ENHANCING STABILITY OF HYDEL POWER SYSTEM DYNAMICS USING BIO INSPIRED GENETIC AND PSO ALGORITHMS

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Abstract: *With the increasing complexity of Modern Interconnected Power Systems, Low frequency inertial oscillations after a disturbance in a Power System are becoming one of the major problem. This paper provides a systematic approach to damp the Low frequency inertial oscillations observed in the Hydel Power System based on Bio inspired Genetic (GA) and Particle Swarm Optimization (PSO) algorithms. The design problem is formulated as a Multiobjective Optimization criterion comprising of Damping ratio based and Time domain based objective functions to compute the optimal controller parameters and also to minimize the integral squared error involving rotor speed and angle deviations for stability. The Contrasting feature of this work is the Mathematical modeling and Simulation of the Hydel power system dynamics model comprising of hydel governor, turbine and generator. To validate the effectiveness and robustness of the proposed controller, Non linear simulations has been implemented under various system loading conditions and also under various parameter variations of the model considered. Also a comparative study has been done between the Bio inspired based controllers and the conventional lead lag controller.*

Keywords: *Genetic Algorithm, Hydel Power system, Multiobjective function, Particle Swarm Optimization, Power System Stability.*

1. Introduction

Power Systems are continuously growing in size and their operation is becoming more complex. Low frequency oscillations, with frequencies ranging from 0.1 to 2 Hz are inherent to Electric Power systems [1].Problems due to inadequate damping of such oscillations have been encountered throughout the history of Power Systems. A Power System Stabilizer (PSS) is one of the most cost effective method to damp the oscillations, thus enhancing Power system stability [2]. In recent years, several approaches based on Modern control theory have been applied to PSS design problem. These include optimal control, adaptive control, variable structure control and intelligent control[3].Despite the potential of modern control techniques, Power System utilities still prefer the conventional lead lag PSS structure[4].Conventional PSS(CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead lag compensator. The gain settings of these stabilizers are determined based on the linearized model of the power system around a nominal operating point to provide desired performance at this point. Since modern power systems are highly dynamic in nature, CPSS will not give the desired performance, as the operating point changes from one to another because of fixed parameters of the stabilizer. Unfortunately, the conventional techniques are time consuming, as they are iterative and require heavy computation burden and slow convergence.

Recently, Bio Inspired optimization techniques like Genetic algorithms, Evolutionary Programming, Tabu search, Simulated annealing, Bacteria foraging and Particle Swarm Optimization have been applied for PSS parameter optimization[5].The main advantage of using these optimization techniques is that, there is no need for having an explicit objective function. Moreover, when the objective function is available, it does not have to be differentiable.

In this work, Genetic Algorithm and Particle Swarm Optimization techniques are implemented in optimizing the PSS Parameters. The Optimization criterion is formulated as a Multiobjective optimization criterion comprising of Damping Ratio enhancement based and also based on Time domain error minimization. The main objective here is to maximize the damping ratio of the system so that the hydel power system stability is improved to a greater extent. The objective also involves minimization of Integral error (Rotor angle deviation and speed

deviation) to damp the low frequency oscillations.

The effectiveness of the proposed Genetic based (GAPSS) and Particle Swarm based (PSOPSS) stabilizer are tested on a Hydel Power system model (consisting of Hydel Governor, Turbine and Synchronous Generator) subjected to various loading conditions and also Parameter variations in the system model considered. The Complete GA and PSO based controller design is compared with the conventional Lead Lag controller to show the robustness of the Bio inspired Controllers over the Conventional Controller.

2. Modeling of Hydel Power System Dynamics

2.1 Hydel Power System Model under study

In this work, the hydel Power system dynamics consists of hydel Governor, Turbine and generator model. Fig.1. shows the Heffron Phillips block diagram equipped with the Power System stabilizer (PSS) in the Excitation feedback loop. The type of Excitation involved in this work (as EXC(s) in Fig.1.) is the IEEE type 1 Excitation Model involving Amplifier, Exciter and Rate Derivative feedback compensation [6].

In all the classical model analysis for Single Machine Infinite Bus System (SMIB) system, the mechanical power input remains constant during the period of the Transient (i.e) Governor Turbine Dynamics is not included in the modeling and simulation. But the contrasting feature of this work is that, the mechanical power input is included in the modeling and simulation.(i.e) Hydel Governor and Turbine dynamics is included in the modeling and simulation along with the hydel Synchronous generator model.

Fig.2. represents the hydel Governor and Turbine model connected to the Heffrons Synchronous Generator Model. Here T_{GH} is the Hydel Governor Time constant, T_R is the reset time (typically 5 secs) and T_W being the Hydel Turbine Time constant (typically 1 sec).

In Fig.2, the output (ΔTm) of hydel Governor Turbine Model is given as input to the Heffron-Phillips generator model.

The abbreviations for the Constants and Variables involved in the model are given in Appendix-2.

The System State Space Model is given by
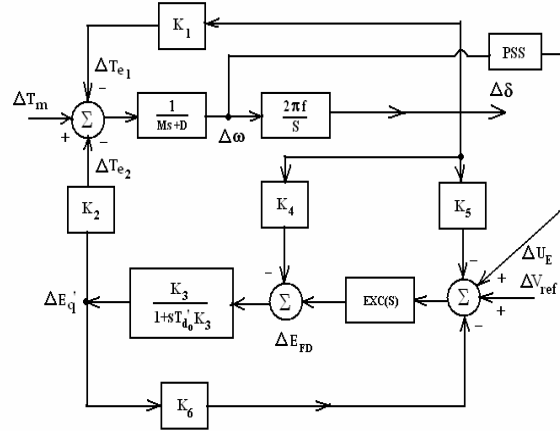
$$\dot{x} = Ax + Bu \qquad (1)$$

Fig.1. Heffrons-Phillips Synchronous Generator Model with PSS.

where [x] = State Variable Vector
A,B = State Matrix and Input Matrix respectively.

In the State Space Modeling of the hydel power system model, 9 Open loop state variables and 12 closed loop (with PSS) state variables were used in the modeling as given in equation 2 and 3 respectively.

$$[x]_{open} = [\Delta\omega, \Delta\delta, \Delta Eq', \Delta E_{FD}, \Delta V_R, \Delta V_E, \\ \Delta Xe, \Delta Xe' \Delta Tm]^T \qquad (2)$$

$$[x]_{Closed} = [\Delta\omega, \Delta\delta, \Delta Eq', \Delta E_{FD}, \Delta V_R, \Delta V_E, \Delta Xe, \\ \Delta Xe', \Delta Tm, \Delta P_1, \Delta P_2, \Delta U_E]^T \qquad (3)$$

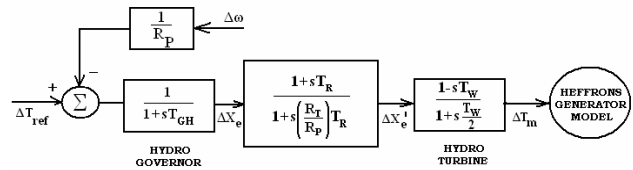All the Test System parameters used for simulation [7] are given in Appendix-1.

Fig.2. Hydel Governor Turbine Model

2.2 Structure of Power System Stabilizer

The PSS model consists of the Gain Block,

Cascaded identical Phase Compensation block and the washout block. The input to the controller is the Rotor speed Deviation ($\Delta\omega$) and output is the Supplementary Control signal (ΔU_E) given to Generator excitation system.

The Transfer function of the PSS Model is given by

$$\left[\frac{\Delta U_E}{\Delta \omega}\right] = Ks\left[\frac{(1+sT_1)}{(1+sT_2)}\right]\left[\frac{(1+sT_3)}{(1+sT_4)}\right]\left[\frac{(sT_w)}{(1+sT_w)}\right] \qquad (4)$$

Where Ks   = Power System Stabilizer gain
       Tw   = Washout Time Constant
T_1, T_2, T_3, T_4 = PSS Time Constants

Here, for Identical Compensator block, it is taken as Time Constants $T_1 = T_3$, $T_2 = T_4$.

Hence Ks, T_1, T_2 are the PSS parameters which should be computed using Conventional Lead Lag stabilizer and optimally tuned using GAPSS and PSOPSS. The washout time constant (Tw) is typically in the range of 1 to 20 seconds and in this work, Tw is taken as 20 seconds.

3. Proposed Multiobjective Optimization Criterion for Stability

3.1 Criteria for System Stability

For the Hydel Power System to be Stable, the Computed Damping Ratio of all system modes of oscillation should exceed a specified value. In Power Systems, Electromechanical oscillations with damping ratios more than 0.05 are considered satisfactory. Hence in this work, the Damping Ratio Threshold is taken as 0.05. (i.e) $\xi_T = 0.05$.

For an Oscillatory mode represented by a Complex Eigen value ($\sigma \pm j\,\omega$), the Damping ratio is given by

$$[\xi] = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \qquad (5)$$

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3.2 Multiobjective Optimization Criterion Formulation

The Main objective of this formulation is to compute the optimal value of PSS parameters for system oscillations damping and thus enhancing the Hydel Power System stability.

(1). **Damping Ratio ξ based objective function**.

$$[J_1] = \min\left(\xi_i\right), \xi_i \varepsilon \xi_{EM} \qquad (6)$$

where ξ_i = Damping Ratio of ith Electromechanical
           Mode of system Oscillation.

ξ_{EM} = Damping Ratios of all the
          Electromechanical modes of Oscillation.

The Objective here is to Maximize J_1, in order to enhance the Damping Ratio of the weakly damped modes of oscillation. The weakly damped Electromechanical modes of oscillation will have its Eigen values located in right half of complex s plane, thus making the system Unstable.

(2). **Time Domain based Objective function**

$$[J_2] = \int_0^{T_s}\left[e^2(t)\right]dt. \qquad (7)$$

Here e(t) is the error involving Rotor Speed deviation [$\Delta\omega$] and the Power angle deviation [$\Delta\delta$].
Ts represent the Time of Simulation.

The objective here is to Minimize the objective function J_2, so that the integral of the squared error deviation is minimized thus enhancing the damping of the low frequency oscillations.

The Design problem including the constraints imposed on the various PSS parameters is given as follows:

Optimize J_1 and J_2
Subject to

$$K_s^{min} \le K_s \le K_s^{max} \qquad (8)$$
$$T_1^{min} \le T_1 \le T_1^{max} \qquad (9)$$
$$T_2^{min} \le T_2 \le T_2^{max} \qquad (10)$$

Various typical ranges selected for Ks, T_1 and T_2 are as follows: For Ks [1 to 70], for T_1 [0.1 to 1] and for T_2 [0.1 to 1].

The above mentioned Damping ratio based and Time domain based optimization criterion are implemented in this work to compute the Optimal PSS parameters namely Ks, T_1 and T_2, so that the Hydel Power System Stability is enhanced to a greater extent.

4. Bio Inspired Optimization Algorithms

4.1 Bio Inspired Genetic Algorithm- An Overview

Genetic Algorithms are numerical optimization algorithms inspired by Natural selection and natural genetics [8-9].GA techniques differ from more traditional search algorithms in that they work with a

number of candidate solutions rather than one candidate solution.

GA includes operators such as Reproduction, Crossover, Mutation and Inversion.

Reproduction is a process in which a new generation of population is formed by selecting the fittest individuals in the current population. *Crossover* is responsible for producing new offsprings by selecting two strings and exchanging portions of their structures. *Mutation* is a local operator which is applied with a very low probability of occurrence. Its function is to alter the value of a random position in a string. Finally, *Inversion* is a process which inverts the order of the elements between two randomly chosen points on the string.

The Proposed Algorithmic Steps involved in Genetic Algorithm implementation are as follows:

Step 1. Specify the various parameters for GA Optimization.

Step 2. Create an Initial Population of individuals randomly.

Step 3. Evaluate the fitness of each individual (i.e) Evaluating the optimization criterion J.

Step 4. If value of J obtained is minimum, then Optimum value of PSS parameters is equal to those obtained in current generation, Otherwise Goto step 5.

Step 5. Based on the fitness, select the best Individuals and Perform recombination through a crossover process.

Step 6. Mutate the new generation with a given Probability.

Step 7. If termination condition (Maximum no of Generations) is not reached, go back to step(3).

4.2 Particle Swarm Optimization –An Overview

PSO is an Evolutionary Computation technique developed by Eberhart and Kennedy in 1995,which was inspired by the social behavior of bird flocking and fish schooling[10-12].It utilizes a population of particles that fly through the problem hyperspace with given velocities.

Each particle has a memory and hence it is capable of remembering the best position in the search space ever visited by it. The position corresponding to the best fitness is called as *Pbest* and the overall best out of all the particles in the population is called *gbest.*

At each iteration, the velocities of the individual particles are updated according to the best position for the particle itself and the neighborhood best position.

The velocity of each agent can be modified by the following equation

$$V_i^{k+1} = W \cdot V_i^k + C_1.rand_1 * \left(Pbest_i - S_i^k \right) +$$
$$C_2 \cdot rand_2 * \left(g_{best} - S_i^k \right) \quad (11)$$

Where
V_i^k = Velocity of agent i at iteration k.
W = Weighting Function.
C_j = Weighting factor.
$rand$ = random number between 0 and 1.
S_i^k = Current position of agent i at iteration k.
$Pbest$ = Pbest of agent i.
$gbest$ = gbest of the group.

The following Weighting Function is usually utilized in equation (11).

$$W = \left[W_{max} \right] - \left[\frac{W_{max} - W_{min}}{iter_{max}} \right] * iter \quad (12)$$

where
W_{max} = Initial Weight
W_{min} = Final Weight.
$iter_{max}$ = Maximum Iteration number
$iter$ = Current iteration number.

The Current position can be modified by the following equation

$$S_i^{k+1} = S_i^k + V_i^{k+1} \quad (13)$$

The Proposed Algorithmic Steps involved in Particle Swarm Optimization Algorithm implementation are as follows:

Step 1: Select the various parameters of PSO.

Step 2: Initialize a Population of particles with random Positions and Velocities in the problem space.

Step 3 : Evaluate the Desired Optimization Fitness

Function for each particle.

Step 4: For each Individual particle, Compare the Particles fitness value with its Pbest. If the Current value is better than the pbest value, then set this value as the Pbest for agent i.

Step 5: Identify the particle that has the Best Fitness Value. The value of its fitness function is identified as gbest.

Step 6: Compute the new Velocities and Positions of the particles according to equation (11) & (13).

Step 7: Repeat steps 3-6 until the stopping Criterion of Maximum Generations is met.

5. Simulation Results and Discussion

For all the Computation, Simulation and Analysis of the results in this work, MATLAB 7.0 / SIMULINK platform was used.
The Two important analysis involved in the simulation in this work are:

(1). **Damping Ratio based Stability Analysis**.
In this work, the stability analysis is based on computation of Eigen values and damping ratios of the system for open loop, with CPSS, GAPSS and PSOPSS and its comparison. The Damping ratios more than the threshold value of damping (ξ_T) will provide better system damping. (here $\xi_T = 0.05$).

(2). **Non Linear Time Domain Analysis**
This analysis is to show the Robustness of the proposed controllers in damping the low frequency oscillations under wide variations in system loading conditions and system parameters considered.
The objective is to minimize the integral squared error (ISE) involved in the system [as in equation 7]. The error refers to the speed deviation ($\Delta\omega$) and the power angle deviation ($\Delta\delta$).

The State Space Modeling of the test hydel power system model was performed and the Open loop Eigen values was computed as in Table 2. The Electromechanical Modes of Oscillation indicate that the test system is Unstable, having positive real part Complex Eigen values located in right side of complex s plane. Also the time domain simulation in Figure(3) and Figure(4) indicate that the Rotor Speed

deviation and Power Angle deviation oscillations respectively are oscillatory in nature having huge Overshoots and large settling time, indicating that the test system is unstable.
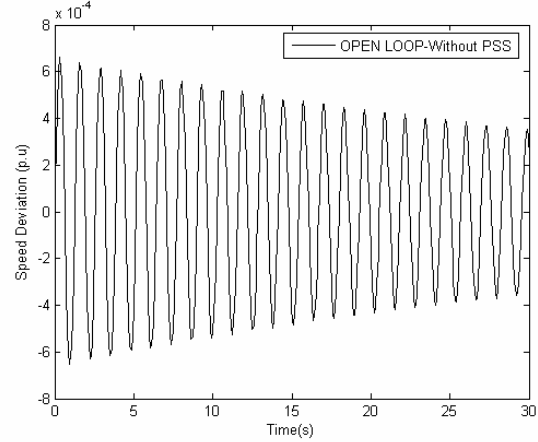

Fig.3. Open Loop Speed Deviation Response (Loading Condition: 0.4, -0.001p.u)
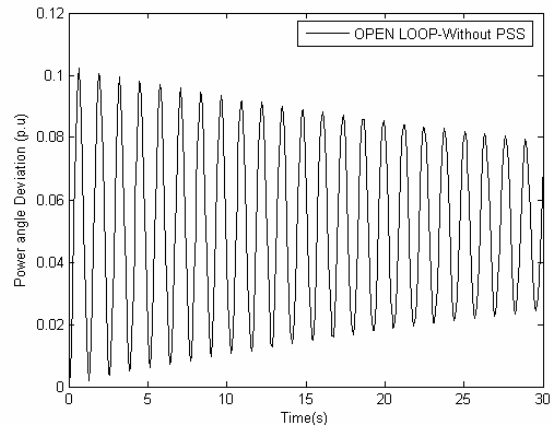

Fig.4. Open Loop Power Angle Deviation Response (Loading Condition: 0.4, -0.001p.u)

The unstable system requires better damping design to mitigate the oscillations. In this work, Conventional Lead lag stabilizer (CPSS), Genetic Based PSS (GAPSS) design and Particle swarm based design are being implemented to compute the Optimal PSS parameters. Implementation of CPSS, GAPSS and PSOPSS provide the Optimal PSS parameters as listed in Table 3.

Table 1 gives the various parameters selected for GA and PSO implementation.

Table 1.Various parameters selected for GA and PSO implementation

S.No	Genetic Algorithm Parameters		Particle Swarm Optimization Parameters	
1	Population Size	30	Swarm Size	30
2	No of Generations	10	Wmax, Wmin	1,0.5
3	Selection Operator	Roulette Wheel Selection	C_1	1.0
4	Generation Gap	0.90	C_2	1.0
5	Cross over Probability	0.95	No of Generations	15
6	Mutation Probability	0.10	No of Variables	03
7	Termination Method	Maximum Generation	Termination Method	Maximum Generation

Table 2. Computed Eigen Values Chart   for Conventional, GA based and PSO based Controllers

S. No	Loading Conditions (P,Q) in p.u.	Eigen Values for Stability Analysis			
		Open Loop without PSS [9 Eigen Values]	Conventional PSS [CPSS] [12 Eigen Values]	GA based PSS [GAPSS] [12 Eigen Values]	PSO based PSS [PSOPSS] [12 Eigen Values]
1	(0.4 , -0.001)	-2.0000 -0.0250 -5.0000 -13.0575 -3.2429 ± j 4.6081 -1.3277 **0.0419 ± j 5.1478** **[Unstable]**	-17.9842 ± j 10.0363 -2.1181 ± j 11.3700 -6.1283 **-0.2503 ± j 5.0784** -0.8550 ± j 0.9428 -1.0000 -1.2173 -0.0248	-17.0270 ± j 7.5633 **-0.4895 ± j 8.9917** -6.1934 -0.5345 ± j 3.7301 -2.6100 -0.0246 -1.0000 -1.6941 -1.3559	-14.4872 ± j 4.8818 **-1.0575 ± j 6.4067** -1.2135 ± j 4.4033 -6.6369 -4.5157 -2.1846 -1.0000 -1.1016 -0.0246
2	(0.4, -0.005) With 10 % decrease in Gain K_A	-2.0000 -0.0250 -5.0000 -14.0384 -2.7529 ± j 4.3639 -1.3277 **0.0436 ± j 5.1513** **[Unstable]**	-19.8634 ± j 11.5811 -3.4804 ± j 12.7454 -6.1282 **-0.2235 ± j 3.8728** -0.4865 ± j 1.0138 -0.9738 -1.0000 -0.0252	-19.5924 ± j 9.9591 -1.3811 ± j 11.1035 -6.1527 **-0.3650 ± j 5.2977** -2.1521 -0.0239 -1.2493 ± j 0.3115 -1.0000	-18.1847 ± j 8.6344 -0.8333 ± j 9.8524 -6.1935 **-0.5246 ± j 3.2764** -3.2167 -1.9567 -0.8375 -1.0000 -0.0234

Table 3. Computed Optimal Controller Parameters and Damping Ratios

S. No	Loading Conditions (P, Q) in p.u	Optimal Damping Controller Parameters			Damping Ratios of Weakly Damped Electromechanical (Complex Eigen Value) Modes of Oscillation Threshold Level of Damping Ratio (ξ_T)= **0.05**			
		CPSS $[K_s,T_1,T_2]$	GAPSS $[K_s,T_1,T_2]$	PSOPSS $[K_s,T_1,T_2]$	Open Loop Without PSS	CPSS	GAPSS	PSOPSS
1	(0.4 , -0.001)	0.9986 4.5346 0.1500	5.3941 0.7749 0.8588	5.6801 0.3767 0.9143	-0.0081391	0.0492274	0.0543486	**0.1628579** **(Greater than ξ_T)**
2	(0.4, -0.005) With 10 % decrease in Gain K_A	0.5562 8.5974 0.1500	14.1145 0.8637 0.1168	24.1295 0.5172 0.1953	-0.0084636	0.0576143	0.0687349	**0.158101** **(Greater than ξ_T)**

The Damping Ratios are computed for the weakly damped Electromechanical modes of oscillation using the optimal PSS parameters and eigen values, listed in Table 3.The Damping ratios calculated for weakly damped modes of oscillation reveal that the proposed controllers provide better damping to the oscillatory modes. Though CPSS and GAPSS provide good damping , the PSO based controller (PSOPSS) provide better damping to the oscillatory modes, with damping ratios more than the threshold level of damping (ξ_T=0.05) for the loading conditions involved (last Column of Table 3).

To validate the robustness of the proposed Bio Inspired Controllers, Non linear Time domain simulation (Based on minimizing the Integral Squared Error) has been carried out in this work under wide system loading conditions, and also introducing variations in Amplifier gain (K_A).
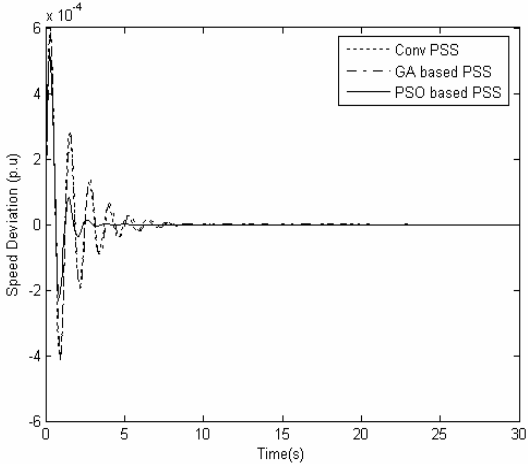

Fig (5) Speed Deviation response with Conv PSS & GAPSS and PSOPSS for (0.4, -0.001) Loading condition

Fig(5) and Fig (6) indicate the dominance of the PSO based PSS in damping the Electromechanical oscillations in a better manner compared to CPSS and GAPSS for the loading condition (0.4,-0.001).

Fig (7) and Fig (8) shows the Speed deviation and Power angle deviation response for 10% decrease in Amplifier gain K_A. (K_A taken as 45, the normal condition value being 50).

These responses reveal the dominance of the Bio Inspired damping controllers (in particular the PSOPSS) in damping out the low frequency oscillations better than the Conv PSS and the Genetic based PSS (GAPSS). The Speed deviation and Power Angle deviation overshoots are considerably reduced thus enhancing the Hydel Power System Stability.
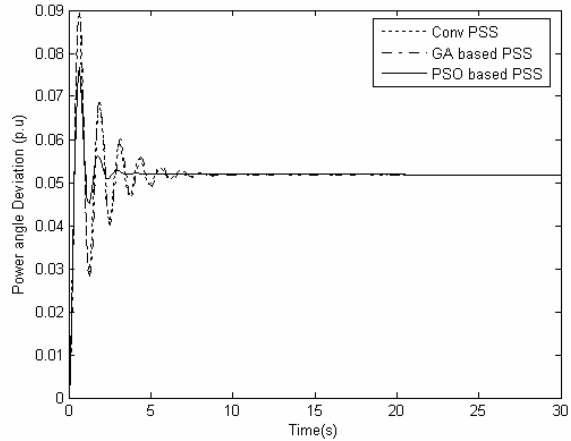

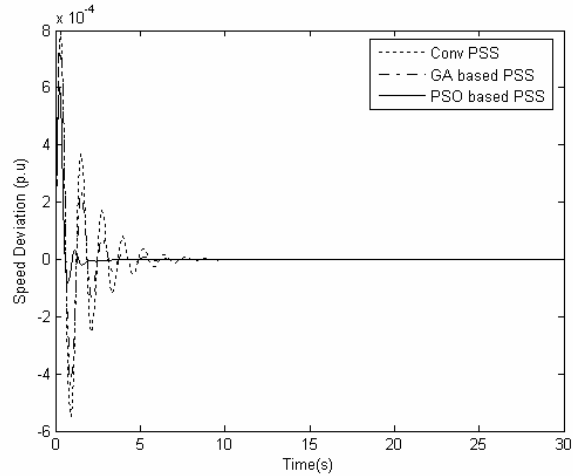Fig (6) Rotor Power Angle Deviation response with Conv PSS & GAPSS and PSOPSS for (0.4, -0.001)condition.

Fig (7) Speed Deviation response with Conv PSS & GAPSS and PSOPSS for 10 % decrease in Gain K_A.
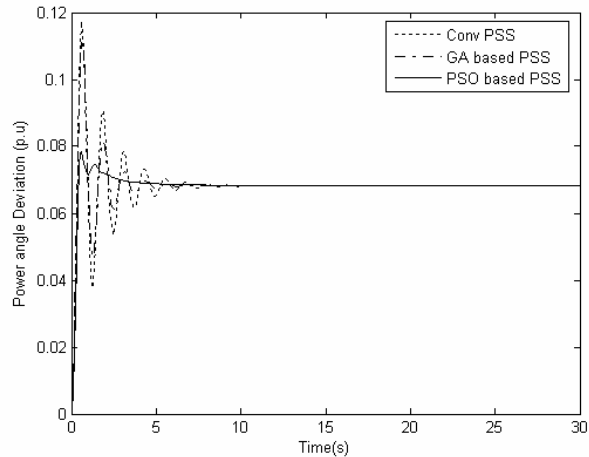

Fig (8) Rotor Power Angle Deviation response with CPSS & GAPSS and PSOPSS for 10 % decrease in Gain K_A.

6. Conclusion

In this paper, a better and efficient solution to damp the Low frequency oscillations which affect Hydel Power system Stability is presented. The Damping Ratio analysis and Non linear Time domain analysis clearly indicate the importance of Bio Inspired Algorithm applications in enhancing the system damping ratio and also in damping the oscillations. The Robustness of the proposed Bio Inspired based Controller is clearly tested by simulating the Hydel Power System Model with various loading conditions and also under parameter variations. The Comparitive study between Conventional, Genetic and PSO based stabilizer is also an evidence for the effectiveness of the proposed Bio Inspired damping controller.

Appendix 1.

Hydel Power System Dynamics Parameters

Generator   : $x_d = 0.973$, $x_d' = 0.190$, $x_q = 0.550$,
                          D=0, M= 9.26, Tdo' = 7.76 secs
Excitation: IEEE ST1A type Excitation
                          $K_A = 45$, $T_A = 0$, $K_F = 0$, $T_F = 1$Sec
Line and Load: R = 0.034, Xe = 0.997, G = 0.249,
                          B= 0.262, $V_{to} = 1.05$, = 0.4, Q = 0.008.
Hydel Governor: $T_{GH} = 0.2$, $T_R = 5$
 And Turbine $R_P = 0.05$, $R_T = 0.4$, $T_W = 1$ sec.
All Parameters are in p.u unless specified otherwise.

Appendix 2.

Nomenclature

$\Delta\omega$ = Incremental Change in Rotor Speed
$\Delta\delta$ = Incremental Change in Rotor Power Angle
$\Delta E_q'$ = Incremental Change in Generator Voltage
ΔE_{FD} = Incremental Change in Generator Field voltage
ΔV_R = Incremental Change in Amplified Voltage
ΔV_E = Incremental Change in Rate Feedback
                          Compensation output voltage.
K_F = Gain of Rate Feedback compensation
T_F = Time Constant of Rate Feedback Compensation
K_E, T_E = Gain and Time constant of Exciter
K_A, T_A = Gain and Time constant of Amplifier
T_{do}' = Field Open circuit Time constant
ΔP_1 = Output State Variable of PSS Washout Block
ΔP_2 = Output State variable of first PSS Phase
                          Compensation block

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