Implementation of a Novel Nature Inspired Firefly Optimizer for Power System Stability Enhancement

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Abstract: Enhancement of stability in interconnected power systems is a vital task in recent years. This paper provides a best solution to mitigate the low frequency inertial oscillations in a multimachine network, thereby enhance the system stability. An optimization criterion based on generator speed and load angle is developed with constraints to optimize the controller parameters required for closed loop model of the system. The controller is tuned using a novel nature inspired Improved Firefly Optimization Algorithm (FOA) and the simulation results of the proposed FOA based controller is compared and analyzed with that of Traditional controller and Genetic Algorithm based controllers to confirm the best performance of the proposed controller in enhancing the system stability.

Keywords: Damping controller, Firefly optimization, Genetic algorithm, Global search, Small signal stability.

1. Introduction

Due to rapid increase in demand for electric energy worldwide, power system operators are facing a challenging task in maintaining power system stability. Stability of power systems is affected by various practical operating conditions and difficulties [1]. Low frequency inertial oscillations experienced in large scale interconnected systems cause instability. They have frequency range around 0.1 to 3.5 Hz [2-3]. These oscillations have to be damped quickly, otherwise cause worse effects in the system. Implementing Power System Stabilizer (PSS) in excitation system of alternator is the best technique for damping these power oscillations. In earlier years, modern control theory was very much implemented for PSS design. Linear model of the system was developed and controller was designed using lead-lag theory [4]. Further techniques namely pole assignment, root locus, variable structure and adaptive control was implemented. These techniques provide good results, but under dynamic operating conditions and disturbances, their performance is not satisfactory [5-6].

Fuzzy logic and Neural network algorithms were implemented for PSS design in multimachine systems [7]. Back propagation algorithm was implemented for multimachine network to enhance the small signal stability [8]. A fuzzy based PSS was implemented in IEEE power system network to tune the controller parameters for stability [9-10]. But these intelligent controllers had drawbacks like complex design procedure, difficulty in training neural network, complex membership functions etc. Nature inspired optimization methods was found to be a better solution for the design of power system stabilizers in power system. Literature provide many optimization algorithms developed from nature namely Ant colony optimization, Genetic Algorithm, Tabu search, Water cycle algorithm, Cuckoo search optimization, Whale optimization etc [11-16]. Among these algorithms, Firefly optimization algorithm developed during 2007 was found to be suitable for complex design requirement in power systems [17]. The algorithm involved simple model, easy to implement and results will be effective.

In this paper, stability of multimachine power systems is enhanced using three power system stabilizers namely Conventional PSS (CPSS), Genetic Algorithm PSS (GAPSS) and Improved Firefly Optimization based PSS (FOAPSS). The modeling of multimachine system was performed to develop the state model. Since modern power system conditions are highly variable, PSS designed using one input is not possible to mitigate the inter area oscillations. For this reason, dual input PSS has been modelled and implemented in the system. Also, the firefly algorithm has been improved and implemented for better tuning of controller parameters. The system has been simulated using MATLAB and the simulated responses (Speed and Load angle) and results are tabulated and analyzed in this work. The damping performances of the three PSSs are also compared.

2. Modelling Of Power System And Pss

A. Power System Modelling

The IEEE three machine nine bus network is taken for modelling and the network is given in Fig. 1.

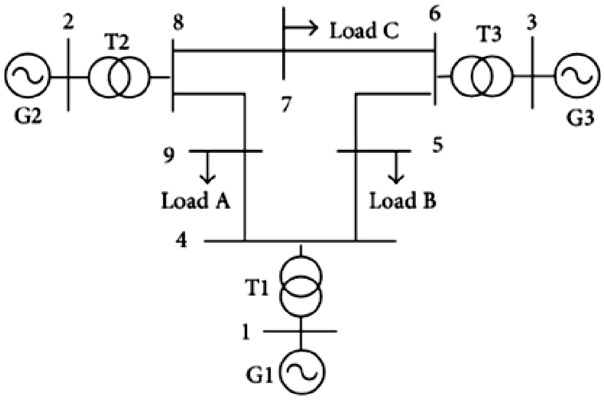

Fig.1. IEEE Power System Network

The state equation is modelled using Equation 1. [A] is the state matrix developed from the first order differential equations written from Heffron's generator model [18].

$$\left[\dot{x}\right] = Ax + Bu, \quad (1)$$

The state variables are assigned in the Heffron's model and the variables are given in Equations 2 and 3.

$$[x]_{OS} = [\delta, \omega, E_f, Eq] \quad (2)$$

$$[x]_{CS} = [\delta, \omega, E_f, Eq, V_1, V_2, V_3, V_4] \quad (3)$$

The suffix OS and CS indicate open loop and closed loop system. For the closed loop system, PSS will be added in closed loop, so that the number of state variables will be 8.

B. Modelling of Dual input PSS

The primary task of power system stabilizer is to give auxiliary feedback signals to excitation system of generator model. These signals will compensate the system so that the error deviations are damped to enhance the stability of the system. In general, speed signal will be taken as input to PSS for the system. Since power systems experience different disturbances and transient changes, single input PSS is not effective to control and mitigate the multi- area inter oscillations. As a result, modern power systems are implemented with dual input power system stabilizers, in order to damp the multi-area power oscillations. The IEEE dual input PSS model is given in Fig. 2.

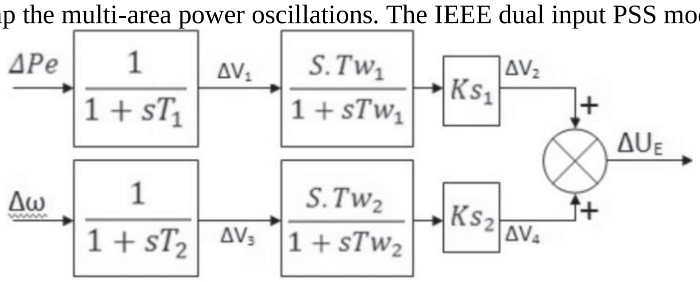

Fig.2. Model for Dual input PSS

Here, accelerating power and rotor speed are taken as inputs to the PSS. The controller output signal is ΔU_E, that provides stabilizing output to generator- excitation model. The relation between accelerating power and speed are represented as given in Equation (4). H indicate the inertial constant of generator.

$$[\Delta\omega] = \frac{1}{2H}(\Delta P_m - \Delta P_e).dt. \quad (4)$$

V_1, V_2, V_3 and V_4 are the four PSS state variables used for modelling to make the state matrix order to 8 by 8.

3. Proposed Error Based Criterion

In this paper, an error-based optimization criterion is set to implement the conventional, Genetic and Improved Firefly algorithms and also to show the effectiveness of these controllers in damping the electromechanical oscillations experienced at various conditions of the system. The oscillations are taken in the form of error deviations. Two deviations namely rotor speed deviation and power angle deviation are investigated in this work.

The Optimization criterion is represented as given in Equation (5).

$$\text{Optimize } J\left[\text{Minimize}(J_{OF})\right] \quad (5)$$

Here, J_{OF} indicate the objective function for the criterion. J_{OF} is related to squared error and it is given in Equation (6).

$$[J_{OF}] = \int_0^{T_S} \left[e_d^{\,2}(t)\right].dt \quad (6)$$

The squared error deviations are integrated from zero to time of simulation Ts. The task here is to minimize the speed deviation error and power angle deviation error. Constraints are also set for the proposed criterion. The four constraints are given in equations 7 to 10.

$$K_s^{min} \leq K_s \leq K_s^{max} \quad (7)$$

$$T_1^{min} \leq T_1 \leq T_1^{max} \quad (8)$$

$$T_2^{min} \leq T_2 \leq T_2^{max} \quad (9)$$

$$\gamma^{min} \leq \gamma \leq \gamma^{max} \quad (10)$$

An important feature in the proposed Improved FOA is that the absorption coefficient γ is included in the constraints for optimization. This parameter of absorption is a vital parameter in FOA to calculate the optimal results. The range of values used in simulation are given as follows: Gain Ks (1 to 55), Time constants of PSS (0.15 to 0.95 secs), Absorption coefficient γ (01 to 0.65).

4. Proposed Improved Foa

a) Firefly Algorithm

Firefly Optimization Algorithm was initially developed at Cambridge University in the year 2007[19]. It is a Bio-inspired optimization algorithm developed based on the social characteristics of fireflies in nature. Even though various metaheuristic algorithms have been developed inspiring the swarm behavior of natural species like birds, ant, cuckoo, fish etc., this firefly inspired developed algorithm has many merits compared to other algorithms. The main merits being simple modelling, easier to implement, global search outcome etc. Fireflies have many peculiar flashing features.

a. Fireflies shall not look for male or female while they are attracted by other fireflies.
b. Brightness feature is directly related to attractiveness and both are directly proportional in nature.
c. Fireflies will move randomly, if there are no brighter fireflies [20].

Firefly algorithm is modelled as follows:

Light intensity of fireflies is related to attractiveness using Equation 11.

$$[I] = I_0 . \exp[-\gamma . r^2] \quad (11)$$

Here, Io represents initial intensity and γ indicates absorption coefficient. Attractiveness is denoted by β and it is given by,

$$[\beta] = \beta_I . \exp[-\gamma . r^b] \quad (12)$$

β_I gives the initial attractiveness and parameter b will be greater than or equal to one. Position of fireflies is one of the important features of firefly modelling.

The distance between i^{th} firefly and j^{th} is calculated as given in equation 13.

$$[R_{ij}] = \sqrt{\sum_{K=1}^{D} [x_{i,k} - x_{j,k}]^2} \quad (13)$$

The position updating of fireflies is given by:

$$[x_i] = [x_i] + \beta_I . \exp[-\gamma . R_{ij}^{m}] . [x_j - x_i] + [\alpha . Q_i] \quad (14)$$

The last part of equation 14 indicates randomization. α and Qi values are selected from 0 to 1.

b) Improved Firefly Algorithm

In the Firefly algorithm, absorption parameter γ is the vital parameter for algorithm convergence and to get best solution. Hence, in the proposed improved firefly algorithm this parameter is included in equation 10, (i.e.) constraints in optimization search. The algorithm will tune the PSS parameters along with absorption parameter to find the suitable parameters required for damping to the system.

In order to calculate the optimal values for Power System Stabilizer parameters, the following Improved Firefly Optimization algorithm is implemented in this work:

Step 1: Generate an initial population comprising of 100 fireflies in search space.

Step 2: Initialize the firefly parameters namely R, β, γ, m, b, D etc. Also, the parameters of PSS: Gain and Time constants.

Step 3: Calculate the fitness values of the random fireflies in the population.

Step 4: Compute intensity and absorption coefficients of the fireflies.

Step 5: The best brightness values for the fireflies are calculated and they are ranked based on brightness values using Equation 11.

Step 6: The distance between fireflies are determined using Equation 12.

Step 7: Update the location of fireflies using Equation 13.

Step 8: If current iteration value is less than maximum iteration value, Goto Step 5.

Step 9: If current iteration value is equal to maximum iteration value, stop the process and determine the optimal PSS parameters.

Genetic Algorithm [21-22] is also implemented for the PSS design in this paper. The simulation results obtained from the GAPSS is compared with that of CPSS and the improved Firefly Optimizer for system stability.

5. Simulation Results And Analysis

Non-linear time-based simulations were done in this paper using MATLAB tool. The IEEE three machine system data sheet was taken from reference 18. First, the multimachine power system was simulated without any controller in the system (open loop). The deviation in speed response obtained for the open loop system is given in Fig.3. Here, the responses are growing and oscillatory, which means the system is unstable. Controllers are to be implemented for the system to damp these deviations. Table 1 provides the various parameters used for simulation for GA and improved FOA.

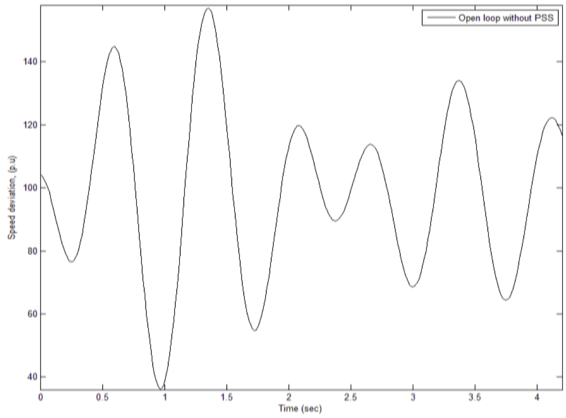

Fig.3. Deviations in Speed Response– Open loop system

Table 1. GA and FOA parameters for simulation

SI.No.	GA parameters		Improved FOA parameters	
1.	Population size	90	Population size	90
2.	Variables for tuning	03	Variables for tuning	03
3.	Operator for selection	Roulette wheel	Attraction (β)	0.15
4.	Cross over and its probability	Uniform / 0.90	Absorption (γ)	From Table 2
5.	Probability for mutation	0.15	Exponential parameter (b)	3.00
6.	Replacement operator	0.85	Distance (D)	2.50
7.	Max. Iterations	100`	Max. Iterations	100`
8.	Stopping criteria	Maximum iterations	Stopping criteria	Maximum iterations

The closed loop simulation of the system derives the optimal values for the four parameters as per equations 7 to 10. These tuned values are given in Table 2 for various system conditions of real power, reactive power and load disturbance Pd. These values will be used in closed loop simulation of the system for obtaining the load angle and speed deviation responses.

Table 2. Optimal PSS parameters obtained

SI.No	Conditions analyzed	Obtained Tuned PSS parameters	
		Ks, γ	***T₁, T₂***
1.	P= 0.84, Q=0.23, Pd = 0.01 p.u	41.23, 0.35	0.22, 0.14
2.	P= 0.92, Q=0.35, Pd = 0.02 p.u	64.37, 0.62	0.37,0.21
3.	P= 0.84, Q=0.23, Pd = 0.03p.u, 20% variation in Exciter Gain	78.05, 0.57	0.44, 0.31

The deviation responses obtained for speed deviations and load angles for P=0.83, Q=0.23, Pd=0.01p.u are given in Figures 4 and 5. Analysis of figures 4 and 5 reveal that the three types of PSSs damp the power oscillations for improving stability. But the proposed improved FOA based PSS provide better performance comparatively. For example, in figure 4, the overshoot is $2.4x10^{-3}$ p.u for CPSS, it is $1.24x10^{-3}$ p.u for GAPSS and it is only $0.84x10^{-3}$ p.u for improved FOA based PSS. Also, the settling time is around 6 seconds for CPSS, 3 seconds for GAPSS and deviations settle at 2.5 seconds for FOA based PSS. These findings confirm the enhancement of system stability to a good extent, as the improved FOA based PSS mitigate the oscillations at a rapid phase.

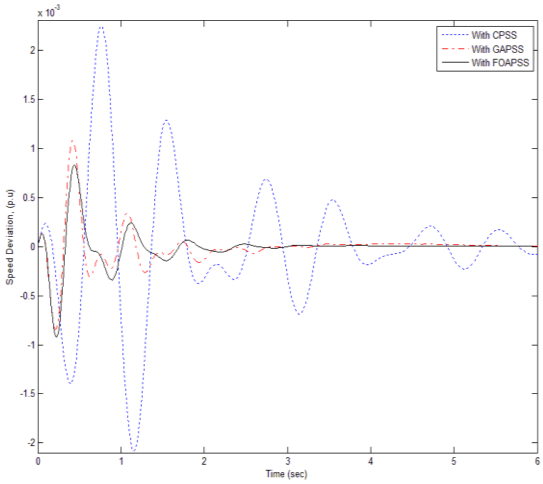

Fig. 4. Deviations in speed responses, P=0.83, Q=0.23, Pd=0. 01p.u

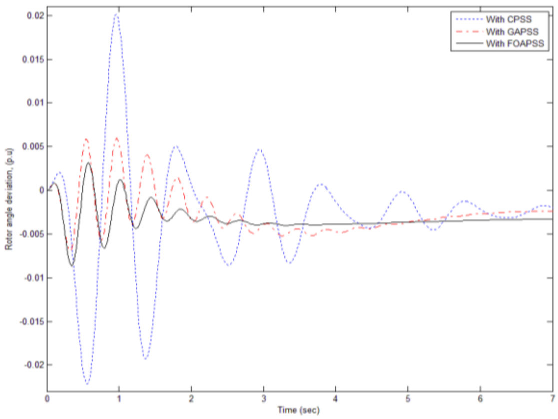

Fig. 5. Deviations in rotor angle responses, P=0.83, Q=0.23, Pd=0. 01p.u

Figures 6 and 7 provides the deviation responses of the system for P=0.92, Q=0.35, Pd=0. 02p.u condition. These responses also show the good damping provided by the controllers, particularly FOA-PSS. Equations 5 and 6 indicate the error-based criterion formulated for deviations damping for stability enhancement. The responses given here clearly satisfy the criteria set for stability.

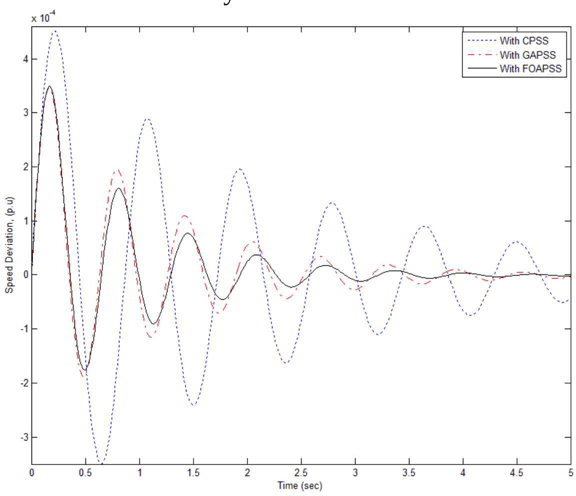

Fig. 6. Deviations in speed responses, P=0.92, Q=0.35, Pd=0. 02p.u

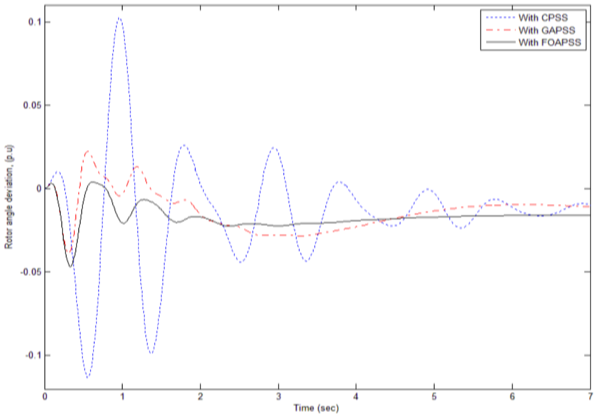

Fig. 7. Deviations in rotor angle responses, P=0.92, Q=0.35, Pd=0.01p.u

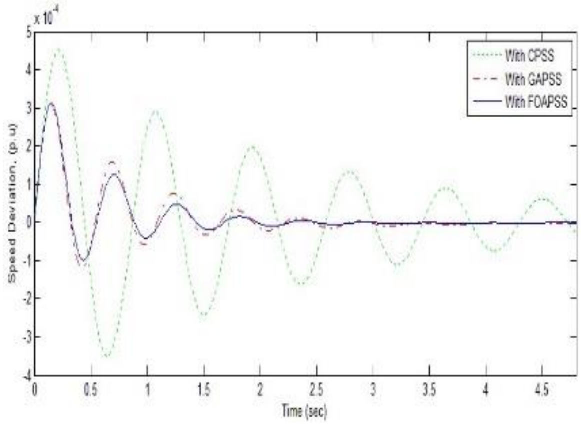

Fig. 8. Deviations in speed, P=0.84, Q=0.23, Pd=0. 03p.u+20% Ke

In order to prove the robustness of the proposed FOA based PSS, load disturbances of various percentage magnitudes (p.u) and percentage increase in exciter gain is given to the system. Figure 8 indicates the deviations in speed for the dynamic condition real power 0.84 p.u, reactive power 0.23p.u, disturbance of 0.03 p.u with increasing the gain of exciter to 20 percentage compared to its rated value. Analyzing the figure 8, it is clear that the controllers show good damping behavior for the dynamic disturbances. But the performance is better and robust for the proposed FOA based power system stabilizer in having less overshoots and less settling time.

The simulated responses in terms of deviations in speed and rotor angle from figures 4 to 8 confirm the superiority of the proposed FOA-PSS towards increasing the small signal stability of the multimachine system.

6. Conclusion

A best solution to enhance the system stability by designing a nature-inspired damping controller is investigated in this paper. A detailed modelling of power system and PSS is performed based on the optimization criterion formulated for stability improvement. Implementation of three types of PSS is discussed with their simulation results. The firefly algorithm is improved in the form of including absorption parameter in the optimization constraints. The simulation results are analyzed in terms of deviations in load angle and speed of the generator. The deviation responses reveal the better performance of the proposed improved firefly optimization algorithm-based PSS compared with that of the conventional and Genetic PSSs.

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