Synergy of Particle Swarm Optimization and Bacterial Foraging for TCSC Damping Controller Design

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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 paper comes up with a hybrid approach involving Particle Swarm Optimization (PSO) and BFOA algorithm called Bacterial Swarm Optimization (BSO) for designing Thyristor Controlled Series Capacitor (TCSC) in a multimachine 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. Simulations results have shown the validity of the proposed BSO in tuning TCSC 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: - TCSC; Multimachine Power System; Particle Swarm Optimization; Bacterial Foraging; Hybrid Algorithm; Damping Oscillations.

1. Introduction

The power transfer in an integrated power system is constrained by transient stability, voltage stability 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 limit and thermal limit [1].

Thyristor controlled series compensator (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 oscillations; and enhancing transient stability [2]. The applications of TCSC for power oscillations damping and stability enhancement can be found in [3-9].

In last few years, many researchers have posed techniques for designing TCSC to enhance the damping of electromechanical oscillations of power systems and application of different optimization techniques in improving power system stability. The power system stability enhancement via power system stabilizer (PSS) and TCSC based stabilizer when applied independently and also through coordinated application is discussed and investigated in [10]. A pole placement technique for PSS and TCSC based stabilizer using simulated annealing (SA) algorithm is presented in [11]. A procedure for modelling and tuning the parameters of TCSC compensation controller in a multimachine power system to improve system stability using (genetic algorithm) GA is introduced in [12]. To eliminate the disadvantage of GAs, a new optimization scheme known as bacterial foraging (BF) is used for the PSS parameter design in a multimachine power system [13]. The application and performance comparison of particle swarm optimization (PSO) and GA optimization techniques, for FACTS based controller design is discussed in [14]. A supplementary damping control system design for TCSC based on natural inspired Virtual Bees Algorithm (VBA) is presented in [15]. A new design procedure for simultaneous coordination designing of the TCSC damping controller and PSS in multimachine power system is developed in [16] using PSO. Coordination of

TCSC controllers is conducted by applying a linear matrix inequality is discussed in [17]. A probabilistic evaluation of total transfer capability and its improvement using probabilistic model of FACTS devices are presented in [18]. An efficient parallel GA (EPGA) for the solution of large scale optimal power flow problems to reduce the high CPU time execution is designed in [19]. A novel scheme of damping power system multimode oscillations by using a single FACTS device is illustrated in [20]. A reduced rule base self-tuning fuzzy PI controller (STFPIC) for TCSC is discussed in [21]. The application of the decentralized modal control method for pole placement in multimachine power system utilizing FACTS devices is developed in [22]. The parameter tuning of a PID controller for a FACTS based stabilizer employing multi-objective evolutionary algorithm is introduced in [23].

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. However, 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 [24]. 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 [25-26]. 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 proposed by [27-29] and further established recently by [30-32]. 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 proposed that combine the above mentioned optimization algorithms [33-34]. 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 TCSC damping controller in a multimachine power system to damp power system oscillations. The performance of BSO has been compared with these of PSO and BFOA in tuning the TCSC 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. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio is optimized for different operating conditions. Simulations 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. Bacteria foraging optimization: A brief overview

The survival of species in any natural evolutionary process depends upon their fitness criteria, which relies upon their food searching and motile behaviour. The law of evolution supports those species who have better food searching ability and either eliminates or reshapes those with poor search ability. The genes of those species who are stronger gets propagated in the evolution chain since they possess ability to reproduce even better species in future generations. So a clear understanding and modelling of foraging behaviour in any of the evolutionary species, leads to its application in any nonlinear system optimization algorithm. The foraging strategy of *Escherichia coli* bacteria present in human intestine can be explained by four processes, namely chemotaxis, swarming, reproduction, and elimination dispersal [25-26].

2.1 Chemotaxis

The characteristics of movement of bacteria in search of food can be defined in two ways, i.e. swimming and tumbling together knows 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.

2.2 Swarming

For the bacteria to reach at the richest food location (i.e. for the algorithm to converge at the solution point), 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 (solution point) 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.

2.3 Reproduction

The original set of bacteria, after getting evolved through several chemotactic stages reaches the reproduction stage. Here, best set of bacteria (chosen out of all the chemotactic stages) 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.

2.4 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 behaviour. In its application to optimization, it helps in reducing the behaviour of *stagnation* (i.e. being trapped in a premature solution point or local optima) often seen in such parallel search algorithms. The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [26-27].

3. Problem statement

3.1 Power system model

A power system can be modelled by a set of nonlinear differential equations are:

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

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 TCSC 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 TCSC, the linearized incremental models around an equilibrium point are usually employed. Therefore, the state equation of a power system with n machines and m TCSC can be written as:

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

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

Fig. 1 shows the single line diagram of the system under study. Details of system data are given in [35]. 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) indicates 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).
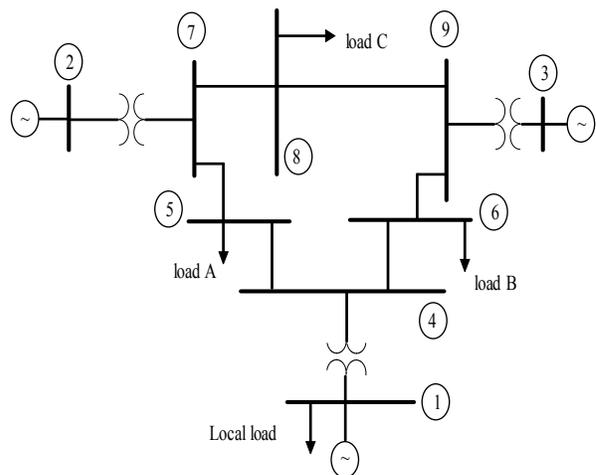

Fig. 1. System under study.

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

Generator	Eigenvalues	Frequencies	Damping ratio ζ
G1	**+0.15 ± 1.49j**	0.2371	**-0.1002**
G2	-0.35 ± 8.14j	1.2295	0.0430
G3	-0.67 ± 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	-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
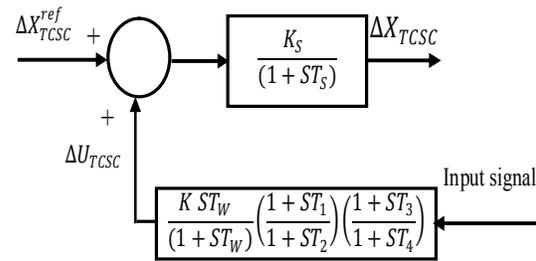
Fig. 2. Block diagram of TCSC

3.2 TCSC Modelling and Damping Controller Design

A typical TCSC module consists of a fixed series capacitor in parallel with a thyristor controlled reactor (TCR). The TCR is formed by a reactor in series with a bi-directional thyristor valve which is fired by a phase angle α ranging between 90 and 180° with respect to the capacitor voltage. For the load flow and dynamic stability analysis studies, a TCSC can be modelled as a variable reactance. The dynamic equation of TCSC reactance can be expressed as following:

$$\dot{\Delta X}_{TCSC} = \frac{1}{T_s}(K_s(\Delta X_{TCSC}^{ref} + \Delta U_{TCSC}) - \Delta X_{TCSC}) \quad (3)$$

Where X_{TCSC}^{ref} is the reference reactance of the TCSC; K_s and T_s are the gain and time constant of TCSC.

The structure of the TCSC based damping controller is shown in Fig. 2. The parameters of the damping controllers are obtained using the various optimization algorithms. 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 [16, 17] 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 line flow data are given in Table (3). The power flow in line 5-7 is the largest power flow in the system under study. Moreover, this line is the longest line in the system. So, one will consider this line as the best location for installing the TCSC controller in this paper.

Table (3) Base case (line flow) on 100 MVA base.

From bus	To bus	Real power (p.u)
4	6	0.3070
6	9	0.6082
4	5	0.4094
5	7	0.8662
7	8	0.7638
8	9	0.2410

4. Objective function

To maintain stability and provide greater damping, the parameters of the TCSC may be selected to minimize the following objective function:

$$J_t = \sum_{j=1}^{np} \sum_{\sigma_{ij} \geq \sigma_0} (\sigma_0 - \sigma_{ij})^2 + \sum_{j=1}^{np} \sum_{\xi_{ij} \geq \xi_0} (\xi_0 - \xi_{ij})^2 \quad (4)$$

This will place the system closed loop eigenvalues in the D-shape sector characterized by $\sigma_{ij} \leq \sigma_0$ and $\xi_{ij} \rangle \xi_0$ as shown in Fig. 3.

Where, np is the number of operating points considered in the design process, σ and ξ are the real part and the damping ratio of the eigenvalue of the operating point. In this study, σ_0 and ξ_0 are chosen to be -0.5 and 0.10 respectively [36]. To reduce the computational burden in this study, the value of the wash out time constant T_W is fixed to 10 second, and the values of T_2 and T_4 are kept constant at a reasonable value of 0.05 second and tuning of T_1 and T_3 are undertaken to achieve the net phase lead required by the system. Typical ranges of the optimized parameters are [0.01- 50] for K and [0.01-1.0] for T_1 and T_3. Based on the

objective function J_t optimization problem can be stated as: Minimize J_t subjected to:

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

$$T_1^{min} \le T_1 \le T_1^{max}$$

$$T_3^{min} \le T_3 \le T_3^{max} \qquad (5)$$

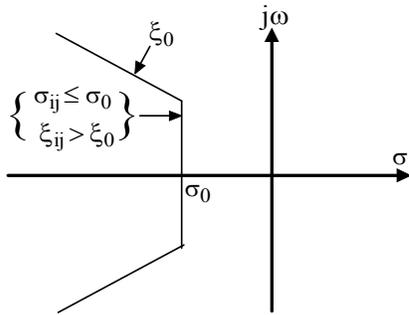Fig. 3. A D-shape sector in the s-plane.

5. The Bacterial Swarm 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 [24]. The velocity and position update equations for the d-th dimension of the i-th particle in the swarm may be given as follows:

$$V_{id}(t+1) = \omega V_{id}(t) + C_1 \varphi_1 (V_{lid} - X_{id}(t)) + C_2 \varphi_2 (P_{gd} - X_{id}(t)) \qquad (6)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \qquad (7)$$

On the other hand, the BF is based upon search and optimal foraging decision making capabilities of the Escherichia coli bacteria [33]. 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 [33-34].

[Step 1] Initialize parameters n, S, N_C, 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_C: The number of chemotactic steps,

N_{re}: The number of reproduction steps,

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: 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

$\Delta_m (i), m = 1,2,...... ., p,$ 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

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

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 (and the copies that are made are placed at the same location as their parent).

[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.

The detailed mathematical derivations as well as theoretical aspect of this new concept are presented in [33-34].

6. Results and Simulations

In this section, the superiority of the proposed BSO algorithm in designing TCSC (BSOTCSC) in compare to optimized TCSC with PSO (PSOTCSC) and optimized TCSC controller based on BFOA (BFTCSC) is illustrated.

Fig. 4. shows the variations of objective function with various optimization techniques. The objective functions decrease monotonically over generations of BFOA, PSO and BSO. The final value of the objective function is J_t=0 for all algorithms, indicating that all modes have been shifted to the specified D-shape sector in the S-plane and the proposed objective function is satisfied. Moreover, BSO converges at a faster rate (45 generations) compared to that for PSO (61 generations) and BFOA (82 generations).

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 26.84 second while it is 34.28 and 42.56 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 (4), shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear that the BSOTCSC shift substantially the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed BSOTCSC are significantly improved to be (σ=-0.74,-0.75,-0.98) for light, normal, and heavy loading respectively. Also, the damping ratios corresponding to BSOTCSC controllers are almost greater than these corresponding to PSOTCSC and BFTCSC ones. Hence, compared to BFTCSC and PSOTCSC, BSOTCSC greatly enhances the system stability and improves the damping characteristics of electromechanical modes. Results of TCSC parameters set values based on the proposed objective function using BSO, PSO, and BFOA are given in Table (5).
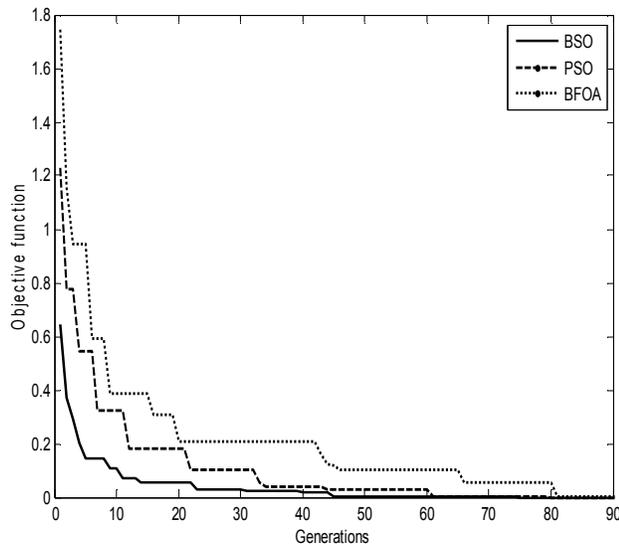
Fig. 4. Variations of objective function.

Table (4) Mechanical modes and ζ under different loading conditions and controllers.

	BSOTCSC	PSOTCSC	BFTCSC
Light load	$-3.99 \pm 9.12j, 0.40$	$-3.96 \pm 9.25j, 0.39$	$-3.46 \pm 9.28j, 0.35$
	$-1.97 \pm 6.20j, 0.30$	$-1.57 \pm 6.18j, 0.25$	$-1.29 \pm 6.09j, 0.21$
	$-0.74 \pm 0.64j, 0.76$	$-0.73 \pm 0.65j, 0.74$	$-0.67 \pm 0.68j, 0.70$
Normal load	$-3.39 \pm 11.2j, 0.29$	$-3.27 \pm 11.2j, 0.28$	$-3.18 \pm 11.14j, 0.27$
	$-1.31 \pm 6.31j, 0.20$	$-1.29 \pm 6.24j, 0.20$	$-1.08 \pm 6.41j, 0.17$
	$-0.75 \pm 0.76j, 0.70$	$-0.73 \pm 0.76j, 0.69$	$-0.70 \pm 0.77j, 0.67$
Heavy load	$-3.81 \pm 11.5j, 0.31$	$-3.45 \pm 11.4j, 0.29$	$-3.29 \pm 11.75j, 0.27$
	$-0.79 \pm 5.61j, 0.14$	$-0.78 \pm 5.57j, 0.14$	$-0.75 \pm 5.95j, 0.13$
	$-0.98 \pm 0.79j, 0.78$	$-0.96 \pm 0.78j, 0.77$	$-0.94 \pm 0.78j, 0.76$

Table (5) Parameters of TCSC damping controller.

	BSOTCSC	PSOTCSC	BFTCSC
K	4.2531	3.2459	2.9155
T_1	0.6754	0.5348	0.3384
T_3	0.2859	0.2516	0.1252

6.1 Response for light load condition:

The effectiveness of the performance under severe disturbance is verified by applying a three phase fault of 6 cycle duration at 1.0 second near bus 2. Figs. 5-7, show the response of $\Delta\omega_{12}, \Delta\omega_{23}$, and $\Delta\omega_{13}$ due to severe disturbance for light loading condition. From these figures, it can be seen that the BSOTCSC using the proposed objective function achieves good robust performance, and provides superior damping in comparison with the other controllers. Moreover, the required mean time to suppress these oscillations is approximately 3.07 second with BSOTCSC, 3.78 second for PSOTCSC, and 4.3 second with BFTCSC so the designed controller is capable of providing sufficient damping to the system oscillatory modes.
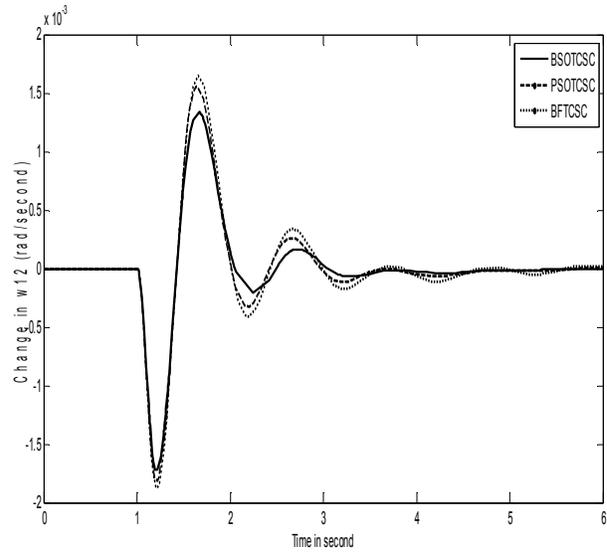

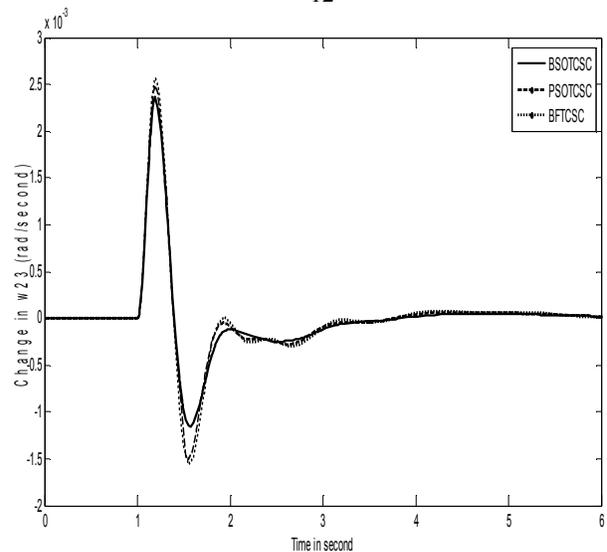Fig. 5. Response of $\Delta\omega_{12}$ for light load condition.

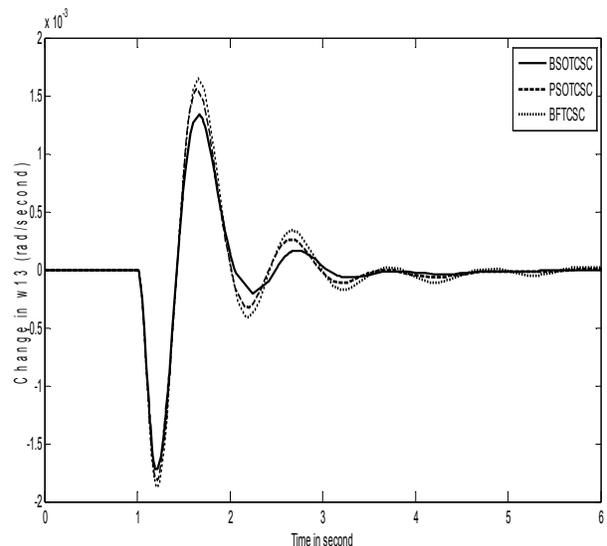Fig. 6. Response of $\Delta\omega_{23}$ for light load condition.

Fig. 7. Response of $\Delta\omega_{13}$ for light load condition.

6.2 Response for normal load condition:

Figs. 8-10, show the response of $\Delta\omega_{12}$, $\Delta\omega_{23}$, and $\Delta\omega_{13}$ due to same disturbance for normal loading condition. These figures indicate the capability of the BSOTCSC in reducing the settling time and damping power system oscillations. Moreover, the mean settling time of these oscillations is 4.4, 6.1, and 7.0 second for BSOTCSC, PSOTCSC, and BFTCSC respectively. In addition, the proposed BSOTCSC outperforms and outlasts PSOTCSC and BFTCSC controller in damping oscillations effectively and reducing settling time. Hence, BSOTCSC controller greatly enhances the system stability and improves the damping characteristics of power system.
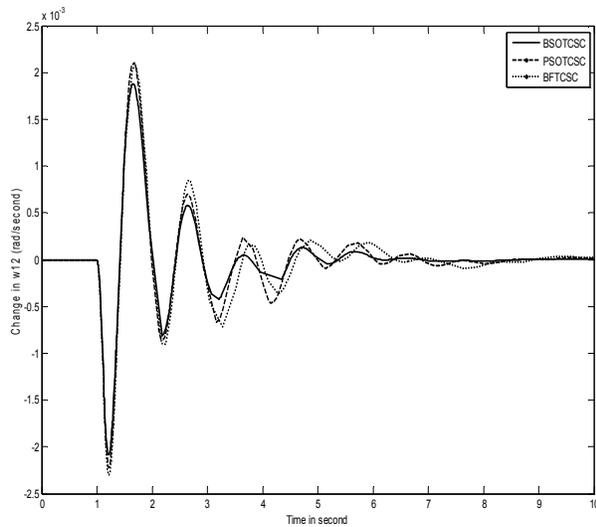

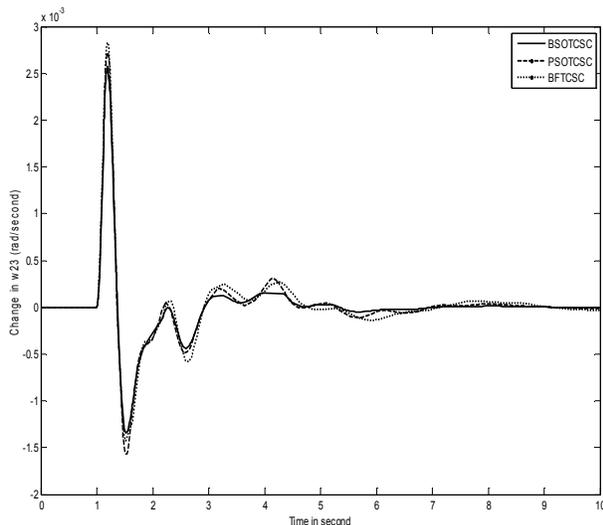Fig. 8. Response of $\Delta\omega_{12}$ for normal load condition.

Fig. 9. Response of $\Delta\omega_{23}$ for normal load condition.
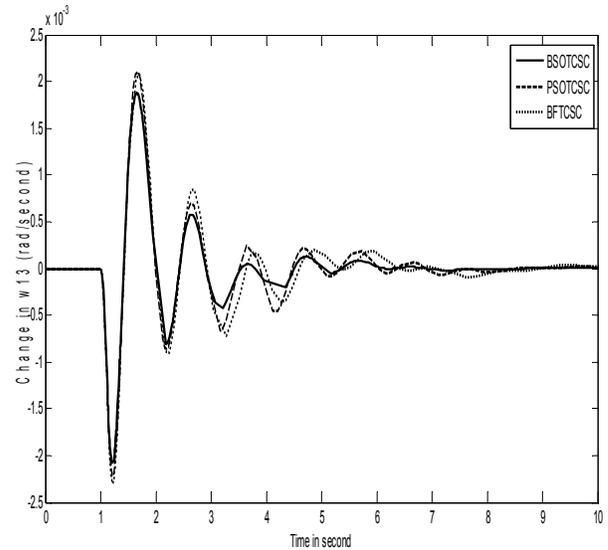

Fig. 10. Response of $\Delta\omega_{13}$ for normal load condition.

6.3 Response for heavy load condition:

Figs. 11-13, show the system response at heavy loading condition with fixing the controller parameters. From these figures, it can be seen that the response with the proposed BSOTCSC shows good damping characteristics to low frequency oscillations and the system is more quickly stabilized than PSOTCSC and BFTCSC. The mean settling time of oscillation is 5.6, 9.4, and 13.1 second for BSOTCSC, PSOTCSC, and BFTCSC respectively. Hence, the proposed BSOTCSC extend the power system stability limit and the power transfer capability.
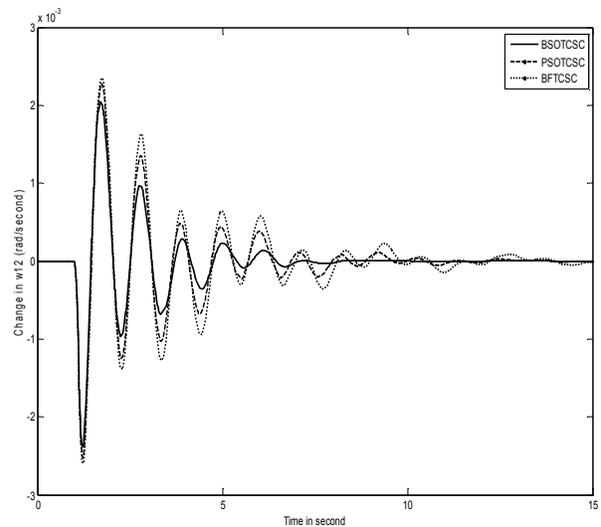

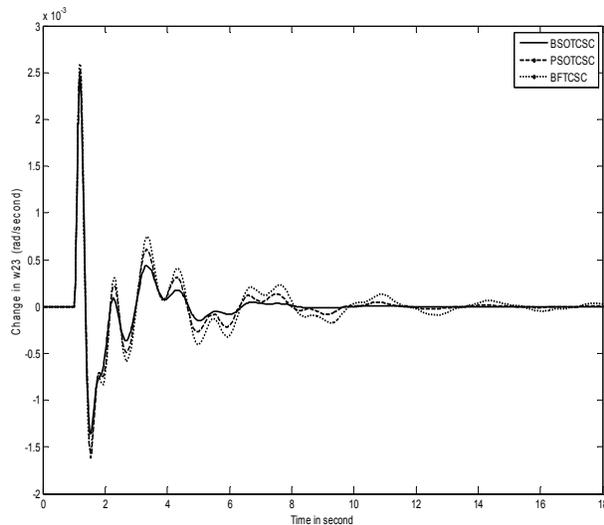Fig. 11. Response of $\Delta\omega_{12}$ for heavy load condition.

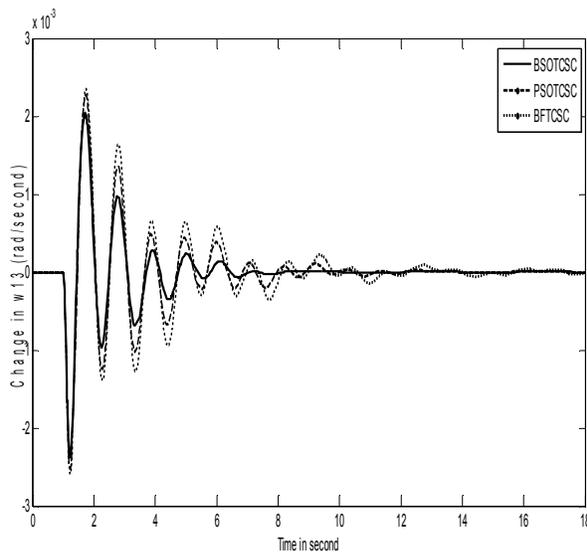Fig. 12. Response of $\Delta\omega_{23}$ for heavy load condition.

Fig. 13. Response of $\Delta\omega_{13}$ for heavy load condition.

6.4 Robustness and performance index:

To demonstrate the robustness of the proposed controller, a performance index: the Integral of the Time multiplied Absolute value of the Error (ITAE) is being used as:

$$ITAE = \int_{0}^{30} t\left(\left|\Delta w_{12}\right| + \left|\Delta w_{23}\right| + \left|\Delta w_{13}\right|\right)dt \qquad (8)$$

Where $\Delta w_{12} = \Delta w_1 - \Delta w_2$, $\Delta w_{23} = \Delta w_2 - \Delta w_3$, and $\Delta w_{13} = \Delta w_1 - \Delta w_3$. It is worth mentioning that the lower the value of this index is, the better the system response in terms of time domain characteristics. Numerical results of performance robustness for all cases are listed in Table (6). It can be seen that, the values of these system performance

characteristics with the BSOTCSC are smaller compared to that of PSOTCSC and BFTCSC. This demonstrates that the overshoot, undershoot; settling time, and speed deviations of all units are greatly reduced by applying the proposed BSO based tuned TCSC damping controller.

Table (6) Values of performance index.

	ITAE		
	BSOTCSC	PSOTCSC	BFTCSC
Light load	0.0029	0.0037	0.0042
Normal load	0.0040	0.0049	0.0056
Heavy load	0.0064	0.0083	0.0095

7. Conclusions

This paper proposes a new optimization algorithm known as BSO, which synergistically couples the BFOA with the PSO for optimal designing of TCSC damping controller. The design problem of the proposed controller is formulated as an optimization problem and BSO is employed to search for optimal controller parameters. An eigenvalue based objective function reflecting the combination of damping factor and damping ratio is optimized for different operating conditions. Simulations 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 PSO and BFOA.

8. References

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Appendix

The system data are as shown below:

a) Excitation system: K_A = 400; T_A = 0.05 second; K_f = 0.025; T_f = 1 second.

b) TCSC Controller: T_s = 0.015 second; firing angle (α_o) =147.5; K_s =50;

c) 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.

d) PSO parameters: $C_1 = C_2$ =2.0, ω=0.9.