Optimal SSSC Design for Power Systems via Hybrid Approach

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Abstract- A novel hybrid approach involving Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization Algorithm (BFOA) called Bacterial Swarm Optimization (BSO) is illustrated for designing Static Synchronous Series Compensator (SSSC) for single and multimachine power systems. In BSO, the search directions of tumble behavior 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 the original BFOA algorithm and the PSO algorithm. Simulation results have shown the validity of the proposed BSO in tuning PSSs compared with BFOA and PSO. Moreover, the results are presented to demonstrate the effectiveness of the proposed controller to improve the power systems stability over a wide range of loading conditions.

Key-Words: SSSC; Particle Swarm Optimization; Bacterial Foraging; Hybrid Algorithm; Damping Oscillations; Different Power Systems.

1. Introduction

The Flexible AC Transmission System (FACTS) is designed to overcome the limitations of the present mechanically controlled AC power transmission systems. By using reliable and high-speed power electronic controllers, the technology offers a great control on power flows of the prescribed transmission routes, secure loading of transmission lines to levels nearer their thermal limits, a major ability to transfer power between controlled areas, prevention of cascading outages, and damping of power system oscillations [1-3].

FACTS can be classified into two generations. The first generation of FACTS devices has a common characteristic that is the required necessary reactive power for the compensation is generated or absorbed by traditional capacitor or reactor banks, and thyristor switches are used to control the combined reactive impedance. Consequently, conventional thyristor controlled compensator presents a variable reactive admittance to the transmission network. Some of the first generation of FACTS devices are: Static VAR Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC).

In last few years, many researchers have posed techniques for designing SVC to enhance the damping of electromechanical oscillations of power systems, regulate the transmission voltage, and improve power quality [4-9]. The main advantage of SVCs over simple mechanically-switched compensation schemes is their near-instantaneous response to changes in the system voltage [2]. Also, they are cheaper, higher-capacity, faster and more reliable than dynamic compensation schemes such as synchronous condensers. However, SVCs are more expensive than mechanically switched capacitors and produce harmonic currents.

TCSC is one of the important members of FACTS family that is increasingly applied by the utilities in modern power systems with long transmission lines. It has various roles in the operation and control of power systems, such as scheduling power flow, reducing net loss, providing voltage support, limiting short circuit currents, mitigating sub-synchronous resonance (SSR), damping the power oscillation, and enhancing transient stability. On the other hand, TCSC is significantly affecting the impedance of the transmission system and, therefore, there is major danger of having resonance problem. The applications of TCSC for power oscillation damping and stability enhancement can be found in [10-14].

The second generation of FACTS controllers is based on Voltage Source Converter (VSC), which use turn off devices like GTOs. These controllers require lower ratings of passive elements and the voltage source characteristics present several advantages over conventional variable impedance controllers. Some of the FACTS controllers belonging to this category are: Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), and Unified Power Flow Controller (UPFC) [2].

STATCOM is an advanced SVC using VSC with capacitors connected on DC side. STATCOM resembles in many respects a rotating synchronous condenser used for voltage control and reactive power compensation. As compared to conventional SVC, STATCOM does not require expensive large inductors. Moreover, it can also operate as reactive power sink or source flexibly which makes STATCOM more attractive. Because of its several advantages over conventional SVC, it is expected to play a major role in the optimum and secure operation of AC transmission system in future. In addition, the speed of response of a STATCOM is faster than that of an SVC and the harmonic emission is lower. On the other hand, STATCOMs typically exhibit higher losses and may be more expensive than SVCs, so the (older) SVC technology is still widespread. The development, design and use of STATCOM controllers in power system transmission and control have been discussed in [15-17].

SSSC as a second generation of FACTS has several advantages over the conventional one due to its storage element. Also, the main control objective of the SSSC is to directly control the current, and indirectly the power flowing through the line by controlling the reactive power exchange between the SSSC and the AC system. The main advantage of this controller over a TCSC is that it does not significantly affect the impedance of the transmission system and, therefore, there is no danger of having resonance problem.

The theory, modeling, and applications of SSSC have been illustrated in [18-24].

Several optimization techniques have been adopted to solve different 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 [25]. 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 [26-27]. 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 [28-30] and further established recently by [31]. 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 which combine the above mentioned optimization algorithms [32-38]. 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.

This paper proposes a new optimization algorithm known as BSO for optimal designing of the SSSC to damp power systems oscillations. The performance of BSO has been compared with these of PSO and BFOA in tuning the SSSC damping controller parameters for different power systems. 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.

2. 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 [1]. Details of single machine infinite bus system (SMIB) data are given in appendix.

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

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

where P_m and P_e are the input and output powers of the generator, respectively; τ_j and D are the inertia constant and damping coefficient, respectively; δ and ω are the rotor angle and speed, respectively; ω_B is the synchronous speed.
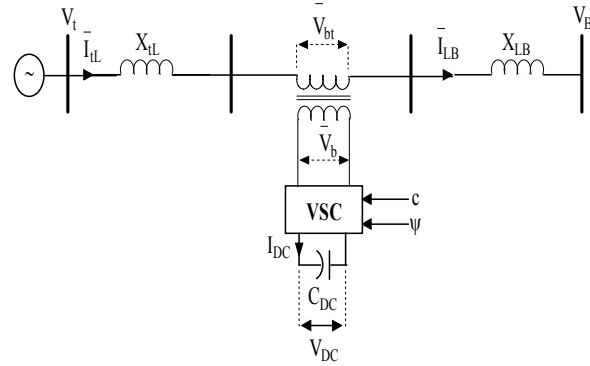

Fig. 1. SMIB with SSSC.

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

$$P_e = v_d i_d + v_q i_q \tag{3}$$

The internal voltage, E'_q, equation is shown below:

$$\dot{E}'_q = \frac{-1}{\tau'_{do}} E'_q + \frac{1}{\tau'_{do}} E_{fd} + \left(\frac{X_d - X'_d}{\tau'_{do}}\right) i_d \tag{4}$$

where E_{fd} is the field voltage; τ'_{do} is the open circuit field time constant; X_d and X'_d are the d axis reactance and d axis transient reactance of the generator, respectively.

Modelling 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 the following equation [39-40]:

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

Where c is the amplitude modulation ratio, ψ is the phase angle modulation ratio of the SSSC and V_{DC} is the SSSC DC voltage.

The transmission line current is described by the following equation:

$$I_{tL} = I_{tLq} + jI_{tLd} \tag{6}$$

The SSSC DC voltage differential equation is given below:

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

The induced AC system voltage due to SSSC voltage is described by the following equation:

$$\overline{V}_{bt} = \overline{V}_b + jX_b\overline{I}_{tL} \tag{8}$$

Substitute from equations (5) and (6) into equation (8), and then divide it into d and q axis as following:

$$V_{btq} + jV_{btd} = cV_{DC}(\cos\psi + j\sin\psi) + jX_b(I_{tLq} + jI_{tLd}) \tag{9}$$

The machine terminal voltage is described as following:

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

From equations (6), and (9) the transmission line current in d and q axis are defined as following:

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

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

AC Voltage Regulator

The AC voltage regulator controls [16-17] 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 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.
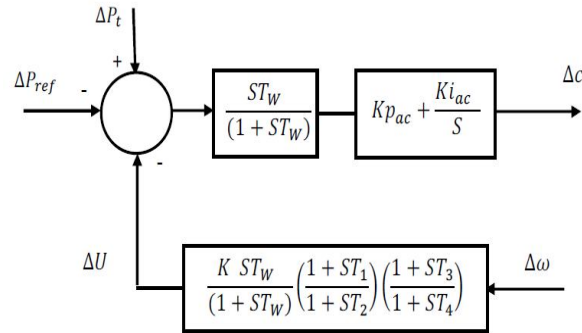

Fig. 2. SSSC dynamic model of AC voltage regulator.

DC Voltage Regulator

The DC voltage regulator controls [16-17] the DC voltage across the DC capacitor of the SSSC controller as shown in Fig. 3.

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 second, the values of T_2 and T_4 are kept constant at a reasonable value of 0.05 second. The parameters of the AC,

DC, and additional controller are to be determined via various optimization techniques.
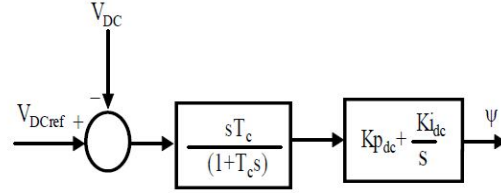

Fig. 3. SSSC dynamic model of DC voltage regulator.

3. 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:

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

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 (13)   Subject to

$$Kp_{dc}^{min} \leq Kp_{dc} \leq Kp_{dc}^{max} \tag{14}$$

$$Ki_{dc}^{min} \leq Ki_{dc} \leq Ki_{dc}^{max} \tag{15}$$

$$Kp_{ac}^{min} \leq Kp_{ac} \leq Kp_{ac}^{max} \tag{16}$$

$$Ki_{ac}^{min} \leq Ki_{ac} \leq Ki_{ac}^{max} \tag{17}$$

$$K^{min} \leq K \leq K^{max} \tag{18}$$

$$T_1^{min} \leq T_1 \leq T_1^{max} \tag{19}$$

$$T_3^{min} \leq T_3 \leq T_3^{max} \tag{20}$$

4. Hybrid BFOA-PSO Optimization Algorithm
4.1 Overview of BFOA

Natural selection tends to eliminate animals with poor foraging strategies and favor the propagation of genes of those animals that have successful foraging strategies since they are more likely to enjoy reproductive success. After many generations, poor foraging strategies are either eliminated or shaped into good ones. The Escherichia coli bacteria that are present in human intestine also undergo a foraging strategy. The control system of these bacteria that dictates how foraging should proceed can be subdivided into four sections namely Chemotaxis, Swarming, Reproduction and Elimination and Dispersal [28-29].

Chemotaxis

The characteristics of movement of bacteria in search of food can be defined in two ways, i.e. swimming and tumbling together known as chemotaxis. A bacterium is said to be

'swimming' if it moves in a predefined direction, and 'tumbling' if moving in an altogether different direction. Mathematically, tumble of any bacterium can be represented by a unit length of random direction $\varphi(j)$ multiplied by step length of that bacterium $C(i)$. In case of swimming, this random length is predefined.

Swarming

For the bacteria to reach at the richest food location, it is desired that the optimum bacterium till a point of time in the search period should try to attract other bacteria so that together they converge at the desired location more rapidly. To achieve this, a penalty function based upon the relative distances of each bacterium from the fittest bacterium till that search duration, is added to the original cost function. Finally, when all the bacteria have merged into the solution point, this penalty function becomes zero. The effect of swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density.

Reproduction

The original set of bacteria, after getting evolved through several chemotactic stages reaches the reproduction stage. Here, best set of bacteria gets divided into two groups. The healthier half replaces with the other half of bacteria, which gets eliminated, owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

Elimination and Dispersal

In the evolution process, a sudden unforeseen event can occur, which may drastically alter the smooth process of evolution and cause the elimination of the set of bacteria and/or disperse them to a new environment. Most ironically, instead of disturbing the usual chemotactic growth of the set of bacteria, this unknown event may place a newer set of bacteria nearer to the food location. From a broad perspective, elimination, and dispersal are parts of the population level long distance motile behavior. In its application to optimization, it helps in reducing the behavior of *stagnation* often seen in such parallel search algorithms. The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [30-31]. Fig. 4. shows the flow chart of BFOA algorithm.

The algorithm of this technique involves two steps.

[Step 1] Initialization

i) p is the number of parameters to be optimized.

ii) S is the number of bacteria to be used for searching the total region.

iii) N_S is the swimming length after which tumbling of bacteria will be undertaken in a chemotactic loop.

iv) N_C is the number of iteration to be undertaken in a chemotactic loop ($N_C > N_S$).

v) N_{re} is the maximum number of reproduction to be undertaken.

vi) N_{ed} is the maximum number of elimination and dispersal events to be imposed over the bacteria.

vii) P_{ed} is the probability with which the elimination and dispersal will continue.

viii) P (1-p, 1-S, 1) is the location of each bacterium which is specified by random numbers on [-1, 1].

ix) The value of C (i) which is assumed to be constant in this case for all the bacteria to simplify the design strategy.

x) The values of $d_{attract}$, $\omega_{attract}$, $h_{repelent}$ and $\omega_{repelent}$.

Step-2 Iterative algorithm for optimization

This section models the bacterial population chemotaxis, swarming, reproduction, elimination and dispersal (initially, j=k=l=0). For the algorithm updating θ^i automatically results in updating of P.

[1] Elimination-dispersal loop: l=l+1

[2] Reproduction loop: k=k+1

[3] Chemotaxis loop: j=j+1

a) For i=1, 2,..., S, calculate cost function value for each bacterium i as follows.

- Compute value of cost function $J(i,j,k,l)$.

Let

$$J_{sw}(i,j,k,l) = J(i,j,k,l) + J_{cc}(\theta^i(j,k,l), P(j,k,l))$$ J_{cc} is defined by the following equation

$$J_{cc}(\theta, P(j,k,l))) = \sum_{i=1}^{S} J_{cc}(\theta, \theta^i(j,k,i))$$

$$= \sum_{i=1}^{S}\left[-d_{attract} \, exp\left(-\omega_{attract} \sum_{m=1}^{p}(\theta_m - \theta_m^i)^2 \right)\right]$$

$$+ \sum_{i=1}^{S}\left[h_{repelent} \, exp\left(-\omega_{repelent} \sum_{m=1}^{p}(\theta_m - \theta_m^i)^2 \right)\right] \quad (21)$$

- Let $J_{last} = J_{sw}(i,j,k,l)$ to save this value since one may find a better cost via a run.
- End of For loop

b) For i=1, 2,....S take the tumbling/swimming decision

- Tumble: generate a random vector $\Delta(i) \in \Re^p$ with each element $\Delta_m(i)$ m=1,2,...p,
- Move: Let

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

Fixed step size in the direction of tumble for bacterium i is considered.

Compute $J(i,j+1,k,l)$ and

$$J_{sw}(i,j+1,k,l) = J(i,j+1,k,l) + J_{cc}(\theta^i(j+1,k,l), P(j+1,k,l))$$
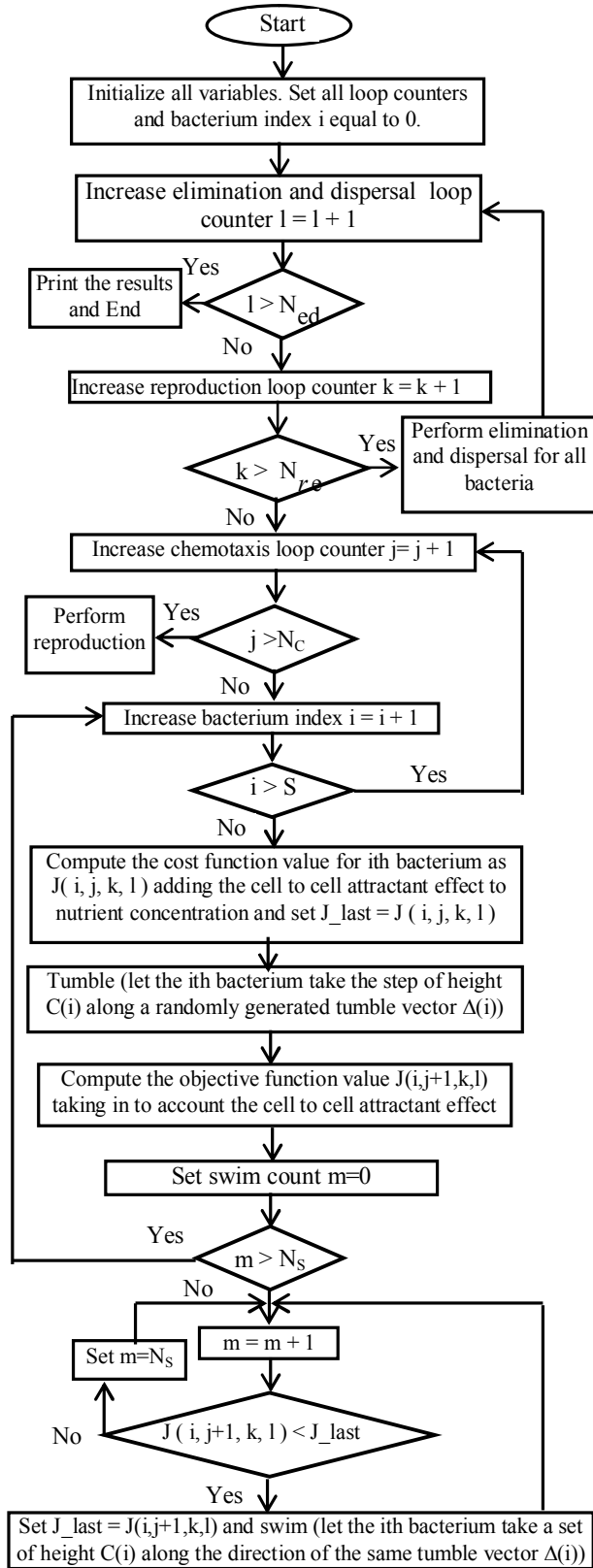
Swim

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

Fig. 4. Flow chart of BFOA.

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

- Let m=m+1
- If $J_{sw}(i, j+1, k, l) < J_{last}$ (if doing better), let $J_{last} = J_{sw}(i, j+1, k, l)$ and let

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

  use this $\theta^i(j+1, k, l)$ to compute the new $J(i, j+1, k, l)$

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

iii) Go to next bacterium (i+1) if $i \neq S$

[4] If j< N_c, go to [step 3]. In this case, continue chemotaxis, since the life of the bacteria is not over.

[5] Reproduction

a) For the given k and l, and for each i=1,2, ..S, let

$$J_{health}^i = \min_{j \in \{1...N_c\}} \left\{ J_{sw}(i, j, k, l) \right\} \text{ be the health}$$

of the bacterium i(a measure of how many nutrients it got over its life time and how successful it was at avoiding noxious substance). Sort bacteria in order of ascending cost J_{health}.

b) The $S_r = S/2$ bacteria with highest J_{health} values die and other S_r bacteria with the best value split.

[6] If k< N_{re}, go to [step 2]. In this case, one has not reached the number of specified reproduction steps, so one starts the next generation in the chemotactic loop.

[7] Elimination-dispersal: for $i = 1,2,...., N$, with probability P_{ed}, eliminate and disperse each bacterium, and this result in keeping the number of bacteria in the population constant. To do these, if you eliminate a bacterium, simply disperse one to a random location on the optimization domain. If l< N_{ed}, then go to [step 2]; otherwise end.

The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [29-31].

4.2 Overview of PSO

PSO is a stochastic optimization technique that draws inspiration from the behavior 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 [25-26]. The velocity and

position update equations for the d-th dimension of the i-th particle in the swarm may be given as follows:

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

$$+ C_2.\varphi_2.(X_{gd} - X_{id}(t)) \qquad (22)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \qquad (23)$$

Where

$V_{id}(t+1)), V_{id(t)}$: The updated and current particles velocities, respectively.

$X_{id}(t+1)), X_{id(t)}$: The updated and current particles positions, respectively.

X_{lid}, X_{gd}: The local and global best position of each particle.

C_1, C_2: are two positive constants.

φ_1, φ_2: are unit random numbers within the range [0, l].

w: is the inertia weight.

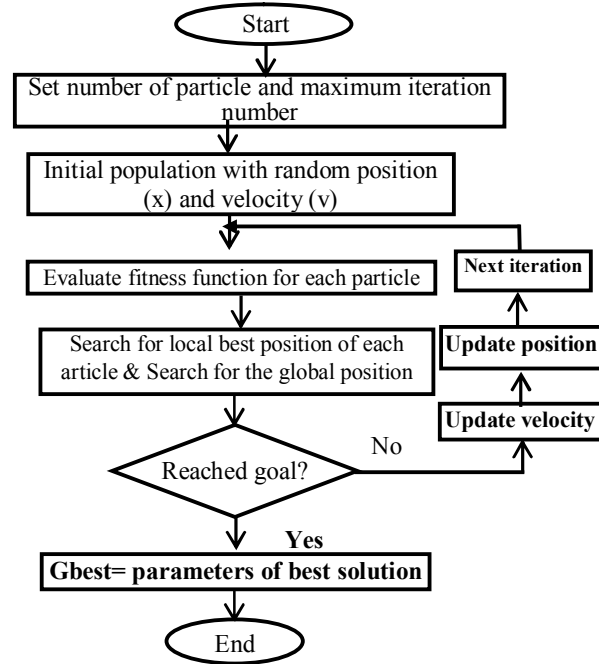Fig. 5. shows the flow chart of PSO algorithm.

Fig. 5. Flow chart of PSO algorithm

4.3 Overview of BSO

BSO combines both algorithms BFOA and PSO thus using advantages of both techniques. The aim is to make use of PSO ability to exchange social information and BFOA ability in finding a new solution by elimination and dispersal. In BFOA, a unit length direction of tumble behavior is randomly generated which may lead to delay in reaching the global solution. In the BSO, technique the unit length random direction of tumble behavior can be obtained by the global best position and the best position of each bacterium by PSO algorithm. The proposed BSO algorithm to search optimal

values of parameters is shown in Fig. 6 and described as follows [32-33]:

[Step 1] Initialize parameters

$n, S, N_C, N_{re}, N_{ed}, P_{ed}, C(i)(i=1,2,.........,N), \phi^i$.

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

[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

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

$$V_{id}^{new} = \omega V_{id}^{new} + C_1.\varphi_1\left(\theta_{g\_best_d} - \theta_d^{old}(i,j+1,k)\right)$$
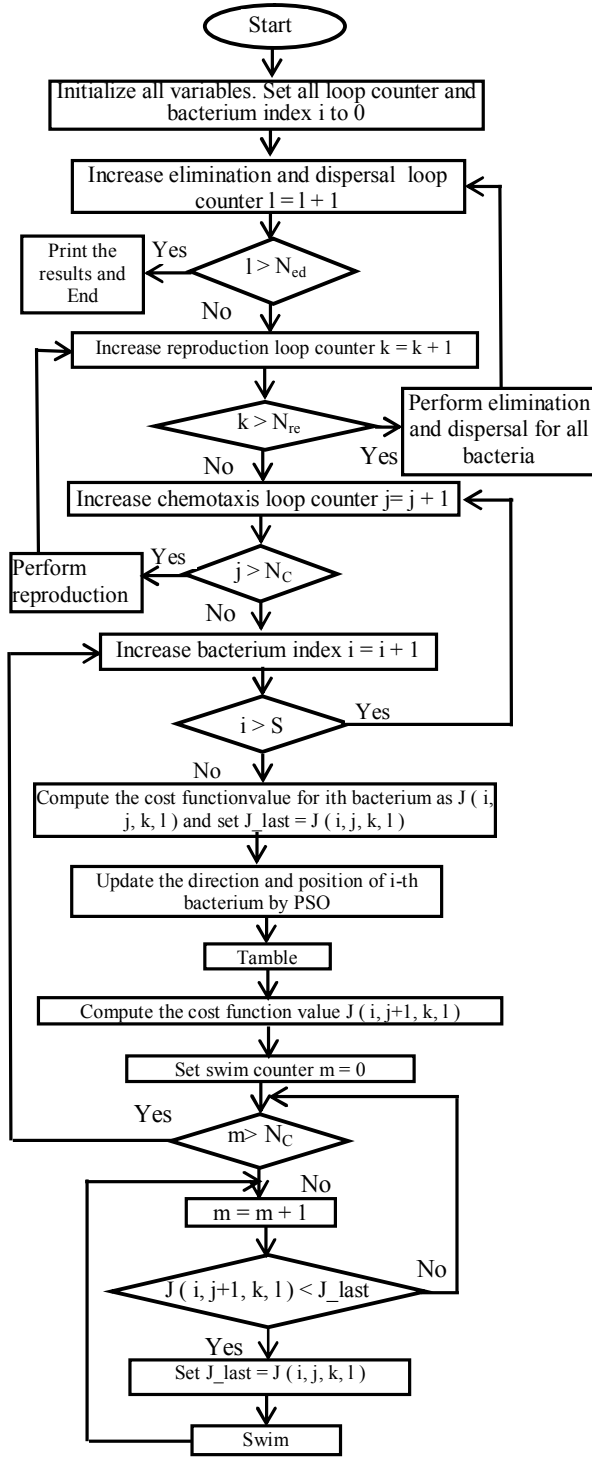
Fig. 6. Flow chart of BSO algorithm.

The flowchart contains the following elements:

- Start
- Initialize all variables. Set all loop counter and bacterium index i to 0
- Increase elimination and dispersal loop counter l = l + 1
- $l > N_{ed}$ — Yes → Print the results and End; No ↓
- Increase reproduction loop counter k = k + 1
- $k > N_{re}$ — Yes → Perform elimination and dispersal for all bacteria; No ↓
- Increase chemotaxis loop counter j = j + 1
- $j > N_C$ — Yes → Perform reproduction; No ↓
- Increase bacterium index i = i + 1
- $i > S$ — Yes; No ↓
- Compute the cost functionvalue for ith bacterium as J (i, j, k, l) and set J_last = J (i, j, k, l)
- Update the direction and position of i-th bacterium by PSO
- Tamble
- Compute the cost function value J (i, j+1, k, l)
- Set swim counter m = 0
- $m > N_C$ — Yes; No ↓
- m = m + 1
- J (i, j+1, k, l) < J_last — No; Yes ↓
- Set J_last = J (i, j, k, l)
- Swim

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

[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 1]. 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.

5. Results and Simulation of SMIB

In this section, the superiority of the proposed BSO algorithm in designing SSSC (BSOSSSC) compared with optimized SSSC with PSO (PSOSSSC) and optimized SSSC controller based on BFOA (BFSSSC) is illustrated.

Fig. 7. shows the variations of objective function with different optimization techniques. The algorithm is run keeping limiting value of cost function at 10^{-5}. The objective functions decrease monotonically over generations of BFOA, PSO and BSO. Moreover, BSO converges at a faster rate (43 generations) compared to that for PSO (62 generations) and BFOA (75 generations).
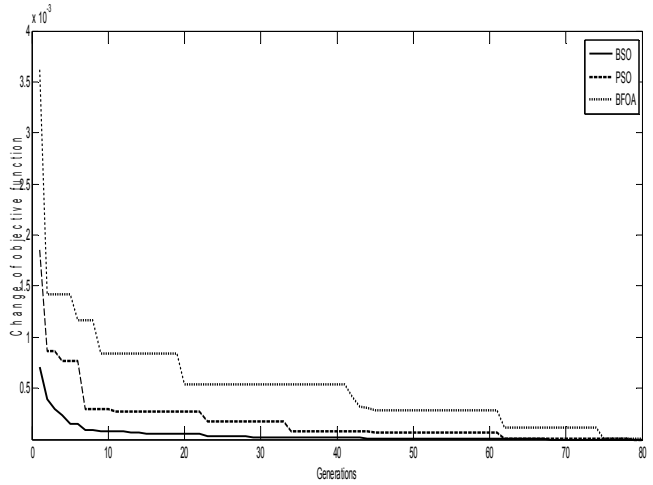

Fig. 7. Variations of objective function.

Computational time (CPU) of all algorithms is compared based on the average CPU time taken to converge the solution. The average CPU for BSO is 21.34 second while it is 27.42 and 34.26 second for PSO and BFOA respectively. It is clear that, average convergence time for BSO is less than other methods. The higher computational time for BFOA is expected due to its dependence on random search directions which may lead to delay in reaching the global solution. On the other hand, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. 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.

Table 1, shows the system eigenvalues, 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.

Table 1. Mechanical modes and damping ratios for various Controllers and operating condition.

	BFSSSC	PSOSSSC	BSOSSSC
Light load	-1.448 ± 7.804j (0.183)	-1.778 ± 8.89j (0.196)	-2.291 ± 10.36j (0.216)
Normal load	-1.222 ± 6.161j (0.195)	-1.474 ± 6.54j (0.22)	-1.802 ± 6.915j (0.2521)
Heavy load	-0.656 ± 4.95j (0.1314)	-0.785 ± 5.26j (0.148)	-1.11 ± 6.18j (0.1768)

Table 2. The controller parameters for various controllers.

	BFSSSC	PSOSSSC	BSOSSSC
Kp_{dc}	0.5398	0.8594	1.8077
Ki_{dc}	1.7412	0.1041	1.814
Kp_{ac}	1.9673	2.5581	3.6947
Ki_{ac}	0.0527	1.2907	0.6113
K	0.0994	0.1432	0.1016
T_1	0.761	0.4984	0.5655
T_3	0.5569	0.3121	0.4937

5.1 Response under normal load condition:

The effectiveness of the performance under 0.2 step increase in mechanical torque is applied. Fig. 8 shows the response of speed for normal loading condition. This figure 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 2.5, 3.8, and 4.2 second 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.
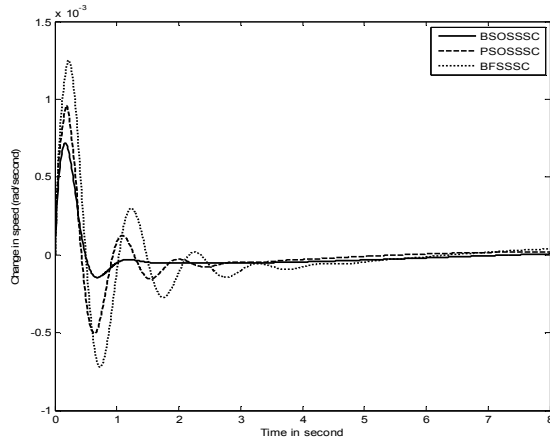
Fig. 8. Change in speed for normal load condition.

5.2 Response under heavy load condition:

Fig. 9 shows the system response under heavy loading condition with fixing the controller parameters. From this figure, 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. Hence, the proposed BSOSSSC extend the power system stability limit.
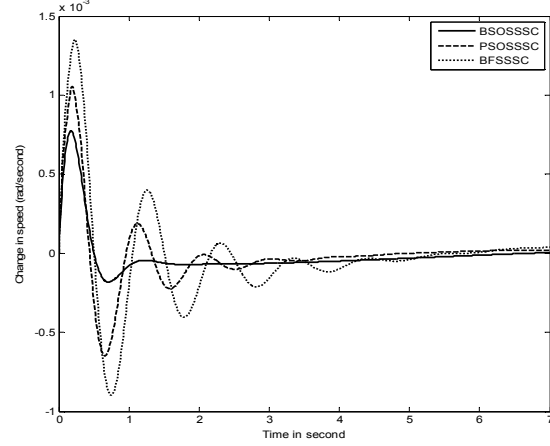
Fig. 9. Change in speed for heavy load condition.

6. Multimachine Power System Results and Simulation

Fig. 10 shows the single line diagram of the tested multimachine system. Details of system data are given in [41]. The system and generator loading levels are given in Table 3. Many input signals have been proposed for the FACTS to damp the system oscillations. Signals which carry invaluable information about the interarea mode can be considered as the input signals. Since FACTS controllers are located in the transmission systems, local input signals are always preferred. For example, line active power and current carry such valuable information. Transmission line active power has been proposed as an effective input signal in [13, 14] for series FACTS devices damping controller design. For this reason, here, the active power of the transmission line is selected as the input signal. The power flow in line 5-7 is the largest power flow in the system under study [13]. Moreover, this line is the longest line in the system. So, one will consider this line as the best location for installing the SSSC controller in this paper. Also, the objective function is modified to be

$$J = \int_0^{t_{sim}} t\left\{\left|\Delta\omega_{12} + \Delta\omega_{23} + \Delta\omega_{13}\right| + \left|\Delta V_{DC}\right| + \left|\Delta P_{line57}\right|\right\}dt$$

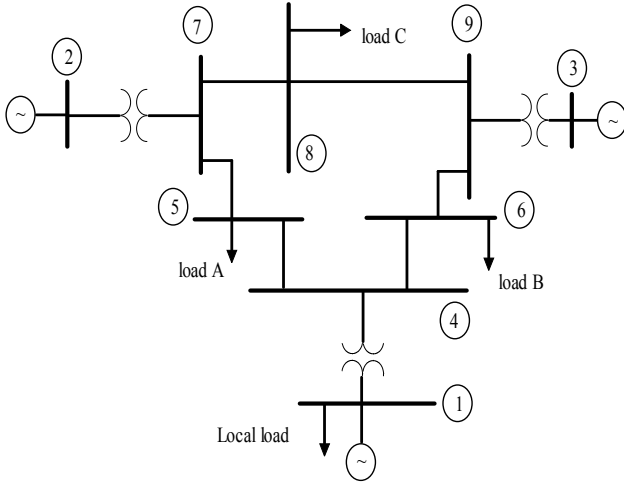Table 4, shows the parameters of SSSC controller obtained by various algorithms for multimachine system.

Fig. 10. Multimachine power system.

Table 3. Loading of the system (in p.u)

	Light		Normal case		Heavy	
	P	Q	P	Q	P	Q
Generator						
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	-0.267	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 4. The controller parameters for various controllers.

	BFSSSC	PSOSSSC	BSOSSSC
Kp_{dc}	0.7852	1.0964	2.7304
Ki_{dc}	2.1182	0.1332	2.3841
Kp_{ac}	2.2483	2.9877	3.9861
Ki_{ac}	0.0877	1.6774	0.6715
K	0.1297	0.2442	0.1324
T_1	0.8758	0.5972	0.6445
T_3	0.7561	0.4523	0.5847

6.1 Step Response for Normal Load Condition

Fig. 11 shows the responses of $\Delta\omega_{12}$ for a 0.1 step increase in reference voltage of generator (1) for normal loading condition. This figure 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 2.2, 2.7, and 3.4 second for BSOSSSC, PSOSSSC, and BFSSSC respectively, so the proposed BSOSSSC is capable of providing sufficient damping to the system oscillatory modes compared with PSOSSSC and BFSSSC.
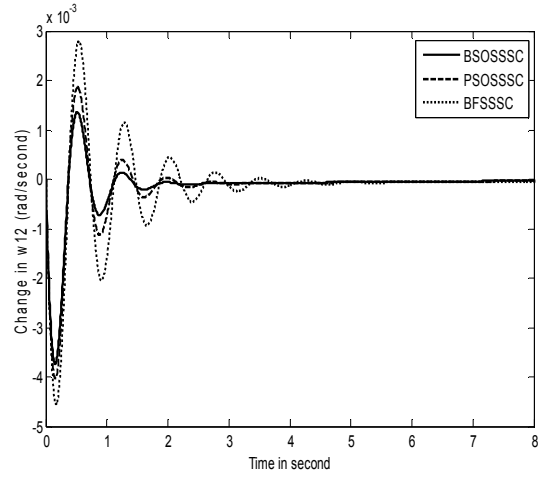

Fig. 11. Change in $\Delta\omega_{12}$ for normal load condition.

6.2 Response under heavy load condition:

Fig. 12 shows the system response at heavy loading condition with fixing the controller parameters. From this figure, 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 2.0, 2.7, and 3.4 second for BSOSSSC, PSOSSSC, and BFSSSC respectively. Hence, the proposed BSOSSSC extend the power system stability limit.
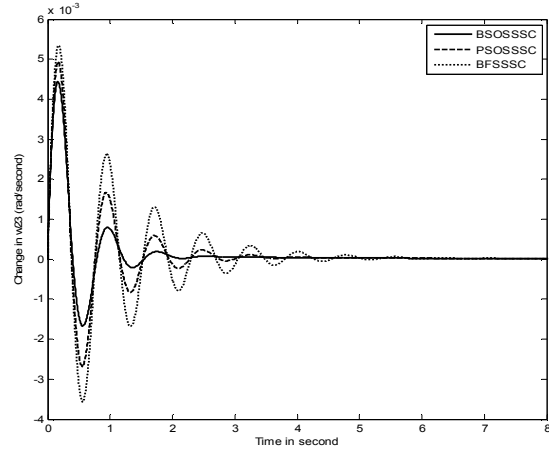

Fig. 12. Change in $\Delta\omega_{23}$ for heavy load condition.

7. Conclusions

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 different power systems. 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. The superiority of this objective function is that the effect of SSSC signal is taken into consideration. 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 and valid over a wide range of operating conditions.

8. References

[1] P. Kundur, "Power System Stability and Control", McGraw-Hill, 1994.
[2] N. G. Hingorani, L. Gyugyi, "Understanding FACTS," New York: IEEE Press, 2000.
[3] H. M. Soliman, Ehab H. E. Bayoumi, and M. Awadallah, "Design of Reconfigurable Fault-Tolerant PSS and FACTS Controllers," Electric Power Components and Systems, Vol.38, No.13, pp.1446-1468, 2010.
[4] K. A. Ellithy, and S.M. Al-Alawi, "Tuning a Static Var Compensator Controller over a wide Range of Load Models Using an Artificial Neural Network", Int. J. of Electric Power System Research, Vol. 38, No. 2, August 1996, pp. 97-104.
[5] J. Lu, M. H. Nehrir, and D. A. Pierre," A Fuzzy Logic based Adaptive Damping Controller for Static VAR Compensator", Int. J. of Electric Power Systems Research, Vol. 68, No. 2, February 2003, pp.113- 118.
[6] N. Karpagam, and D. Devaraj, "Fuzzy Logic Control of Static Var Compensator for Power System Damping", Int. J. of Electrical and Electronics Engineering Vol.3, No.10, 2009, pp. 625-631.
[7] 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.
[8] 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.
[9] S. M. Abd-Elazim, and E. S. Ali, "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.
[10] Y. L. Abdel-Magid, and M. A. Abido, "Robust Coordination Design of Excitation and TCSC Based Stabilizer Using Genetic Algorithms", Int. J. of Electric Power Systems Research, Vol. 69, No. 2-3, May 2004, pp. 129-141.
[11] S. Panda, N. P. Padhy, and R.N. Patel, "Genetically Optimized TCSC Controller for Transient Stability Improvement", Int. J. of Computer and Information Engineering, Vol. 1, No. 1, 2007, pp. 19-25.
[12] L. Khan, I. Ullah, T. Saeed, and K. L. Lo, "Virtual Bees Algorithm Based Design of Damping Control System for TCSC", Australian Journal of Basic and Applied Sciences, Vol. 4, No. 1, 2010, pp. 1-18.
[13] H. Shayeghi, A. Safari, and H. A. Shayanfar, "PSS and TCSC Damping Controller Coordinated Design Using PSO in Multimachine Power System", Int. J. of Energy Conversion and Management, Vol. 51, No. 12, 2010, pp. 2930-2937.
[14] 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.
[15] Y. S. Lee, and S. Y. Sun, "STATCOM Controller Design for Power System Stabilization with Suboptimal Control and Strip Pole Assignment", Int. J. Electrical Power and Energy Systems, Vol. 24, No. 9, November 2002, pp. 771-779.
[16] S. M. Bamasak, and M. A. Abido, "Robust Coordinated Design of PSS and STATCOM Controllers for Damping Power System Oscillation", 15th PSCC, Liege, 22-26 August 2005.
[17] M. E. Mandour, and S. M. Abd-Elazeem, "Robust Design of STATCOM Controller for Improving Power System Damping Performance Via GA", Ain Shams Journal of Electrical Engineering, Vol. 43, No. 2 December, 2008, pp. 237-248.
[18] K. K. Sen, "SSSC: Theory, Modeling, and Applications", IEEE Transactions on Power Delivery, Vol. 13, No.1, January 1998, pp. 241-246.
[19] I. Ngamroo, "A Stabilization of Frequency Oscillations in an Interconnected Power System Using SSSC", Thammasat Int. J. Sc. Tech., Vol. 6, No. 1, January – April 2001, pp. 52-59.
[20] I. Ngamroo, and W. Kongprawechnon, "A Robust Controller Design of SSSC for Stabilization of Frequency Oscillations in Interconnected Power Systems", Int. J. of Electric Power and Systems Research, Vol. 67, 2003, pp. 161-176.
[21] A. Kazemi, M. Ladjevardi, and M. A. S. Masoum, "Optimal Selection of SSSC Based Damping Controller Parameters for Improving Power System Dynamic Stability Using Genetic Algorithm", Iranian Journal of Science and Technology, Transaction, Engineering, Vol. 29, No. B1, 2005, pp. 1-10.
[22] S. Panda, and N. P. Padhy, "Application of Genetic Algorithm for FACTS Based Controller Design", Int. J. Computer, Information, and Systems Science, Vol. 1, No. 1, 2007, pp. 40-47.
[23] S. Panda, and N. P. Padhy, "A PSO Based SSSC Controller for Improvement of Transient Stability Performance", Int. J. of Intelligent Technology, Vol. 2, No. 1, 2007, pp. 28-35.
[24] S. Panda, "Modelling, Simulation and Optimal Tuning of SSSC Based Controller in a Multimachine Power System", World Journal of Modelling and Simulation, Vol. 6, No. 2, 2010, pp. 110-121.
[25] J. Kennedy and R. Eberhart, "Particle Swarm Optimization", Proceedings of IEEE International Conference on Neural Networks, 1995, pp. 1942-1948.
[26] 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.
[27] 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.
[28] 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.
[29] 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.
[30] S. M. Abd-Elazim, and E. S. Ali, "Bacteria Foraging: A New Technique for Optimal Design of FACTS Controller to Enhance Power System Stability", Journal of Electric Engineering, Vol. 13, No. 2, June 2013, pp. 220-227.
[31] 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.
[32] E. S. Ali, S. M. Abd-Elazim, "Optimal Power System Stabilizers Design for Multimachine Power System via Hybrid Approach", Journal of Electric Engineering, Vol. 13, No. 3, September 2013, pp. 83-90.
[33] S. M. Abd-Elazim, and E. S. Ali, "Hybrid BFOA-PSO Approach for Robust Design of TCSC Based Controller", Journal of Electric Engineering, Vol. 13, No. 2, June 2013, pp. 251-258.
[34] E. S. Ali, S. M. Abd-Elazim, "Hybrid BFOA-PSO Approach for SSSC Damping Controller Design", Journal of Electric Engineering, Vol. 13, No. 3, September 2013, pp. 257-262.
[35] E. S. Ali, and S. M. Abd-Elazim, "Hybrid BFOA–PSO Approach for Damping Power System Oscillations by Using Facts Devices", Journal of Engineering and Applied Sciences, Vol. 8, Issue 3, 2013, pp. 89-96.
[36] 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.
[37] S. M. Abd-Elazim, and E. S. Ali, "A Hybrid Particle Swarm Optimization and Bacterial Foraging for Optimal Power System Stabilizers Design", Int. Journal of Electrical Power and Energy Systems, Vol. 46, March 2013, pp. 334-341.
[38] E. S. Ali, and S. M. Abd-Elazim, "Statistical Assessment of New Coordinated Design of PSSs and SVC via Hybrid Algorithm", Int. J. of Engineering and Advanced Technology, Vol. 2, No. 3, February 2013, pp. 647-654.
[39] F. Al-Jowder, "Improvement of Synchronizing Power and Damping Power by Means of SSSC and STATCOM, A Comparative Study", Int. J. Electric Power Systems Research, Vol. 77, No. 8, 2007, pp. 1112-1117.
[40] M. S. Castro, H. M. Ayres, V. F. Da-Costa, and L. C. P. Da-Silva, "Impacts of SSSC Control Modes on Small-Signal and Transient Stability of a Power System", Int. J. Electric Power Systems Research, Vol. 77, No. 1, 2007, pp. 1-9.
[41] P. M. Anderson and A. A. Fouad, "Power System Control and Stability", Iowa State University Press, Iowa, 1977.

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, ω =0.9.