOM Controller Design for Power System Stabilization with Sub-optimal Control and Strip Pole Assignment*", Int. J. of Electrical Power and Energy Systems, Vol. 24, No. 9, November 2002, pp. 771-779.

[3] M. A. Abido, "*Optimal Design of Power System Stabilizers using Particle Swarm Optimization*" *IEEE Transactions on Energy Conversion*, Vol. 17, No. 3, September 2002, pp. 406-413.

[4] Y.L. Abdel-Magid, and M.A. Abido, "*Coordinated Design of a PSS and a SVC Based Controller to Enhance Power System Stability*", Int. J. of Electrical Power and Energy Systems, Vol. 25, No. 9, November 2003, pp. 695-704.

[5] J. Baskaran, and V. Palanisamy, "*Optimal Location of FACTS Devices in a Power System Solved by a Hybrid Approach*", Int. J. of Nonlinear Analysis, Vol. 65, No. 11, December 2006, pp. 2094-2102.

[6] S. Kodsi, C. Canizares, and M. Kazerani, "*Reactive Current Control Through SVC for Load Power Factor Correction*", Int. J. of Electric Power Systems Research, Vol. 76, No. 9-10, June 2006, pp. 701-708.

[7] S. A. Al-Baiyat, "*Design of a Robust SVC Damping Controller Using Nonlinear H_∞ Technique*", The Arabian Journal for Science and Engineering, Vol. 30, No. 1B, April 2005, pp. 65-80.

[8] K. Ellithy, and A. Al-Naamany, "*A Hybrid Neuro-Fuzzy Static Var Compensator Stabilizer for Power System Damping Improvement in the Presence of Load Parameters Uncertainty*", Int. J. of Electric Power Systems Research, Vol. 56, No. 3, December 2000, pp. 211-223.

[9] P. K. Modi **,** S. P. Singh , and J. D. Sharma, "*Fuzzy Neural Network Based Voltage Stability Evaluation of Power Systems with SVC*", Applied Soft Computing , Vol. 8 , No.1, January 2008, pp. 657-665.

[10] M. H. Haque, "*Best Location of SVC to Improve First Swing Stability of a Power System*", Int. J. of Electric Power System Research, Vol. 77, No. 10, August 2007, pp. 1402-1409.

[11] Y. Chang, and Z. Xu, " *A Novel SVC Supplementary Controller Based on Wide Area Signals*", Int. J. of Electric Power System Research, Vol. 77, No. 12, August 2007, pp. 1569-1574.

[12] S. Panda, N. P. Patidar, and R. Singh, "*Simultaneous Tuning of SVC and Power System Stabilizer Employing Real- Coded Genetic Algorithm*", Int. J. of Electrical and Electronics Engineering, Vol. 4, No. 4, 2009, pp. 240-247.

[13] C. Rakpenthai, S. Premrudeepreechacharn, and S. Uatrongjit, "*Power System with Multi-Type FACTS Devices States Estimation Based on Predictor-Corrector Interior Point Algorithm*", Int. J. of Electrical Power and Energy Systems, Vol. 31, No. 4, May 2009, pp. 160–166.

[14] E. Zhijun, D. Z. Fang, K. W. Chan, and S. Q. Yuan, "*Hybrid Simulation of Power Systems with SVC Dynamic Phasor Model*", Int. J. of Electrical Power and Energy Systems, Vol. 31, No. 5, June 2009, pp. 175–180.

[15] Y. Yuan, G. Li, L. Cheng, Y. Sun, J. Zhang, and P. Wang, "*A Phase Compensator for SVC Supplementary Control to Eliminate Time Delay by Wide Area Signal Input*", Int. J. of Electrical Power and Energy Systems, Vol. 32, No. 3, March 2010, pp. 163-169.

[16] E. S. Ali, "*Static Var Compensator Design for Power System Stabilization Using Bacteria Foraging Optimization Algorithm*", 13th International Middle East Power Systems Conference (MEPCON 2009), Assiut University, Assiut, Egypt, December 20-23, 2009, pp. 578-582.

[17] 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.

[18] X. Y. Bian , C. T. Tse , J. F. Zhang , and K. W. Wang, "*Coordinated Design of Probabilistic PSS and SVC Damping Controllers*", Int. J. of Electrical Power and Energy Systems, Vol. 33, No. 3, March 2011, pp. 445-452.

[19] M. A. Furini, A. L. S. Pereira, and P. B. Araujo, "*Pole Placement by Coordinated Tuning of Power System Stabilizers and FACTS POD Stabilizers*", Int. J. of Electrical Power and Energy Systems, Vol. 33, No. 3, March 2011, pp. 615-622.

[20] S. Panda, "*Multi-objective PID Controller Tuning for a FACTS Based Damping Stabilizer Using Non-dominated Sorting Genetic Algorithm-II*", Int. J. of Electrical Power and Energy Systems, Vol. 33, No. 7, September 2011, pp. 1296-1308.

[21] E. S. Ali, and 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.

[22] A. V. Doroshin, F. Neri, "*Open Research Issues on Nonlinear Dynamics, Dynamical Systems and Processes*", WSEAS Transactions on Systems, 13, 2014, in press.

[23] C. Ciufudean, F. Neri, "*Open Research Issues on Multi-Models for Complex Technological Systems*", WSEAS Transactions on Systems, 13, 2014, in press.

[24] F. Neri, "*Open Research Issues on Computational Techniques for Financial Applications*", WSEAS Transactions on Systems, 13, 2014, in press.

[25] Karthikeyan, P., F. Neri, "*Open Research Issues on Deregulated Electricity Market: Investigation and Solution Methodologies*", WSEAS Transactions on Systems, 13, 2014, in press.

[26] M. Panoiu, F. Neri, "*Open Research Issues on Modeling, Simulation and Optimization in Electrical Systems*", WSEAS Transactions on Systems, 13, 2014, in press.

[27] F. Neri, (2014) "*Open Research Issues on Advanced Control Methods: Theory and Application*", WSEAS Transactions on Systems, 13, in press.

[28] P. Hájek, F. Neri, "*An Introduction to the Special Issue on Computational Techniques for Trading Systems, Time Series Forecasting, Stock Market Modelling, Financial Assets Modelling*", WSEAS Transactions on Business and Economics, Vol. 10, No. 4, 2013, pp. 201-292.

[29] M. Azzouzi, F. Neri, "*An introduction to the special issue on advanced control of energy systems*", WSEAS Transactions on Power Systems, Vol. 8, No. 3, 2013, p. 103.

[30] Z. Bojkovic, F. Neri, (2013) "*An Introduction to the Special Issue on Advances on Interactive Multimedia Systems*", WSEAS Transactions on Systems, Vol. 12, No. 7, pp. 337-338.

[31] L. Pekař, F. Neri, "*An Introduction to the Special Issue on Advanced Control Methods: Theory and Application*", WSEAS Transactions on Systems, Vol. 12, No. 6, 2013, pp. 301-303.

[32] C. Guarnaccia, F. Neri, "*An Introduction to the Special Issue on Recent Methods on Physical Polluting Agents and Environment Modelling and Simulation*", WSEAS Transactions on Systems, Vol. 12, No. 2, 2013, pp. 53-54.

[33] F. Neri, "*An Introduction to The Special Issue on Computational Techniques for Trading*

Systems, Time Series Forecasting, Stock Market Modelling, and Financial Assets Modelling", WSEAS Transactions on Systems, Vol. 11, No. 12, 2012, pp. 659-660.

[34] M. Muntean, F. Neri, "*Foreword to the Special Issue on Collaborative Systems*", WSEAS Transactions on Systems, Vol. 11, No. 11, 2012, p. 6.

[35] L. Pekař, F. Neri, "*An Introduction to the Special Issue on Time Delay Systems: Modelling, Identification, Stability, Control and Applications*", WSEAS Transactions on Systems, Vol. 11, No. 10, 2012, pp. 539-540.

[36] C. Volos, F. Neri, "*An Introduction to the Special Issue: Recent Advances in Defence Systems: Applications, Methodology, Technology*", WSEAS Transactions on Systems, Vol. 11, No. 9, 2012, pp. 477-478.

[37] J. Kennedy and R. Eberhart, "*Particle Swarm Optimization*", Proceedings of IEEE International Conference on Neural Networks, 1995, pp. 1942-1948.

[38] D. P. Rini, S. M. Shamsuddin, and S. S. Yuhaniz, "*Particle Swarm Optimization: Technique, System and Challenges*", Int. J. of Computer Applications, Vol. 14, No. 1, January 2011, pp. 19-27.

[39] V. Selvi and R. Umarani, "*Comparative Analysis of Ant Colony and Particle Swarm Optimization Techniques*", Int. J. of Computer Applications, Vol. 5, No. 4, August 2010, pp. 1-6.

[40] A. S. Oshaba, and E. S. Ali, "*Speed Control of Induction Motor Fed from Wind Turbine via Particle Swarm Optimization Based PI Controller*", Research Journal of Applied Sciences, Engineering and Technology, Vol. 5, No. 18, May 2013, pp. 4594-4606.

[41] A. S. Oshaba, and E. S. Ali, "*Swarming Speed Control for DC Permanent Magnet Motor Drive via Pulse Width Modulation Technique and DC/DC Converter*", Research Journal of Applied Sciences, Engineering and Technology, Vol. 5, No. 18, May 2013, pp. 4576-4583.

[42] 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.

[43] S. Mishra, "*A Hybrid Least Square Fuzzy Bacteria Foraging Strategy for Harmonic Estimation*", IEEE Trans. Evolutionary Computer, Vol. 9, No.1, February 2005, pp. 61-73.

[44] D. B. Fogel, "*Evolutionary Computation towards a New Philosophy of Machine Intelligence*", IEEE, New York, 1995.

[45] 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.

[46] 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.

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

[48] 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.

[49] 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.

[50] E. S. Ali, 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.

[51] E. S. Ali, S. M. Abd-Elazim, "*Optimal PSS Design in a Multimachine Power System via Bacteria Foraging Optimization Algorithm*", Int. J. of WSEAS Transactions on Power Systems, Vol. 8, No. 4, October 2013, pp. 186-196.

[52] E. S. Ali, S. M. Abd-Elazim, "*Hybrid BFOA-PSO Approach for Optimal Design of SSSC Based Controller*", Int. J. of WSEAS Transactions on Power Systems, Vol. 9, No. 1, January 2014, pp. 54-66.

[53] A. Biswas, S. Dasgupta, S. Das, and A. Abraham, "*Synergy of PSO and Bacterial Foraging Optimization: A Comparative Study on Numerical Benchmarks*", Innovations in Hybrid Intelligent Systems, ASC 44, 2007, pp. 255-263.

[54] W. Korani, "*Bacterial Foraging Oriented by Particle Swarm Optimization Strategy for PID Tuning*", GECCO'08, July 12-16, 2008, Atlanta, Georgia, USA, pp. 1823-1826.

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

[56] E. S. Ali, "*Optimization of Power System Stabilizers Using BAT Search Algorithm*", Int. J. of Electrical Power and Energy Systems, Vol. 61, No. C, October 2014, pp. 683-690.

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

[58] S. M. Abd- Elazim, "*Comparison between SVC and TCSC Compensators on Power System Performance*", Master thesis, 2006, Zagazig University, Egypt.

[59] S. M. Abd-Elazim, and E. S. Ali, "*A Hybrid Particle Swarm Optimization and Bacterial Foraging for Power System Stability Enhancement*", IEEE, 15th International Middle East Power Systems Conference "MEPCON'12", Alexandria University, Egypt, December 23-25, 2012.

[60] The MathWorks, Inc. ,"*MATLAB Simulink Toolbox*", Version 7.10 (R2010a), MATLAB Software.

[61] S. M. Ross, "*Introduction to Probability and statistics for Engineers and Scientists*", 3rd edition, Elsevier Academic Press, 2004.

[62] W. L. Martinez, and A. R. Martinez, "*Computational Statistics Handbook with MATLAB*", Chapman & Hall/CRC, 2002.

Appendix

The system data are as shown below:

The system data	
Excitation system	$K_A = 400;$ $T_A = 0.05\,\text{second};$ $K_f = 0.025;$ $T_f = 1\,\text{second}.$
SVC Controller	$T_r = 15\,\text{msecod};$ $K_r = 50;$ $\alpha 0 = 140.$
Bacteria parameters	Number of bacteria =10; number of chemotatic steps =10; number of elimination and dispersal events = 2; number of reproduction steps = 4; probability of elimination and dispersal = 0.25; the values of $d_{attract}$ =0.01; the values of $\omega_{attract}$ =0.04; the values of $h_{repelent}$ =0.01; the values of $\omega_{repelent}$ =10.
PSO parameters	$C_1 = C_2 = 2.0,$ $\omega = 0.9.$