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# Implementation of an Efficient Bio-Inspired Shuffled Frog Leaping Algorithm for Power System Stability Enhancement

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**Abstract**

Low frequency electromechanical oscillations are becoming one of the vital problems affecting the stability of modern power system operation. This paper provides a novel technique to design an optimal controller to mitigate the electromechanical oscillations based on Bio-inspired shuffled frog leaping (SFL) algorithm. The controller design is based on formulation of damping ratio maximization based optimization criterion to calculate the controller parameters, for system stability. Time domain simulations have been carried out under various operating conditions of the system and parameter variations of the system considered. A comparative study is also done to show the effectiveness of the proposed frog leaping algorithm based controller over the Conventional Lead-lag controller and Particle swarm optimization (PSO) based controller.

## INTRODUCTION

Low frequency electromechanical oscillations after a transient change in a power system can lead the system to unstable condition, if required damping measures are not implemented. An efficient solution for this problem is to provide damping by implementing Power System Damping Controllers (PSDC) in the power system networks[1-2].In recent years, several methods namely, adaptive technique, intelligent technique and optimal technique have been applied for oscillations damping and control[3-6].But, power system researchers incorporate the lead-lag controller design for damping.

Conventional power system damping controllers (CPSDC) designed using the lead-lag theory in the frequency domain, will not give the required performance, as the operating conditions of the system changes from time to time. As a best alternative, Bio-Inspired algorithms can be applied to different types of optimization problems. Bio-Inspired algorithms like Honey bee optimization, Ant colony optimization, Particle swarm optimization and shuffled frog leaping algorithm have been applied for damping controller design [7-10]. In this paper, Particle Swarm Optimization (PSO) and Shuffled frog leaping (SFL) algorithm are implemented in computing the optimal controller parameters, suitable for stability improvement. The proposed optimization concept is based on formulation of damping ratio based criterion with controller parameter constraints. A comparative stability study has been done to show the effectiveness of the proposed SFL based Power system damping controller (SFLPSDC) performance over the conventional lead-lag controller and PSO based power system damping controller (PSOPSDC) design, under various system operating conditions and also variations in the parameters considered.

## MODELLING OF POWER SYSTEM

Figure (1) represents an alternator connected to an infinite bus with line impedance Z.The Heffron Phillips block diagram of synchronous generator has been used in this paper, for the modeling and simulation [11].

The State space equation is given by

$$\dot{x} = Ax + Bu \tag{1}$$

Where $x$ = Vector involving state variables.

A, B = Matrix involving state vector and system inputs respectively

The open loop and closed loop state variables used in the modeling are given by,

$$[x]_{open} = [\Delta\omega\ \Delta\delta\ \Delta E'_q\ \Delta Efd]^T$$

$$[x]_{closed} = [\Delta\omega\ \Delta\delta\ \Delta E'_q\ \Delta Efd\ \Delta P_I\ \Delta U_E]^T \tag{2}$$

The system data used for programming and simulation are given in Appendix A.

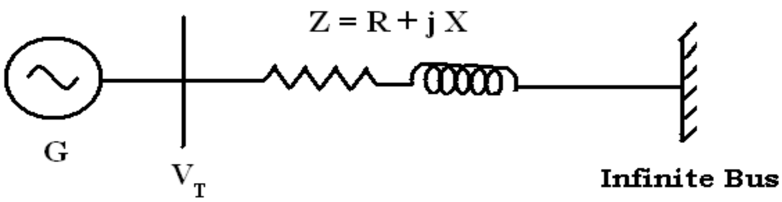


**Figure 1**. Single machine infinite bus power system model

The system damping controller model comprises of the washout block, gain block and the phase lead compensation block.The rotor speed deviation ($\Delta\omega$) is taken as the input and damping control signal ($\Delta U_E$) is taken as output of the controller.

The transfer function of the controller model is given by

$$\left[\frac{\Delta U_s}{\Delta\omega}\right] = K_s\left[\frac{(1+sT_1)}{(1+sT_2)}\right]\left[\frac{(1+sT_3)}{(1+sT_4)}\right]\left[\frac{(sT_w)}{(1+sT_w)}\right] \quad (3)$$

Where
K = Damping controller gain
Tw = Washout block time constant.
$T_1, T_2, T_3, T_4$ = Time constants of controller

In this paper, Time constants are taken as follows: $T_1 = T_3$, $T_2 = T_4$ (phase compensation blocks are identical).The parameters Ks, $T_1$, $T_2$ are implemented in the optimization problem for calculating the optimum solution using PSOPSDC and SFLPSDC.

## PROPOSED OPTIMIZATION CRITERION FOR STABILITY

The aim of this criterion is to compute the optimum value of controller parameters for stability improvement. The proposed objective function is given by:

$$[J] = \min(\xi_i), \xi_i \, \varepsilon \, \xi_{e\,mode} \quad (4)$$

where $\xi_i$ = Damping Ratio of $i^{th}$ eigen value (electromechanical mode)
$\xi_{emode}$ = Damping ratio of all electromechanical mode eigen values.

The proposed objective is to Maximize J, so that the minimum damping ratio of poorly damped eigen value is maximized for better damping.

The optimization criterion is represented as follows:

**Optimize J**
subject to

$$K_s^{min} \le K_s \le K_s^{max} \quad (5)$$

$$K_1^{min} \le K_1 \le K_1^{max} \quad (6)$$

$$K_2^{min} \le K_2 \le K_2^{max} \quad (7)$$

For implementation, the following range of values has been taken. For Ks [1 to 75], for $T_1$ [0.1 to 0.95] and for $T_2$ [0.1 to 0.95].

## PROPOSED BIO-INSPIRED OPTIMIZATION ALGORITHMS

### Bio-Inspired PSO algorithm.

Particle Swarm Optimization (PSO) is a new optimization technique introduced by Eberhart and Kennedy [12-14].It involves a population of particles (random wise) that fly through the solution space with velocities and positions (specified initially). Each particle has a memory for remembering the best position in the solution space. The positions based on best fitness in the population are called [$P_{best}$].The best value out of all the $P_{best}$ values is defined as [gbest]. The $P_{best}$ and gbest values are taken based on the proposed fitness function. In this paper, the fitness function is the damping ratio based criterion formulated for stability. In this algorithm, the velocities and positions of the particles are updated at every iteration.

The velocity of each particle is updated by the following relation:

$$V_1^{K+1} = W \cdot V_1^K + C_1 \cdot rand_1 \cdot \left(P_{best} - S_1^K\right) + C_2 \cdot rand_2 \cdot \left(g_{best} - S_1^K\right) \tag{8}$$

where
$V_i^K$ = Velocity of particle i at iteration K;
W = Weighting function, rand = random number;
Cj = Weighting factor, $P_{best\,i}$ = Pbest of $i^{th}$ particle;
gbest = gbest among various $P_{best}$.
$S_i^K$ = Position of particle i at iteration K.

The weighting function is used in equation (8) is given by:

$$[W] = [W_{max}] - \left[\frac{W_{max} - W_{min}}{iter_{max}}\right] \cdot iter \tag{9}$$

where
$W_{Max}, W_{Min}$ = Initial and final weight taken;
$Iter_{max}$ = Maximum iteration number.

The position updation is carried out using the following relation:

$$S_i^{K+1} = S_i^K + V_i^{K+1} \tag{10}$$

where
$S_i^{K+1}$ = updated position of the particle;
$V_i^{K+1}$ = updated velocity of the particle.

The proposed PSO algorithm to compute the optimal damping controller parameters is given as follows:

**Step 1**: Specify the various parameters involved for PSO algorithm implementation (i.e.) swarm size, minimum and maximum limits for PSDC parameters, number of generations, weighting function, termination criteria etc.

**Step 2:** Initialize a population of particles with positions and velocities (random wise) in the solution space.

**Step 3**: Evaluate the fitness function (P) for each particle in the population.

**Step 4:** For each individual particle, compare the fitness value with its $P_{best}$ value. If the current value (Pi) is better than the $P_{best}$ value, set this value as the $Pbest_i$ for $i^{th}$ particle. (i.e.) set $P_{best\ i}$=Pi.

**Step 5**: Identify the particle that has the best fitness value among various $P_{best}$ values. Set this value as gbest.

**Step 6**: If the termination condition ($g>g_{max}$) is reached, then optimal value of PSDC parameters is equal to those obtained in current generation, (i.e.) gbest values, otherwise goto step7.

**Step 7**: Compute the new velocities and positions of the particles according to equations (8) & (10).

**Step 8**: Repeat steps 3-6 until the termination criterion is met.

**Proposed Bio-Inspired Shuffled Frog leaping (SFL) algorithm**

Shuffled Frog Leaping Algorithm (SFLA) is a bio-inspired search algorithm developed by Eusuff and Lansey in 2003 [15].The main aim of this algorithm is to solve complicated optimization problems without any use of conventional mathematical optimization tools. This algorithm has been inspired from memetic evolution of a group of frogs when seeking for food. In this method, a solution to a given problem is presented in the form of a string, called “frog” which has been considered as a control vector. The initial population of frogs is partitioned into subsets called memeplexes and the number of frogs in each subset is equal. Based on the searching, the frogs in each subset improve their positions to have more foods.

The merits of SFL algorithm over PSO algorithm are: simple concept, fewer parameters adjustment, capability in global search and easy to implement. The fitness function here is the proposed damping ratio based optimization criterion formulated for stability.

In this algorithm, the position of the frog with worst fitness is adjusted using the relation as follows:

$$Xw(new) = Xw + C_i \tag{11}$$

where

$C_i$ = rand x [Xb-Xw], Rand = random number between 0 and 1.

Xb and Xw = frog with best and worst fitness respectively.

The proposed SFL algorithm to compute the optimal damping controller parameters is given as follows:

**Step 1:** Create an initial population of p frogs randomly.

**Step 2**: Specify all the input data namely controller parameters (Ks,$T_1$ and $T_2$), number of memeplexes, frog population etc.

**Step 3:** Evaluate the optimization fitness function (damping ratio based) for each individual.

**Step 4:** Sort the initial population based on the fitness function values in the decreasing manner.

**Step 5:** Divide the sorted population in memeplexes by following process, the first population goes to the first memeplex, the second population goes to the second memeplex, population *qth* goes to the *qth* memeplex, and population $q+1$goes back to the first memeplex etc.

**Step 6:** Select the best and worst population in each memeplex and identify the Xb(best) and Xw(worst) respectively.

**Step 7**: The frog with the global best fitness in all memeplexes is identified as Xg.

**Step 8**: A process is applied to improve only the frog with the worst fitness according to eqn (11); if this process produces a better solution, it replaces the worst frog. Otherwise, a new population is randomly generated to replace that population. This process continues for a specific number of iterations ($iter_{max1}$).

**Step 9**: If the current iteration number ($iter_{max2}$) reaches the predetermined maximum iteration number, the search procedure is stopped, otherwise it goes to Step 5.

**Step 10**: The last *Xg* represent the required optimal controller parameters for stability.

## Simulation results and analysis

For the simulation in this paper, MATLAB programming (version: 7.8.0.347) was used. The mathematical state space modeling of the power system model was carried out and the open loop eigen values and damping ratios was calculated, as presented in Table 1. The open loop poorly damped modes of oscillation indicates that the test power system is unstable. Here, the real part of complex eigen values (poorly damped mode) are located in right half of complex s plane, making the system unstable.

Also in Figure (2) and Figure (3), the Rotor speed deviation and Power angle deviations respectively are oscillatory having large overshoots and also large settling time, indicating that the power system is unstable. The system is in need of proper damping controller to be installed in the system model for better stability. Implementation of CPSDC, PSOPSDC and SFLPSDC design provide the optimum value for the controller parameters, as represented in Table 2. Table 3 provides the parameters selected for PSO and SFL algorithm implementation respectively. In Power Systems, damping ratios of the system with values more than 0.05 are taken for better damping. A damping limit of 0.05 has been taken for damping ratio analysis in this work.

The damping ratios are computed based on the computed closed loop eigen values for CPSDC, PSOPSDC and SFLPSDC, as listed in Table 2.The computed closed loop damping ratios for the poorly damped electromechanical modes reveal that the proposed SFLPSDC provides better damping to the system. Here, the damping ratios exceed the damping limit of 0.05 for all the operating conditions implemented for analysis. This clearly satisfies the proposed damping ratio based optimization criterion formulated for stability improvement.

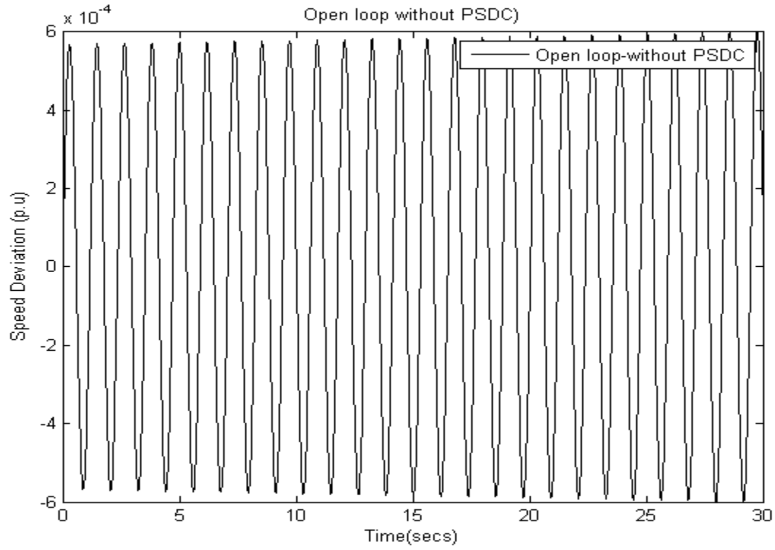


**Figure 2.**Open loop Speed deviation response for (P=0.44, Q=0.02p.u) condition

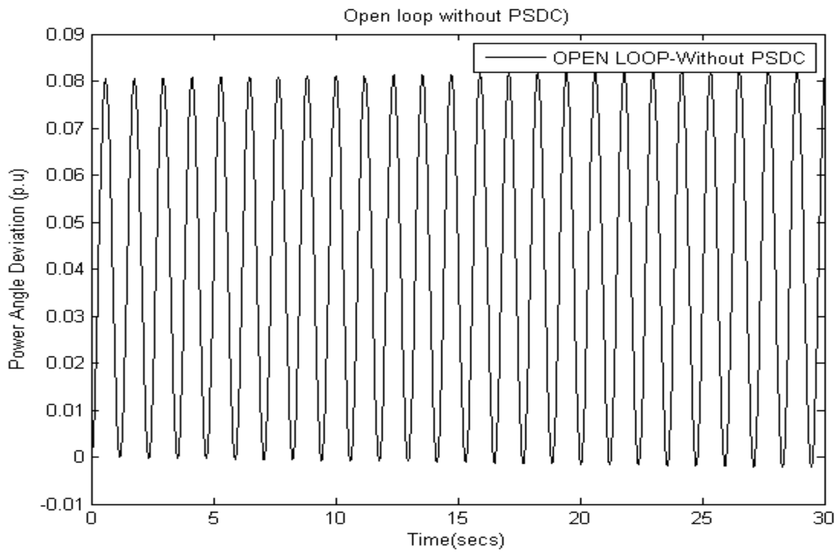


**Figure 3.**Open loop Power angle deviation response for(P=0.44,Q=0.02p.u) condition

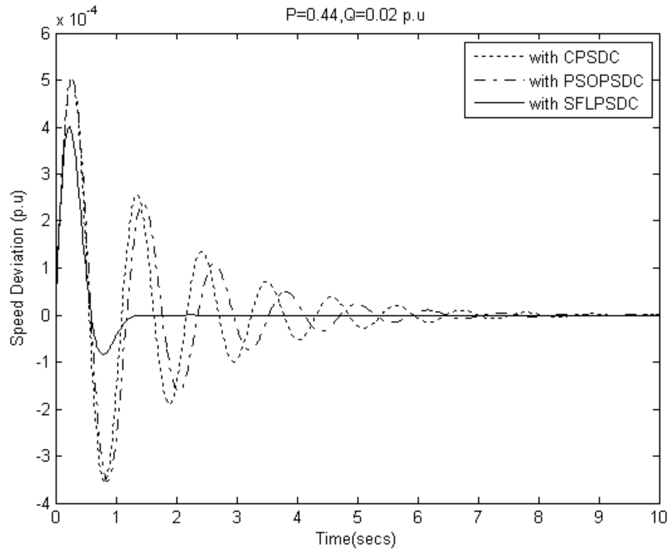


**Figure 4.**Speed deviation response for (P=0.44,Q=0.02p.u)condition

Figure (4) and Figure (5) represent the speed deviation and power angle deviations for the condition P=0.44, Q=0.02p.u respectively. Here, the error deviation overshoots are reduced and the oscillations are damped at an earlier stage for the SFL based controller in comparison with the CPSDC and the PSOPSDC.

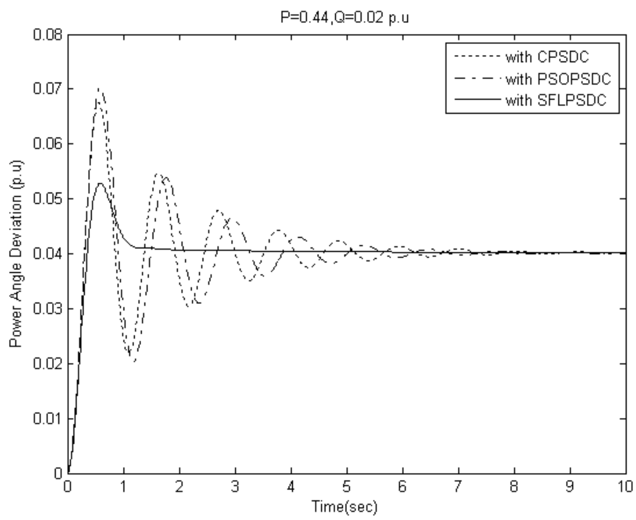


**Figure 5**.Power angle deviation response for (P=0.44,Q=0.02p.u)condition

Figure (6) and Figure (7) indicate the damping action of the SFL based PSDC in damping the oscillations (deviation overshoots) in an effective manner compared to

CPSDC and PSOPSDC for other operating conditions of the power system involved. The deviation overshoots (both rotor speed and power angle deviations) are reduced and settled at the earliest possible due to the implementation of the proposed shuffled frog leaping algorithm based controller design in the system under consideration. These time domain deviation responses show the damping performance of the various controllers for stability. In all the operating conditions involved, the proposed SFLPSDC provide better damping to the low frequency electromechanical oscillations compared to the conventional lead-lag damping controller and the particle swarm optimization based controller.

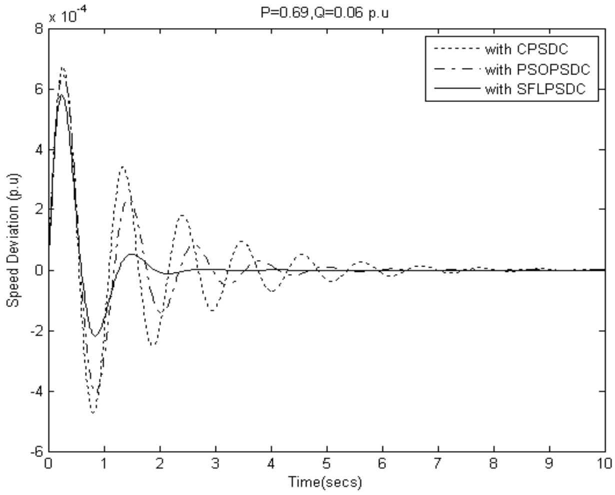


**Figure 6**. Speed deviation response for (P=0.69, Q=0.06p.u) condition

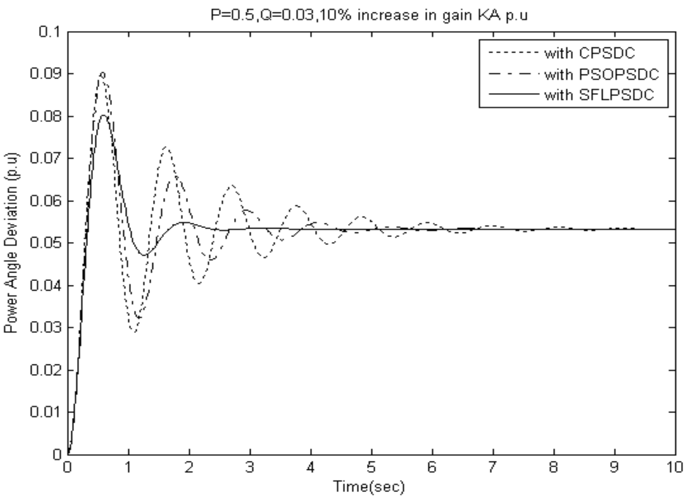


**Figure 7**. Power angle deviation response for (P=0.5, Q=0.03p.u+10%increase in gain $K_A$)

**TABLE 1.** EIGEN VALUES COMPUTED FOR OPEN LOOP, CPSDC, PSOPSDC AND SFLPSDC.

| **S. No** | **Operating conditions (p.u)** | **Open Loop without PSDC** | **CPSDC** | **PSOPSDC** | **SFLPSDC** |
|---|---|---|---|---|---|
| 1. | P=0.44<br>Q=0.02 | **0.0119 ± j 3.8114**<br>-15.1225 ± j 3.9264 | -17.673 ; -0.0437<br>-8.4443 ± j 6.2267<br>**-0.0344 ± j 3.4503** | **-0.0795 ± j 4.7905**<br>-0.0499 ; -11.2320<br>-7.9264 ± j 4.0835 | -17.4367 ; -0.0496<br>-7.7504 ± j 7.3445<br>**-0.1795 ± j 3.2234** |
| 2. | P=0.69<br>Q=0.06 | **0.0149 ± j 4.8012**<br>-17.0841 ± j 3.8123 | -19.6633 ; -0.0452<br>-8.6952 ± j 6.4728<br>**-0.0645 + j 4.9233** | -15.4031 ; -0.0498<br>-8.8087 ± j 5.8988<br>**-0.0719 ± j 4.0745** | -17.4521 ; -0.0497<br>-8.6493 ± j 7.2744<br>**-0.2342 ± j 3.6129** |
| 3. | P = 0.5, Q = 0.03,<br>10 % increase in Gain $K_A$. | **0.0229 ± j 4.7599**<br>-16.0242 ± j 3.8024 | -19.3455 ; -0.0479<br>-8.7022 ± j 6.3723<br>**-0.0612 ± j 3.9128** | -15.6346 ; -0.0498<br>-8.9669 ± j 6.4038<br>**-0.1619 ± j 3.5616** | -18.1502 ; -0.0485<br>-7.1454 ± j 9.2323<br>**-0.2517 ± j 2.8609** |
| 4. | P = 0.6,Q = 0.02,<br>15 % decrease in Te. | **0.0152 ± j 4.3129**<br>-8.3420 ± j 4.4921 | -18.1680 ; -0.0497<br>-7.7615 ± j 6.3452<br>**-0.0822 ± j 3.9105** | -15.5818 ; -0.0497<br>-8.7792 ± j 4.8973<br>**-0.2197 ± j 4.257** | -14.3580 ; -0.049<br>-6.0364 ± j 6.9825<br>**-0.5718 ± j 4.2539** |

TABLE 2. COMPARATIVE LIST OF DAMPING RATIOS COMPUTED FOR OPEN LOOP, CPSDC, PSOPSDC AND SFLPSDC

| **S. No** | **Operating conditions (p.u)** | **Damping Controller Parameters** | | | **Damping Ratios of poorly electromechanical modes Damping limit = 0.05** | | | |
|---|---|---|---|---|---|---|---|---|
| | | **CPSDC [Ks,$T_1$, $T_2$]** | **PSOPSDC [Ks,$T_1$,$T_2$]** | **SFLPSDC [Ks,$T_1$,$T_2$]** | **Without PSDC (Open loop)** | **CPSDC** | **PSO PSDC** | **SFL PSDC** |
| 1 | P=0.44 Q=0.02 | 5.7081 0.5201 0.15 | 34.6061 0.5497 0.1084 | 54.4249 0.3221 0.7320 | -0.003122 | 0.00996 | 0.01659 | **0.05560** |
| 2 | P=0.69 Q=0.06 | 5.7056 0.7607 0.15 | 35.1343 0.5766 0.1763 | 53.1782 0.3083 0.8119 | -0.003103 | 0.01764 | 0.01764 | **0.06468** |
| 3 | P = 0.5, Q = 0.03, 10 % increase in Gain $K_A$. | 4.8772 0.5614 0.15 | 37.7863 0.7419 0.1295 | 66.2549 0.1253 0.3020 | -0.004811 | 0.04541 | 0.04541 | **0.08764** |
| 4 | P = 0.6,Q = 0.02, 15 % decrease in Te. | 3.8733 0.7979 0.15 | 37.5933 0.4538 0.1265 | 60.5216 0.1042 0.4366 | -0.003524 | 0.05154 | 0.05154 | **0.19599** |

TABLE 3. PARAMETERS SELECTED FOR PSO AND SFL IMPLEMENTATION

| **PSO PARAMETER** | | **SFL PARAMETER** | |
|---|---|---|---|
| Swarm size | 50 | Frog population(p) | 50 |
| No of generations | 75 | No of memeplexes(q) | 05 |
| rand1 &rand2 | 0.6 & 0.6 | $iter_{max1}$ | 55 |
| Wmax & Wmin<br>C1 & C2 | 0.8 & 0.7<br>1.4 & 1.4 | $iter_{max2}$ | 65 |
| No of Variables | 03 | No of variables | 03 |

## 6. CONCLUSION

This paper provides a systematic and an efficient solution to the damping of low frequency electromechanical oscillations experienced in the power system model. The salient features of the work carried out in this paper for stability enhancement in the power system considered are as follows:

- In this paper, a detailed mathematical state space modelling of the test power system has been performed.
- In order to compute the optimal controller parameters, a damping ratio maximization based optimization criterion has been formulated. Also, the proposed Bio-inspired SFL based controller design algorithm has been implemented along with the conventional lead-lag design based and PSO based controller.

The stability analysis has been carried out based on the computed damping ratios and also based on the error deviations (Rotor speed and power angle deviations) minimization.

Also, power oscillations damping analysis involving wide variations in operating conditions and parameter variations has been performed based on the damping performance of the proposed controllers.In all the analysis, the proposed Shuffled frog leaping algorithm based damping controller provide the best damping performance than CPSDC and PSOPSDC,so that the power system stability is enhanced to the extent possible.

## Appendix A

Power System data for Simulation:

Generator : M=9.66, Tdo' = 7.5secs, D=0, xd = 0.964, xd'=0.197, Xq=0.530

Excitation system: $K_A$ = 90, $T_A$ =0.04, $K_F$= 0.023, $T_F$ =0.9Sec, Ke=1.02, Te =0.055.

Line data : R=0.021, X = 0.847, G= 0.259, B= 0.232. $V_{t0}$ = 1.04.

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