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Hybrid BFOA-PSO Approach for Damping Power System Oscillations by Using Facts Devices

E.S. Ali and S.M. Abd-Elazim
Department of Electric Power and Machine, Faculty of Engineering,
Zagazig University, Zagazig, Egypt

Abstract: Social foraging behaviour of *Escherichia coli* bacteria has recently been explored to develop a novel algorithm for optimization and control. One of the major driving forces of Bacterial Foraging Optimization Algorithm (BFOA) is the chemotactic movement of a virtual bacterium that models a trial solution of the optimization problem. However during the process of chemotaxis, the BFOA depends on random search directions which may lead to delay in reaching the global solution. This study comes up with a hybrid approach involving Particle Swarm Optimization (PSO) and BFOA algorithm called Bacterial Swarm Optimization (BSO) for designing Static Synchronous Series Compensator (SSSC) in a power system. In BSO, the search directions of tumble behaviour for each bacterium are oriented by the individual's best location and the global best location of PSO. The proposed hybrid algorithm has been extensively compared with BFOA and PSO. Simulation results have shown the validity of the proposed BSO in tuning SSSC compared with BFOA and PSO. Moreover, the results are presented to demonstrate the effectiveness of the proposed controller to improve the power system stability over a wide range of loading conditions.

Key words: Hybrid algorithm, particle swarm optimization, bacterial foraging, SSSC, damping oscillations

INTRODUCTION

The power transfer in an integrated power system is constrained by transient, voltage and small signal stability. These constraints limit a full utilization of available transmission corridors. Flexible AC Transmission System (FACTS) is the technology that provides the needed corrections of the transmission functionality in order to fully utilize the existing transmission facilities and hence, minimizing the gap between the stability and thermal limit (Kundur, 1994). Recently, there has been a surge of interest in the development and use of FACTS controllers in power transmission systems (Lee and Sun, 2002; Sen, 1998; Ngamroo, 2001; Ngamroo and Kongprawechnon, 2003; Zhang, 2003). These controllers utilize power electronics devices to provide more flexibility to AC power systems. The theory and the modelling technique of SSSC device using an Electromagnetic Transients Program (EMTP) simulation package is presented by Sen (1998). SSSC is designed by Ngamroo (2001) to stabilize the frequency of oscillation in an interconnected power system. This SSSC located in series with the tie line between any interconnected areas is applicable to stabilize the area frequency of oscillations by high speed control of tie line power through the interconnections. A robust design of the lead/lag controller equipped with the SSSC for stabilization of frequency oscillations is discussed by Ngamroo and Kongprawechnon (2003). A multi control functional model of SSSC for power system analysis is described by Zhang (2003). This model can be used for steady state control of one of the following parameters:

- The active power flow on the transmission line
- The reactive power flow on the transmission line
- The voltage at the bus
- The impedance (precisely reactance) of the transmission line

A robust damping controller based on Fuzzy Logic Controller (FLC) is introduced by Chen *et al*. (2004). The only input signal for this damping controller is the real power measurement at the location of the SSSC to generate the modulation index for controlling the injected voltage of the Voltage Source Converter (VSC) while its phase angle is required to remain constant with respect to local reference voltage vector. A new genetic based approach for optimal selection of the SSSC damping controller parameters in order to shift the closed loop eigen values toward the desired stability region is designed by Kazemi *et al*. (2005). The dynamic operation of both Static Synchronous Compensator (STATCOM)

Corresponding Author: E.S. Ali, Department of Electric Power and Machine, Faculty of Engineering, Zagazig University, Zagazig, Egypt

and SSSC based on a new model comprising full 48-pulse Gate Turn Off (GTO) VSC is investigated by El-Moursi and Sharaf (2006). These models combined reactive power compensation and voltage stabilization of the electric grid network. The rate of dissipation of transient energy is used as a measure of system damping by Haque (2006). This concept is applied to determine the additional damping provided by a STATCOM and SSSC. GA optimization technique to design FACTS based damping controllers for SMIB is applied by Panda and Padhy (2007). The analytical expressions for this additional damping are derived and compared for classical model of a simple power system. The influence of SSSC and STATCOM on the synchronizing power and damping power of a Single Machine Infinite Bus (SMIB) is introduced by Al-Jowder (2007). The impacts of different SSSC control modes on a small signal and transient stability of a power system is discussed by Castro *et al.* (2007). A robust control design of STATCOM to improve the damping of power system is described by Mandour. The application of a SSSC controller to improve the transient stability performance of a power system is thoroughly investigated by Panda *et al.* (2007). The performance of different input signals to the Power Oscillation Damping (POD) controller is also assessed. The transient energy is used as a tool to assess the effectiveness of FACTS devices to damp power system oscillations by Murali and Rajaram (2009). A systematic procedure for modelling, simulation and optimally tuning the parameters of a SSSC controller for power system stability enhancement is presented by Panda (2010).

Several 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 by Kennedy and Eberhart (1995). 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 (Rini *et al.*, 2011; Selvi and Umarani, 2010). 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 Passino (2002), Mishra (2005) and Fogel (1995) and further established recently by Ali and Abd-Elazim (2011). 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 (Korani, 2008). 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 study to solve the above mentioned problems and drawbacks.

This study proposes a new optimization algorithm known as BSO for optimal designing of the SSSC to damp power system oscillations. The performance of BSO has been compared with these of PSO and BFOA in tuning the SSSC damping controller parameters. 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 the speed, DC voltage and transmission line power are involved; stability performance of the system is improved. Simulation results assure the effectiveness of the proposed controller in providing good damping characteristic to system oscillations over a wide range of loading conditions. Also, these results validate the superiority of the proposed method in tuning controller compared with BFOA and PSO.

POWER SYSTEM MODELING

SSSC is installed in series with transmission line as shown in Fig. 1. The generator is represented by the third order model that comprising of the electromechanical swing equations and the generator internal voltage equation. The IEEE type ST1 excitation system is used (Kundur, 1994). Details of system data are given in Appendix:

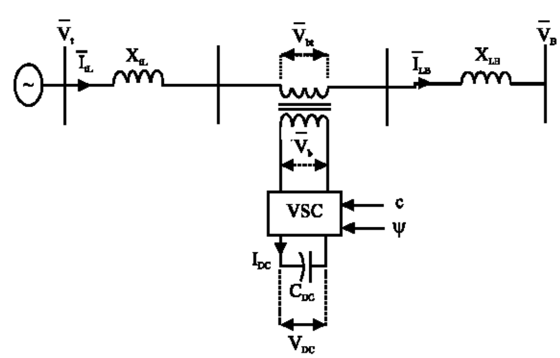

Fig. 1: SMIB with SSSC

$$\dot{\delta} = \omega_B(\omega - 1) \quad (1)$$

$$\dot{\omega} = \frac{1}{\tau_j}(P_m - P_e - D(\omega - 1)) \quad (2)$$

Where:

P_m and P_e = The input and output powers of the generator, respectively
τ_j and D = The inertia constant and damping coefficient
δ, ω = The rotor angle and speed, respectively
ω_B = The synchronous speed

The output power of the generator can be expressed in terms of the d and q-axis components of the armature current and terminal voltage as following:

$$P_e = v_d i_d + v_q i_q \quad (3)$$

The internal voltage, E'_q, Eq. 4 is shown below:

$$\dot{E}'_q = \frac{-1}{\tau'_{do}} E'_q + \frac{1}{\tau'_{do}} E_{fd} + \left(\frac{x_d - x'd}{\tau'_{do}}\right) i_d \quad (4)$$

Where:

E_{fd} = The field voltage
τ'_{do} = The open circuit field time constant
X_d and X'_d = The d-axis reactance and d-axis transient reactance of the generator, respectively

Modeling of SMIB with SSSC: The SSSC is a VSC connected in series with the transmission line at its midpoint through an insertion transformer as shown in Fig. 1. The SSSC output voltage is defined by Eq. 5:

$$\bar{V}_b = cV_{DC}(\cos\psi + j\sin\psi) \quad (5)$$

Where:

c = The amplitude modulation ratio
Ψ = The phase angle modulation ratio of the SSSC
V_{DC} = The SSSC DC voltage

The transmission line current is described by Eq. 6:

$$\bar{V}_b = cV_{DC}(\cos\psi + j\sin\psi) \quad (6)$$

The SSSC DC voltage differential equation is given:

$$\dot{V}_{DC} = \frac{c}{C_{DC}}\{I_{tLq}\cos\psi + I_{tLd}\sin\psi\} \quad (7)$$

The induced AC system voltage due to SSSC voltage is described by Eq. 8:

$$\bar{V}_{bt} = \bar{V}_b + jX_b \bar{I}_{tL} \quad (8)$$

Substitute from Eq. 5 and 6 into Eq. 8 and then divide it into d and q-axis as following:

$$V_{btq} + jV_{btd} = cV_{DC}(\cos\psi + J\sin\psi) + jx_b(I_{tLq} + jI_{tLd}) \quad (9)$$

The machine terminal voltage is described as following:

$$\bar{V}_t = j(X_{tL} + X_{LB})\bar{I}_{tL} + \bar{V}_{bt} + \bar{V}_B = V_q + jV_d \quad (10)$$

From Eq. 6 and 9, the transmission line current in d and q-axis are defined as following:

$$I_{tLq} = \frac{1}{(X_{tL} + X_{LB})}\{V_d - V_{btd} - V_B\sin\delta\} \quad (11)$$

$$I_{tLd} = \frac{1}{(X_{tL} + X_{LB})}\{-V_q + V_{btq} + V_B\cos\delta\} \quad (12)$$

AC voltage regulator: The AC voltage regulator controls the reactive power exchange with the power system as shown in Fig. 2.

Where, Kp_{ac} and Ki_{ac} are the PI controller gains for AC voltage regulator, K and T_1 to T_4 are the lead lag controller gains for additional controller in the AC voltage regulator circuit, U_s is the output signal of additional controller in the AC voltage regulator circuit and T_w is the washout time constants for AC voltage regulator and its additional controller, respectively.

DC voltage regulator: The DC voltage regulator controls the DC voltage across, the DC capacitor of the SSSC controller as shown in Fig. 3.

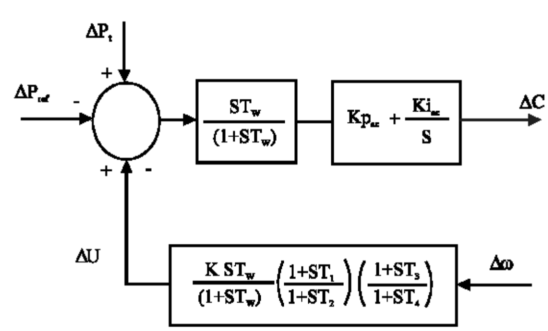

Fig. 2: SSSC dynamic model of AC voltage regulator

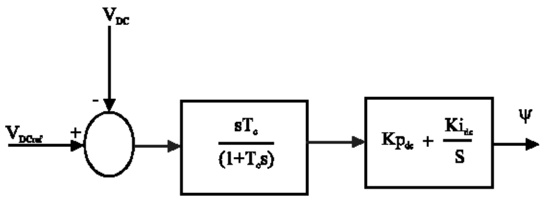

Fig. 3: SSSC dynamic model of DC voltage regulator

Where, Kp_{dc} and Ki_{dc} are the PI controller gains for DC voltage regulator, V_{DC} is the SSSC DC voltage and T_c is the washout time constant for DC voltage regulator, respectively. To reduce the computational burden in this study, the value of the wash out time constant T_w is fixed to 8 sec, the values of T_2 and T_4 are kept constant at a reasonable value of 0.05 sec. The parameters of the AC, DC and additional controller are to be determined via various optimization techniques.

OBJECTIVE FUNCTION

In the present study, an integral time absolute error of the speed deviations, DC voltage and transmission line power of SSSC is taken as the objective function expressed as follows:

$$J = \int_0^{t_{sim}} t\{|\Delta\omega| + |\Delta V_{DC}| + |\Delta P_t|\}dt \quad (13)$$

The great advantage of this objective function is that the effect of SSSC signal is taken into consideration. The problem constraints are the SSSC controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem:
Minimize J (Eq. 13) subject to:

$$Kp_{dc}^{min} \le Kp_{dc} \le Kp_{dc}^{max} \quad (14)$$

$$Ki_{dc}^{min} \le Ki_{dc} \le Ki_{dc}^{max} \quad (15)$$

$$Kp_{ac}^{min} \le Kp_{ac} \le Kp_{ac}^{max} \quad (16)$$

$$Ki_{ac}^{min} \le Ki_{ac} \le Ki_{ac}^{max} \quad (17)$$

$$K^{min} \le K \le K^{max} \quad (18)$$

$$T_1^{min} \le T_1 \le T_1^{max} \quad (19)$$

$$T_3^{min} \le T_3 \le T_3^{max} \quad (20)$$

HYBRID BFOA-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 $\vec{X}_i$ and velocities $\vec{V}_i$ 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 (Kennedy and Eberhart, 1995). The velocity and position update equations for the dth dimension of the ith particle in the swarm may be given as follows:

$$V_{id}^{t+1} = \omega.V_{id}^{t} + C_1.\varphi_1.\left(X_{lid} - X_{id}^{t}\right) + C_2.\varphi_2.\left(X_{gd} - X_{id}^{t}\right) \quad (21)$$

$$X_{id}^{t+1} = X_{id}^{t} + V_{id}^{t+1} \quad (22)$$

Where:
X_{lid} = The best position of each bacterial
X_{gd} = 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. 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 by Korani (2008) and Abd-Elazim. The proposed BSO algorithm to search optimal values of parameters is shown in Fig. 4.

Step 1: Initialize parameters; n, S, N_C, N_S, N_{re}, P_{ed}, C(i) (i = 1, 2,..., N), ϕ^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

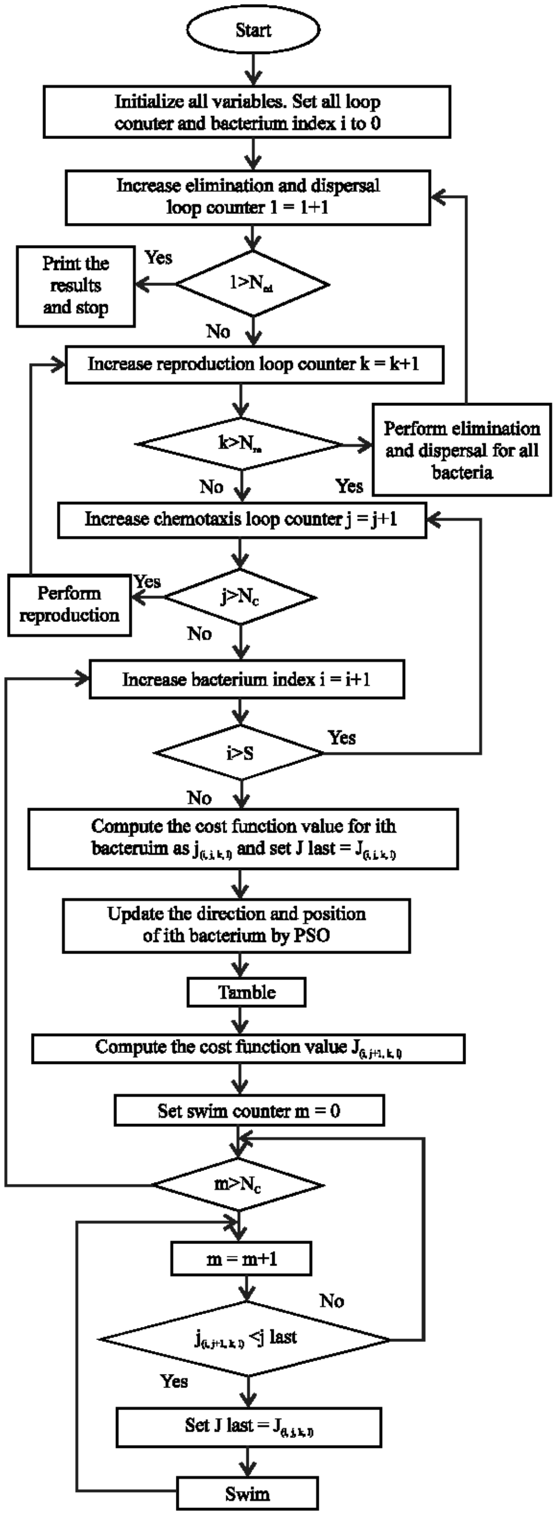

Fig. 4: Flow chart of BSO algorithm

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

$\vec{\theta}(i,j,k)$ = Position vector of the ith bacterium in jth chemotactic step and kth reproduction

$\vec{V}_i$ = Velocity vector of the ith bacterium

Step 2: Update the following; J(i, j, k) cost or fitness value of the ith bacterium in the jth chemotaxis and the k^{th} reproduction loop. $\vec{\theta}g\_best$ is position vector of the best position found by all bacteria J_{best} (i, j, k) is 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 = j + 1
- 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 $\Delta(i) \epsilon R^n$ with each element Δ_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 ith bacterium is swimming while the others are not moving then:
  - Let, m = 0 (counter for swim length)
  - 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 this equation and use this θ (i, j + 1, k) to compute the new J(i, j +1, k) as shown in new, sub step f:

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

- Else, let mN_S. This is the end of the while statement

Step 5: Mutation with PSO operator:
For i = 1, 2,……, S:

- Update the best $\bar{\theta}_{g\_best}$ and J_{best} (i, j, k)
- Update the position and velocit y of the dth coordinate of the ith 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 BFOA and PSO parameters are presented in Appendix.

RESULTS AND SIMULATIONS

In this study, the superiority of the proposed BSO algorithm in designing SSSC (BSOSSSC) in compare to optimized SSSC with PSO (PSOSSSC) and optimized SSSC controller based on BFOA (BFSSSC) is illustrated. Table 1 shows the system eigen values and damping ratio of mechanical mode with three different loading conditions. It is clear that the BSOSSSC shift substantially the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed BSOSSSC are significantly improved to be (σ = -2.291, -1.8016, -1.11) for light, normal and heavy loading, respectively. Also, the damping ratios corresponding to BSOSSSC controllers are almost greater than those corresponding to PSOSSSC and BFSSSC ones. Hence, compared to BFSSSC and PSOSSSC, BSOSSSC greatly enhances the system stability and improves the damping characteristics of electromechanical modes. Table 2 shows the controller parameters of DC voltage regulator, AC voltage regulator and the additional controller obtained by various algorithms.

Response under normal load condition: The effectiveness of the performance under 0.2 step increase in mechanical torque is applied. Figure 5 shows the response of speed for normal loading condition. Figure 5 indicates the capability of the BSOSSSC in reducing the settling time and damping power system oscillations. Moreover, the mean settling time of these oscillations is 3.5, 3.8 and 4.2 sec for BSOSSSC, PSOSSSC and BFSSSC, respectively. In addition, the proposed BSOSSSC outperforms and outlasts PSOSSSC and BFSSSC controller in damping oscillations effectively and reducing settling time.

Response under heavy load condition: Figure 6 shows the system response at heavy loading condition with fixing the controller parameters. From Fig. 6, it can be seen that the response with the proposed BSOSSSC shows good damping characteristics to low frequency oscillations and the system is more quickly stabilized than PSOSSSC and BFSSSC. The mean settling time of oscillation is 3.2, 3.8 and 4.1 sec for BSOSSSC, PSOSSSC and BFSSSC, respectively. Hence, the proposed BSOSSSC extend the power system stability limit.

Table 1: Mechanical modes and damping ratios for various controllers and operating condition

Modes	BSOSSSC	PSOSSSC	BFSSSC
Light load	-2.291±10.36j (0.216)	-1.778±8.89j (0.196)	-1.4487±7.804j (0.183)
Normal load	-1.8016±6.915j (0.2521)	-1.474±6.544j (0.22)	-1.222±6.1608j (0.195)
Heavy load	-1.11±6.18j (0.1768)	-0.785±5.26j (0.148)	-0.656±4.95j (0.1314)

Table 2: The controller parameters for various controllers

Controllers	BSOSSSC	PSOSSSC	BFSSSC
Kp_{dc}	1.8077	0.8594	0.5398
Ki_{dc}	1.8140	0.1041	1.7412
Kp_{ac}	3.6947	2.5581	1.9673
Ki_{ac}	0.6113	1.2907	0.0527
K	0.1016	0.1432	0.0994
T_1	0.5655	0.4984	0.7610
T_3	0.4937	0.3121	0.5569

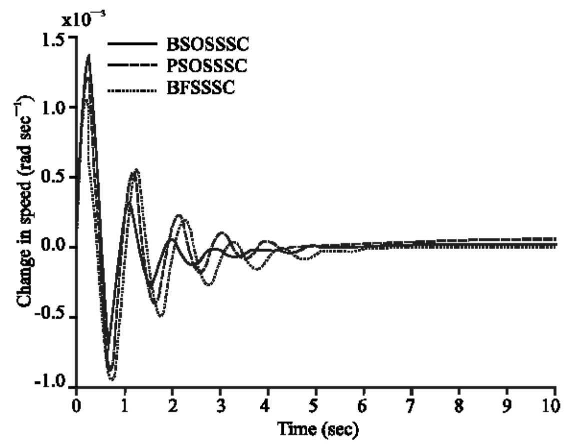

Fig. 5: Change in speed for normal load condition

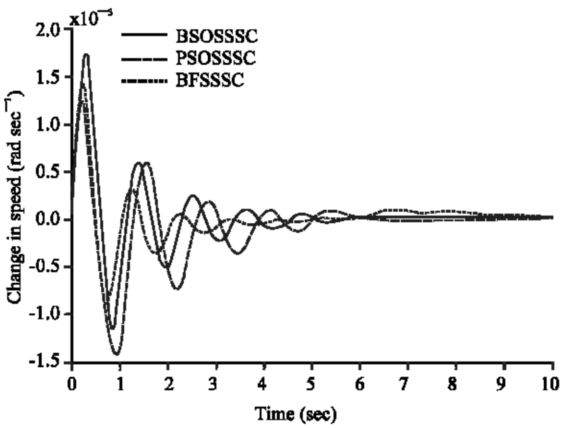

Fig. 6: Change in speed for heavy load condition

CONCLUSION

In this study, a new optimization algorithm known, as BSO which synergistically couples the BFOA with the PSO for optimal designing of SSSC damping controller is thoroughly investigated. For the proposed controller design problem, an integral time absolute error of the speed, DC voltage and transmission line power of SSSC is taken as the objective function to improve the system response in terms of the settling time and overshoots. Simulation results are presented for various loading conditions to verify the effectiveness of the proposed controller design approach. Moreover, the proposed control scheme is robust, simple to implement, yet is valid over a wide range of operating conditions.

APPENDIX

The system data are as shown below:
a) Synchronous generator (p.u) $X_d = 1.07$, $X_q = 1.0$, $X'_d = 0.3$, $\tau'_{do} = 5.9$, H = 2.37, Pe = 0.9, Vt = 1.0; b) Excitation system K_A =400 and $T_A = 0.05$ sec; c) Transmission line (p.u), $X_{tL} = 0.3$, $X_{LB} = 0.3$; d) SSSC parameters (p.u), $X_b = 0.05$, $V_{DC} = 1.0$, $C_{DC} = 1.0$; e) 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 $\omega_{repelent} = 10$; f) PSO parameters: $C_1 = C_2 = 2.0$, $\omega = 0.9$

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