

# Hybrid BFOA-PSO Approach for SSSC Damping Controller Design

E. S. Ali

Electric Power and Machine Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt.

[ehabsalimalisalama@yahoo.com](mailto:ehabsalimalisalama@yahoo.com)

S. M. Abd-Elazim

[sahareldeep@yahoo.com](mailto:sahareldeep@yahoo.com)

**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 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:** - SSSC; 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].

Recently, there has been a surge of interest in the development and use of FACTS controllers in power transmission systems [2 – 6]. 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 in [3]. SSSC is designed in [4] 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 in [5]. A multi control functional model of SSSC for power system analysis is described in [6]. This model can be used for steady state control of one of the following parameters: 1) the active power flow on the transmission line; 2) the reactive power flow on the transmission line; 3) the voltage at the bus; 4) the impedance (precisely reactance) of the transmission line. A robust damping controller based on Fuzzy Logic Controller (FLC) is introduced in [7]. 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 eigenvalues toward the desired stability region is designed in [8]. The dynamic operation of both Static Synchronous Compensator (STATCOM) and SSSC based on a new model comprising full 48-pulse Gate Turn Off (GTO) VSC is investigated in [9]. 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 in [10]. 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 in [11]. 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 in [12]. The impacts of different SSSC control modes on a small signal and transient stability of a power system is discussed in [13]. The application of a SSSC controller to improve the transient stability performance of a power system is thoroughly investigated in [14]. 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 in [15]. A systematic procedure for modelling, simulation and optimally

tuning the parameters of a SSSC controller for power system stability enhancement is presented in [16].

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 in [17]. 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 [18-19]. 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 [20-22] and further established recently by [23]. 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 [24]. 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 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.

## 2. Power System Modelling

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 system data are given in appendix.

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

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

where  $P_m$  and  $P_e$  are the input and output powers of the generator, respectively;  $\tau_j$  and  $D$  are the inertia constant and damping coefficient, respectively;  $\delta$  and  $\omega$  are the rotor angle and speed, respectively;  $\omega_B$  is the synchronous speed.

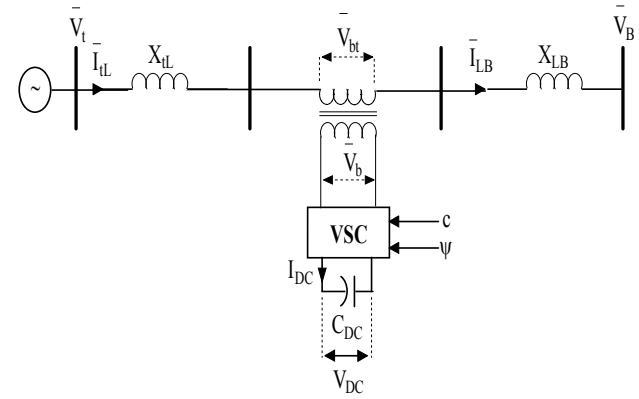


Fig. 1 SMIB with SSSC.

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:

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

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

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

where  $E_{fd}$  is the field voltage;  $\tau'_{do}$  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:

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

Where  $c$  is the amplitude modulation ratio,  $\psi$  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:

$$I_{tL} = I_{tLq} + jI_{tLd} \quad (6)$$

The SSSC DC voltage differential equation is given below:

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

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

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

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

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

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

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

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

### 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.

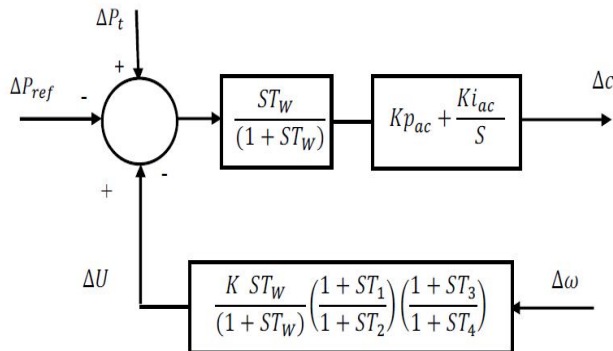


Fig. 2. SSSC dynamic model of AC voltage regulator.

### DC Voltage Regulator

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

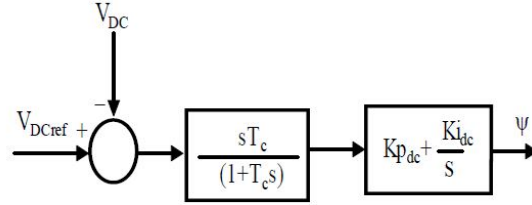


Fig. 3. SSSC dynamic model of DC voltage regulator.

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 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.

### 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:

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

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

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

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

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

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

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

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

$$T_1^{\min} \leq T_3 \leq T_3^{\max} \quad (20)$$

### 4. 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 [17]. The velocity and position update equations for the d-th dimension of the i-th particle in the swarm may be given as follows:

$$V_{id}(t+1) = \omega V_{id}(t) + C_1 \phi_1 (X_{lid} - X_{id}(t)) + C_2 \phi_2 (X_{gd} - X_{id}(t)) \quad (21)$$

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

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

On the other hand, the BF is based upon search and optimal foraging decision making capabilities of the Escherichia coli bacteria. 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 [24].

[Step 1] Initialize parameters

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

Where,

$n$  : Dimension of the search space,

$S$  : The number of bacteria in population,

$N_{re}$  : The number of reproduction steps,

$N_C$  : The number of chemotactic steps,

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

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

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

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

$\omega$  : The inertia weight,

$C_1, C_2$  : The swarm confidence,

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

$\vec{V}_i$  : 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.

$\theta_{g\_best}$  : 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  $i=1, 2, \dots, S$ , 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

$\Delta_m(i), m = 1, 2, \dots, n$ , a random number on  $[-1, 1]$ .

[Sub step e] Move:

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

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

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

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

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

• Let  $m = m + 1$

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

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

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

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

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

[Step 5] Mutation with PSO operator

For  $i=1, 2, \dots, S$

- Update the  $\theta_{g\_best}$  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:

$$V_{id}^{new} = \omega V_{id}^{old} + C_1 \phi_1 \left( \theta_{g\_best_d} - \theta_d^{old}(i, j+1, k) \right)$$

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

[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.

## 5. Results and Simulations

Table 1, shows the system eigenvalues, and damping ratio of mechanical mode with three different loading conditions. It is clear that the BSOSSC shift substantially the electromechanical mode eigenvalues to the left of the S-plane and the values of the damping factors with the proposed BSOSSC are significantly improved to be  $(\sigma = -2.291, -1.8016, -1.11)$  for light, normal, and heavy loading respectively. Also, the damping ratios corresponding to BSOSSC controllers are almost greater than those corresponding to PSOSSSC and BFSSSC ones. Hence, compared to BFSSSC and PSOSSSC, BSOSSC 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	$-1.4487 \pm 7.804j$ (0.183)	$-1.778 \pm 8.89j$ (0.196)	$-2.291 \pm 10.36j$ (0.216)
Normal load	$-1.222 \pm 6.1608j$ (0.195)	$-1.474 \pm 6.544j$ (0.22)	$-1.8016 \pm 6.915j$ (0.2521)
Heavy load	$-0.656 \pm 4.95j$ (0.1314)	$-0.785 \pm 5.26j$ (0.148)	$-1.11 \pm 6.18j$ (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. 4 shows the response of speed for normal loading condition. This figure indicates the capability of the BSOSSC 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 second for BSOSSC, PSOSSSC, and BFSSSC respectively. In addition, the proposed BSOSSC outperforms and outlasts PSOSSSC and BFSSSC controller in damping oscillations effectively and reducing settling time.

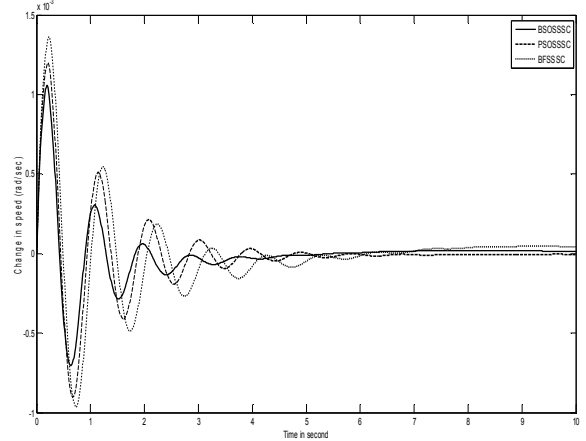


Fig. 4. Change in speed for normal load condition.

### 5.2 Response under heavy load condition:

Fig. 5 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 BSOSSC 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 second for BSOSSC, PSOSSSC, and BFSSSC respectively. Hence, the proposed BSOSSC extend the power system stability limit.

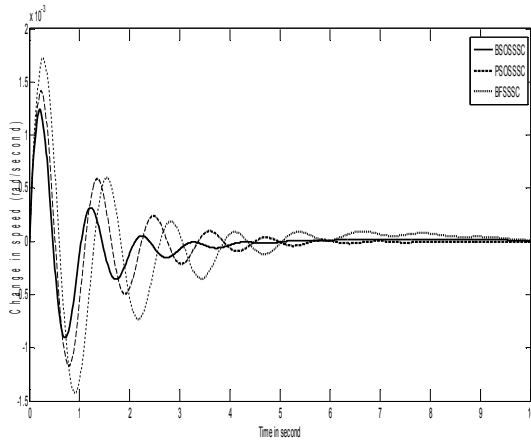


Fig. 5. Change in speed for heavy load condition.

## 6. 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 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.

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## Appendix

The system data are as shown below:

- a) Synchronous generator (p.u)  $X_d = 1.07$ ,  $X_q = 1.0$ ,  $X_d' = 0.3$ ,  $\tau_{do} = 5.9$ ,  $H = 2.37$ ,  $P_e = 0.9$ ,  $V_t = 1.0$ .
- b) Excitation system  $K_A = 400$  and  $T_A = 0.05$  sec.
- c) Transmission line (p.u),  $x_{iL} = 0.3$ ,  $x_{LB} = 0.3$
- 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 chemotactic 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  $h_{repellent} = 0.01$ ; the values of  $\omega_{repellent} = 10$ .
- f) PSO parameters:  $C_1 = C_2 = 2.0$ ,  $\omega = 0.9$ .