RESEARCH ARTICLE OPEN ACCESS

Improvement of Small Signal Stability of SMIB System Using PSO and CSO based Power System Stabilizer

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ABSTRACT
In a power system, Low Frequency Oscillations (LFOs) are dangerous and make system unstable. These oscillations are referred to small signal stability and they are mainly due to lack of damping torque. This insufficient damping torque is because of high gain and low time constant of Automatic Voltage Regulator (AVR). AVR is useful for maintaining the terminal voltage of synchronous machine as constant. While doing so, it will make the system damping torque as negative. For providing required damping torque thereby minimizing the LFOs, Power System Stabilizer is used in conjunction with AVR. In this paper for SMIB system, the stability is studied with the help of eigen values before and after placement of PSS with optimized PSS parameters using Particle Swarm Optimization (PSO) and Cat Swarm Optimization (CSO). The simulation work is performed in the MATLAB/SIMULINK and corresponding results are presented and analyzed.
Keywords-Automatic Voltage Regulator (AVR), Heffron-Phillips model, Low Frequency Oscillations (LFOs), Power System Stabilizer (PSS), Single Machine Infinite Bus (SMIB) system.

I. INTRODUCTION

For every system, stability plays a major role for the effective performance. Especially in electrical power system there are so many stability aspects that affects the system overall performance. Now a days, load demand is increasing at a faster rate than power generation which is causing the transmission lines to operate closer to their stability limits. Because of this, the transmission lines are getting overloaded and systems are becoming unstable even with a minor disturbance. A small disturbance will create low frequency oscillations in the power system. If the system is weaker and operating at the verge of instability, these oscillations may sustain and grow to cause system separation unless sufficient damping is provided. Low frequency oscillations (LFO) in a power system are harmful phenomena which increase the risk of instability. They limit the steady state power transfer and change the operational system economics and security [1].

These low frequency oscillations are related to small signal stability i.e. subclass of torque angle related instability problem. It depends on the ability to maintain equilibrium between electromagnetic torque and mechanical torques of each synchronous machine connected to power system. The change in electromagnetic torque of synchronous machine following a perturbation can be resolved into two components [2]:

- A synchronizing torque component (ΔT_S) in phase with rotor angle deviation ($\Delta\delta$).
- A damping torque component (ΔT_D) in phase with speed deviation (Δw).

Lack of synchronizing torque results in aperiodic or non-oscillatory instability whereas lack of damping torque results in Low Frequency Oscillations (LFOs).

Fast acting Automatic Voltage Regulator (AVR) with high gain can provide sufficient synchronizing torque but it may or may not provide required damping torque. In other words, the introduction of fast AVR was able to give the “coarse adjustment” to keep electrical speed of synchronous generators within the limits and successful in maintaining synchronism by controlling the first swing. However, the fast AVR could not do the “fine adjustment” to control oscillation in the speed. Then, an additional supplementary controller called Power System Stabilizer (PSS) was introduced in conjunction with AVR. This stabilizer will give fine adjustment to damp out power oscillations that are referred to as low frequency oscillations (LFOs) by providing necessary damping torque [3-4].

Apart from the fast exciter, there are number of other sources that contribute to Low frequency oscillations in modern power system such as frequency load dependency, network characteristics and negative interaction of controllers [2]. These LFOs are generator rotor angle oscillations having a frequency between 0.1 to 2Hz. These oscillations are classified as [3]:

- Inter area mode oscillations (0.1-0.7Hz)

- Local plant mode oscillations (0.7-1.5Hz)
- Intra plant mode oscillations (1.5-2Hz)

First two modes of oscillations are dangerous and PSS parameters are to be selected for damping these oscillations. For effective damping of these oscillations, the PSS parameters have to be optimized.

Many optimization techniques are available to optimize the performance of power system stabilizer. In this paper, a classical heuristic technique "Particle Swarm Optimization" and advanced technique "Cat Swarm Optimization" are considered for optimizing PSS parameters.

II. MODELLING TECHNIQUE

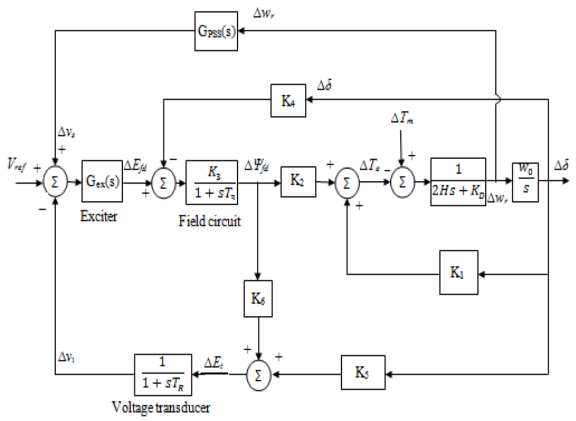

Fig. 1 Block diagram representation with AVR and PSS

The Heffron-Phillips model for SMIB system with AVR and PSS is shown in Fig. 1 [3]. The block diagram consists of Exciter block, Field circuit block, PSS block, Voltage transducer and torque-angle loop of synchronous machine along with Heffron-Phillips constants.

Exciter block represents the overall transfer function of exciter and AVR. The function of the excitation system is to reduce swings due to transient rotor angle instability and to maintain a constant terminal voltage. To do this, it is fed by a reference voltage which is normally a step voltage. Bus fed static exciters with thyristor controllers are increasingly used for both hydraulic and thermal units. They are characterized by high initial response and increased reliability due to advances in thyristor controllers.

AVR is an Automatic Voltage Regulator which is used to change the excitation system automatically for maintaining the terminal voltage as constant. From the Fig.1, K_A represents the gain of exciter and AVR which is typically around 200 and T_A represents the time constant of the AVR which is very small and negligible [5].

Synchronous machine field circuit is modelled by a transfer function $K_3/(1+sK_3T_{do}')$ where T_{do}' is direct axis transient open circuit time constant. Voltage transducer is represented by a transfer function with time constant T_R. This time constant is in the range of 0.01 to 0.02 sec and is necessary for filtering of the rectified terminal voltage waveform. Torque-angle loop of synchronous machine represents the transfer function with inertia constant H and damping coefficient K_D which is neglected.

Heffron-Phillips constants (K_1 - K_6) represent the dynamic characteristics of the system. All Heffron-Phillips constants are always positive except K_4 and K_5. The coefficient K_4 is normally positive. As long as it is positive, the effect of field flux variation due to armature reaction is to introduce a positive damping torque component. However, there can be situations where K_4 is negative. It is negative when a hydraulic generator without damper windings is operating at light load and is connected by a line of relatively high resistance to reactance ratio to a large system. Also, K_4 can be negative when a machine is connected to a large local load, supplied partly by the generator and partly by the remote large system. Under such conditions, the torques produced by induced currents in the field due to armature reaction have components out of phase with Δw, and produce negative damping [3]. The coefficient K_5 can be either positive or negative depending on the operating condition and the external network impedance R_e+jX_e.

With K_5 positive, the effect of the AVR is to introduce a negative synchronizing torque component T_S and a positive damping torque component T_D. The constant K_5 is positive for low values of external system reactance and low generator outputs. The reduction is synchronizing torque coefficient due to AVR action in such cases is usually of no particular concern, because K_1 is so high that the net T_S is significantly greater than zero [3].

With K_5 negative, the AVR action introduces a positive synchronizing torque component and a negative damping torque component. This effect is more pronounced as the exciter response increases. For high values of external reactance and high generator outputs K_5 is negative. In this case because of fast AVR action, it introduces negative T_D which leads to low frequency oscillations. In this paper, the case of K_5 negative is considered for analysis. The parameters that are considered for a typical SMIB system are:

K_A=50, T_A=0.05 sec, Tdo'=6sec, T_R=0.01 sec, H=5sec.

For calculating the Heffron-Phillips constants, reactance data and operating conditions are necessary and represented as follows [6]:

Direct axis reactance of synchronous machine=1.6pu
Quadrature axis reactance of synchronous machine =1.55pu

D-axis transient reactance of synchronous machine =0.32pu
Transmission line reactance =0.4pu
Operating conditions:
Active power (P) =0.8pu
Reactive power (Q) =0.6pu
Frequency (f) =50Hz
Initial terminal voltage (V_{t0}) =1pu

III. THEORETICAL STUDY

3.1 Power System Stabilizer (PSS):

The basic function of a Power System Stabilizer (PSS) is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signals. To provide damping, the stabilizer must produce a component of electrical torque in phase with the rotor speed deviations [3].

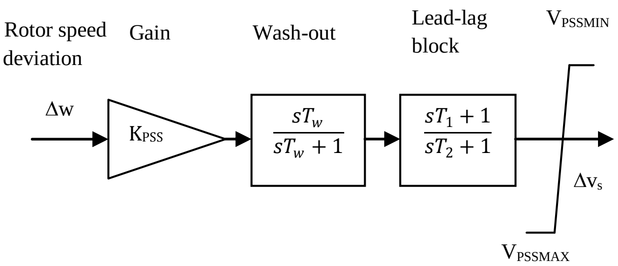

Fig. 2 Basic Power system stabilizer

It basically consists of following blocks [7]:

i. Washout filter
ii. Stabilizer gain
iii. Lead-lag compensator
iv. Limiter

T_w is washout filter time constant which is taken as 10sec, K_{PSS} is stabilizer gain, T_1 and T_2 are lead-lag compensator time constants. Washout circuit is provided to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS should respond only to low frequency oscillations and not to the dc offsets in the signal. So, washout filter acts as a high pass filter whose time constant is selected in such a way that it allows only oscillation frequencies in the range of 0.1 to 2Hz and blocks the steady-state bias [5].

Stabilizer gain is selected based on amount of damping required to damp out the LFO's. Lead-lag compensator provides necessary phase compensation for the phase lag between exciter and the generator transfer functions. Limiter limits the PSS output thereby avoiding the chance of hitting upper and lower limits of excitation.

The objective of PSS is to introduce additional damping torque without affecting the synchronizing torque at critical oscillation frequencies [5].

$$M\frac{d^2\Delta\delta}{dt^2}+\frac{T_D}{w_b}\frac{\mathrm{d}\Delta\delta}{\mathrm{dt}}+T_S\Delta\delta=0 \qquad (1)$$

From this equation, for stabilizing rotor oscillations both synchronizing torque (T_S) and damping torque (T_D) should be positive at all possible frequencies of oscillations. For $T_D>0$ and $T_s<0$ (or) for both T_D and T_S negative, there will be one real root in R.H.S. plane. The instability arises due to the negative damping torque caused by the fast acting exciter under operating conditions that lead to $K_5<0$.

3.2 Particle Swarm Optimization (PSO):

PSO technique is one of the heuristic swarm techniques which search for the best fitness value by generating population for each particle. In a PSO system, each particle changes its position by flying around in a multidimensional search space until computational limitations are exceeded. In social science context, a PSO system combines a social-only model and a cognition-only model. The social-only component suggests that individuals ignore their own experience and adjust their behavior according to successful beliefs of individuals in the neighborhood. On the other hand, the cognition-only component treats individuals as isolated beings. A particle changes its position using these models [8].

3.2.1 Algorithm [9]:

Step 1: Initialize the size of swarm, dimension of search space, maximum number of iterations, and the PSO constants w, c_1, c_2.

Step 2: Assign the particles with some random initial positions (x) and velocities (V). Set the counter for iteration (k) to zero. Find out the current fitness of each particle in the population. For the initial population, local best fitness (pbest) of each particle is its own fitness value, and local best position of each particle is its own current position.

Step 3: The global best fitness value is calculated by Global best fitness (gbest) = min (local best fitness). The position corresponding to global best fitness is the global best position.

Step 4: Update iteration count k and weight w

$$k=k+1 \qquad (2)$$

$$w= ((\max (k)-k)/\max (k)) \qquad (3)$$

Step 5: Update the particle velocity and particle position for next iteration by

$$V_i^{k+1} = wV_i^k + c_1 * rand_1 * (pbest_i - s_i^k) + c_2 * rand_2 * (gbest - s_i^k) \qquad (4)$$

$$x_i^{k+1} = x_i^k + V_i^{k+1} \qquad (5)$$

Step 6: Find out the current fitness of each particle. If current fitness < pbest, then set pbest = current fitness. The position corresponding to local best fitness is assigned to local best position.

Step 7: After calculating the local best fitness of each particle, the current global best fitness for the k^{th} iteration is determined by Current global best fitness = min (local best fitness). If current global best fitness < gbest, then set gbest = current global best fitness. The position corresponding to global best fitness is assigned to global best position.

Step 8: Repeat Steps 4, 5 and 6 until k is equal to the maximum iterations defined in Step 1 or there is no improvement in the global best fitness value.

Step 9: Terminate the iterative algorithm, when there cannot be any further execution of iterations.

3.3 Cat Swarm Optimization (CSO):

The CSO algorithm was developed based on the common behavior of cats. It has been found that cats spend most of their time resting and observing their environment rather that running after things as this leads to excessive use of energy resources. To reflect these two important behavioral characteristics of the cats, the algorithm is divided into two sub-modes and CSO refers to these behavioral characteristics as seeking mode and tracing mode, which represent two different procedures in the algorithm. Tracing mode models the behavior of the cats when running after a target while the seeking mode models the behavior of the cats when resting and observing their environment [10]. In CSO, we first decide how many cats we would like to use in the iteration and then we apply the cats into CSO to solve the problems. Every cat has its own position composed of M dimensions, velocities for each dimension, a fitness value, which represents the accommodation of the cat to the fitness function, and a flag to identify whether the cat is in seeking mode or tracing mode. The final solution would be the best position of one of the cats. The CSO keeps the best solution until it reaches the end of the iterations [11].

3.3.1 Description of cat swarm optimization:

CSO has two sub modes, namely seeking mode and tracing mode. To combine these two modes into the algorithm, we define a mixture ratio (MR) which dictates the joining of seeking mode with tracing mode. Cats which are awake spend most of their time resting and observe their environment. If they decide to move while resting, the movement is done carefully and slowly. This behavior is known as seeking mode. Tracing mode models the chasing of a target by the cat. Cats spend very little time chasing things as this leads to over use of energy resources. Hence to guarantee that the cats spend most of their time resting and observing i.e. most of the time is spent in seeking mode, MR is allocated a very small value. The process of CSO is described below [11]:

Step 1: Create N cats in the process.

Step 2: Randomly sprinkle the cats into the M-dimensional solution space and randomly give values, which are in-range of the maximum velocity, to the velocities of every cat. Then haphazardly pick number of cats and set them into tracing mode according to MR, and the others set into seeking mode.

Step3: Evaluate the fitness value of each cat by applying the positions of cats into the fitness function, which represents the criteria of our goal, and keep the best cat into memory. Note that we only need to remember the position of the best cat (x_{best}) due to it represents the best solution so far.

Step 4: Move the cats according to their flags, if cat_k is in seeking mode, apply the cat to the seeking mode process, otherwise apply it to the tracing mode process.

Step5: Re-pick number of cats and set them into tracing mode according to MR, then set the other cats into seeking mode.

Step 6: Check the termination condition, if satisfied, terminate the program and otherwise repeat Step3 to Step5.

3.4 System model and PSS structure [8]:

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

$$\dot{X} = f(X, U) \qquad (6)$$

where X is the vector of the state variables, and U is the vector of input variables. The above equation in linearized model can be written as

$$\Delta\dot{X} = f(\Delta X, U) \qquad (7)$$

The corresponding state equation is

$$\Delta\dot{X} = A\Delta X + BU \qquad (8)$$

For the block diagram shown in Fig.1, there are 7 state variables and two input signals. Out of two input signals one input signal is taken for analysis. Therefore A is 7x7 matrix and B is 7x1 matrix.

In this paper, a single stage lead-lag PSS is considered and therefore PSS output signal is

$$\Delta v_s = K_{PSS} \frac{sT_w}{1+sT_w} \frac{(1+sT_1)}{(1+sT_2)} \Delta w_r \qquad (9)$$

From this equation, the time constants T_1, T_2 and K_{PSS} are to be optimized. T_w is usually taken as 10sec.

3.5 Objective Function:

In this paper, Integral time absolute error (ITAE) is considered as objective function J [12].

$$J = \int_{t=0}^{t=t_{sim}} t(|\Delta w|)dt \qquad (10)$$

The constraints are stabilizer parameter upper and lower bounds and the design of PSS is formulated as optimization problem as follows:

Minimize J

Subject to

$$K_{pss}^{min} \le K_{pss} \le K_{pss}^{max}$$
$$T_{1pss}^{min} \le T_{1pss} \le T_{1pss}^{max}$$
$$T_{2pss}^{min} \le T_{2pss} \le T_{2pss}^{max}$$

Typical ranges of the optimized parameters are [0.1-100] for K_{PSS}, [0.1-1] for T_1 and [0.01-1] for T_2.

IV. SIMULATION OF SMIB

The following SMIB system is taken as problem as shown in Fig. 3.

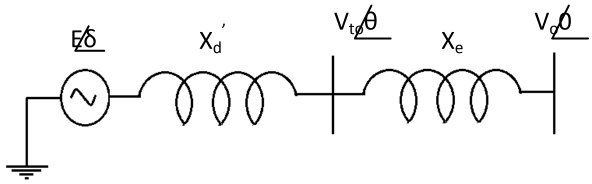

Fig. 3 SMIB system

Heffron-Phillips model for SMIB system without and with PSS is developed using MATLAB/SIMULINK as shown in Fig. 4 and Fig. 5 respectively.

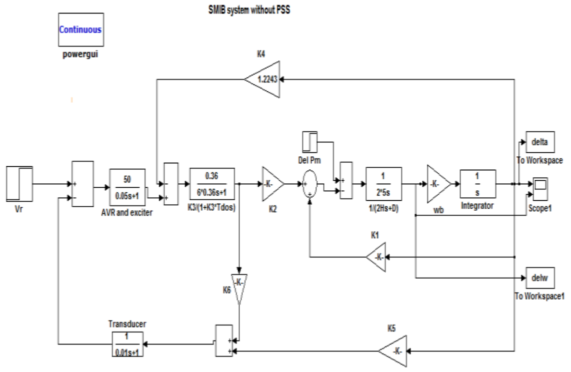

Fig. 4 Simulink diagram without PSS

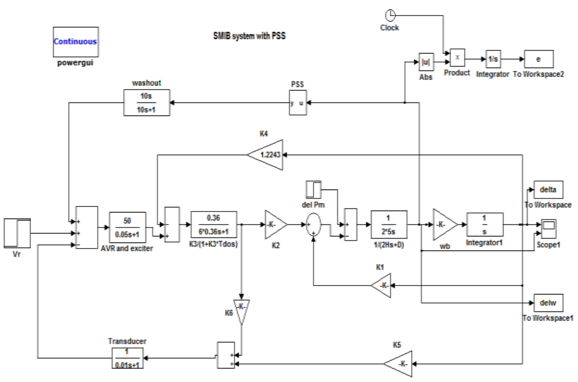

Fig. 5 Simulink diagram with PSS

V. RESULTS AND ANALYSIS

For a step change in excitation reference voltage, the waveforms of rotor angle deviation and speed deviation without PSS are shown in Fig. 6 and Fig. 7 respectively. And corresponding characteristics with optimized PSS parameters using PSO and CSO are shown in Fig. 8 and Fig. 9 respectively.

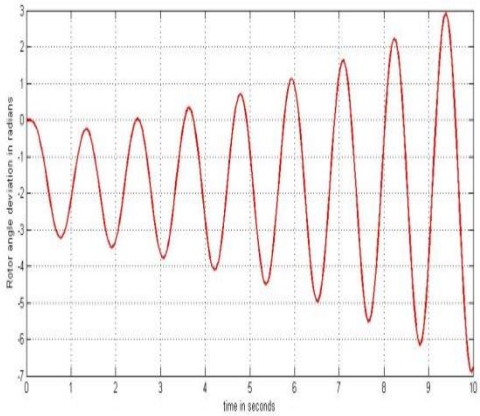

Fig. 6 Rotor angle deviation without PSS

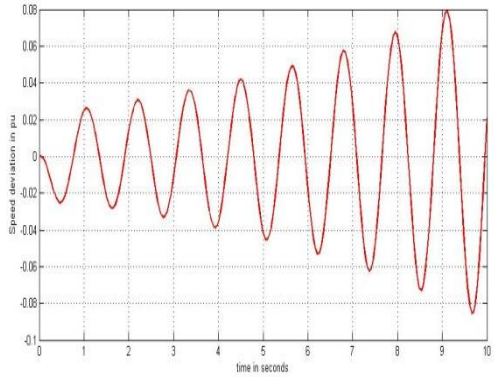

Fig. 7 Speed deviation without PSS

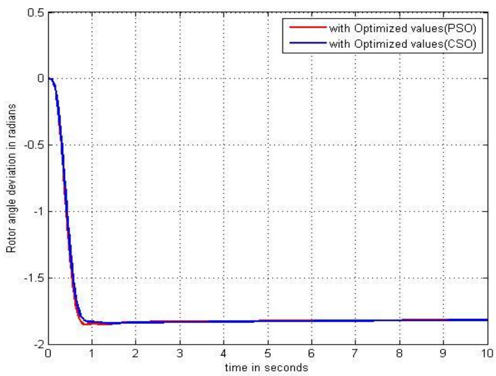

Fig. 8 Rotor angle deviation with PSS

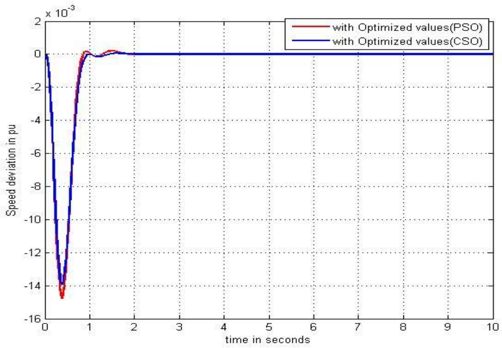

Fig. 9 Speed deviation with PSS

From these figures, it can be clearly observed that without PSS, system is subjected to oscillatory instability. These oscillations are effectively damped using PSS. The tuning of parameters using PSO and CSO produced the same effect of damping of oscillations but with minor variations in undershoot values and settling time.

Table I Time domain specifications

	Undershoot value	Settling time(sec)
With Optimized PSS parameters using PSO	0.0148	0.8221
With Optimized PSS parameters using CSO	0.0139	0.8808

From table I, it was observed that the undershoot value and settling time with PSO tuned PSS are 0.0148 and 0.8221sec respectively. Corresponding values with CSO tuned PSS are 0.0139 and 0.8808sec respectively. The undershoot value in case of CSO tuned PSS is minimum whereas settling time is more compared with PSO tuned PSS. By observing undershoot values and settling times, it can be commented that both CSO and PSO are giving same type of response. The deviation in time domain specifications are minimum, hence both PSO and CSO are effective in properly tuning parameters of PSS.

Bode plots for SMIB system considered for the study with PSS employing PSO and CSO tuning methods are represented from Fig. 10 to Fig. 11.

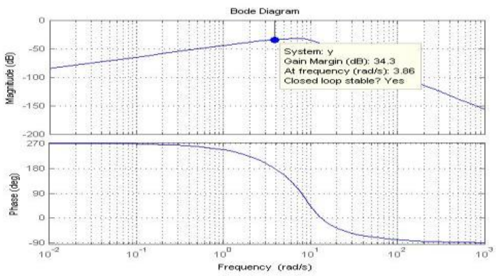

Fig. 10 Bode Plot for SMIB system with optimized PSS parameters using PSO

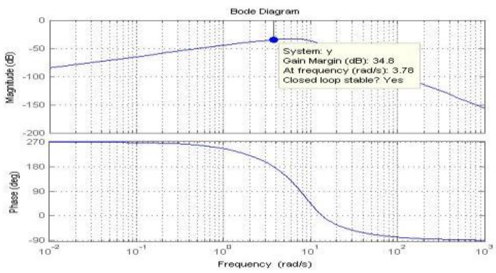

Fig. 11 Bode Plot for SMIB system with optimized PSS parameters using CSO

From Fig. 10, it was observed that the gain margin in case of PSO tuned PSS is 34.3db. The corresponding value in case of CSO tuned PSS is 34.8db and in both cases, system is stable.

The eigen values considered for study without PSS and with optimally tuned PSS using PSO and CSO are represented in Table II.

Table II Eigen values

Cases	Eigen values
Without PSS	-100.96, 0.14 ± 5.48i, 12.42, 7.36
With Optimized PSS parameters using PSO	-100.96, -36.9, -3.65±8.85i, -4.26±2.89i, -0.10
With Optimized PSS parameters using CSO	-91.96, -101.06, -4.18±8.28i, -4.99±2.44i, -0.10

Without PSS, there are four poles located on right half of s-plane indicating that system is unstable. Out of these four poles, two poles are real and remaining two are complex conjugates indicating the oscillatory nature of response with increasing magnitude. With PSO tuned PSS, all poles are located on left half of s-plane indicating the stable nature of response. The same behavior is observed even for CSO tuned PSS. In tuned PSS system with both of the tuning methods, the dominant pole location is same indicating the same relative stability.

VI. CONCLUSIONS

In this paper, Heffron-Phillips model is developed for Single Machine Infinite Bus (SMIB) system using MATLAB/SIMULINK. SMIB system is simulated for a step change in reference voltage without and with optimized PSS. Without PSS, both torque angle and speed deviation are subjected to low frequency oscillations with increasing amplitude. This is because of negative damping torque provided by AVR. For providing necessary damping torque, Power System Stabilizer (PSS) is installed. The PSS parameters are tuned using Particle Swarm Optimization (PSO) and Cat Swarm Optimization (CSO) techniques. Both of the tuning methods produced the same effect of damping of low frequency oscillations. From Fig. 8 and Fig. 9, it is clearly observed that the both optimization techniques are effective in tuning PSS parameters.

ACKNOWLEDGEMENTS

The authors would like to thank the Management and Principal of V.R. Siddhartha Engineering College for their consistent encouragement and providing necessary facilities to carry out this research work and also like to thank the Department of Electrical and Electronics Engineering of V.R.

Siddhartha Engineering College for their support and facilities rendered for this work.

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