ISSN: 2277-3754
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 1, Issue 4, April 2012

Damping of Low- frequency Oscillations Using Swarm Optimized Controller for SMIB System

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Abstract— ***Damping of Low frequency oscillations using Swarm optimized controller for Single Machine Infinite Bus (SMIB) system is presented in this paper. Power System Stabilizer (PSS) based on speed and electrical power deviation (IEEE std 421.5 PSS4B) is implemented in this paper. Particle Swarm Optimization (PSO) has gained growing popularity in the recent years and is finding a wide range of important applications. Like other population based stochastic meta-heuristics, PSO has a few algorithm parameters that need to be carefully set to achieve best execution results. Power system stabilizer based on the Particle Swarm Optimization (PSO) algorithm is presented for tuning dual input Power System Stabilizer (PSS4B) parameters. In the proposed method, based on the optimization of a suitable objective function, optimal values for PSS controlling parameters including lead-lag compensator time constants as well as the controller gain are calculated. The employed objective function is the error between the reference voltage and the signal produced from the terminal voltage (i.e. to minimize the overshoot of low-frequency oscillations). The proposed algorithm is applied to a single machine power system and for various operating conditions. SMIB system performance is analyzed "without Power System Stabilizer (PSS)", "with Conventional Dual Input Power System Stabilizer (CPSS4B)", "with PSO Dual Input Power System Stabilizer (PSOPSS4B)". Simulation results prove the capability of the proposed algorithm in damping the oscillations to enhance the Power System stability.***

Index Terms—- **IEEE STD 421.5 PSS4B, PSS, SMIB, Particle Swarm Optimization.**

I. INTRODUCTION

A power system consists of generators, loads, transformers and transmission lines. Any disturbance in the power system will cause electromechanical oscillations and hence, system variables will start to oscillate. These variables may include system voltage, frequency, load angles of generators or other parameters of the system. Stabilizing these parameters is of great importance in power system stability [3]. To damp out the low frequency oscillations caused by disturbances or system topology changes such as network switches in the power system, power system stabilizers (PSSs) have long been regarded as a viable solution. These oscillations may occur locally or inter-area wide, especially when the system has some generators of significantly different inertia constants interconnected by weak transmission channels. The underlying concept of PSS is to add a supplementary control signal to the exciter/automatic voltage regulator (AVR) to increase the damping of oscillation. Most of the existing PSSs are designed based on the linearized generator/exciter model near some operating points [3].

Most recently, several power equipments are operated with dual input PSSs which use machine speed and electrical output power to synthesize an accelerating power variable (P_{acc}). One of the advantages of dual input PSS is that it reduces the interaction of the PSS with excitation mode and thus allows a higher gain to be used for improved damping. The damping performance of generator's electromechanical mode of oscillations of PSS4B is better than CPSS. PSS4B yield robust dynamic performance over a wide range of system operating conditions for the particular SMIB system [6].

Controllers designed with classic methods, despite their simplicity, are only suitable for specific operating conditions of the system and will not work for many unpredicted situations. Once the structure of controller is specified, it can be said that the method for parameter setting is not that much important since an accurate design means the accurate setting of parameters. In applications in which a simple, fast and a suitable setting for at least several points of system operating conditions are needed, the effectiveness of classic methods may be restricted. Optimization methods which are based on random search algorithms are very suitable for solving complex problems that are difficult or even impossible to be solved using conventional mathematical methods such as gradient. Power system stability is one of these problems as solving differential equations of power system in order to investigate its stability is an intricate problem. Application of such methods in solving complicated problems has recently been in the focus of researchers' attention. The over all excitation control system is designed so as to maximize the damping of local plant mode as well as inter-area mode oscillations without compromising the stability of other modes and to enhance system transient stability. Inputs to PSS are rotor speed deviation and electrical power deviation which would result in damping torque. The state space model of the system with PSS and AVR is designed. The time constants in the PSS are tuned using Particle Swarm Optimization (PSO). From the simulation results, the optimum design of PSS is obtained.

II.SYSTEM REPRESENTATION

A. Representation of Synchronous Machine Excitation System

The general functional block diagram shown in Fig.1 indicates various synchronous machine excitation

ISSN: 2277-3754
International Journal of Engineering and Innovative Technology (IJEIT)
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subsystems. These subsystems may include a terminal voltage transducer and load compensator, excitation control elements, an exciter, and in many instances, a power system stabilizer (PSS). Supplementary discontinuous excitation control may also be employed. Models for all of these functions are presented in this recommended practice. Excitation control elements include both excitation regulating and stabilizing functions. The terms excitation system stabilizer and transient gain reduction are used to describe circuits in several of the models encompassed by the excitation control elements shown in Fig.1 that affect the stability and response of those systems.

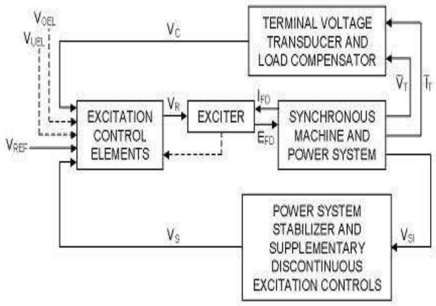

Fig. 1: General Functional Block Diagram for Synchronous Machine Excitation System

B. Types of Excitation systems

Three distinctive types of excitation systems are identified on the basis of excitation power source as follows.

1) Type DC excitation systems, which utilize a direct current generator with a commutator as the source of excitation system power.

2) Type AC excitation systems, which use an alternator and either stationary or rotating rectifiers to produce the direct current needed for the synchronous machine field.

3) Type ST excitation systems, in which the excitation power is supplied through transformers or auxiliary generator windings and rectifiers.

The following key accessory functions common to most excitation systems are identified and described as follows:

i. Voltage sensing and load compensation
ii. Power system stabilizer
iii. Over-excitation limiter
iv. Under-excitation limiter
v. Power factor and var control
vi. Discontinuous excitation controls

C. SMIB with AVR and PSS

The reaction of the AVR in front of the terminal voltage oscillate is to force field current changes in the generator. This so-called negative damping may be eliminated by introducing a supplementary control loop, known as the power system stabilizer. The basic function of a PSS is to extend the stability limits by modulating the generator excitation to provide damping for the rotor oscillations of synchronous machines. The PSS can enhance the damping of power system, increase the static stability and improve the transmission capability. The PSS output is added to the difference between reference and actual value of the terminal voltage. Usual input signal for the PSS are rotor speed deviations, accelerating power, active power output or the system frequency. A diagram illustrating the principle mode of operation of a PSS is given in Fig.2.

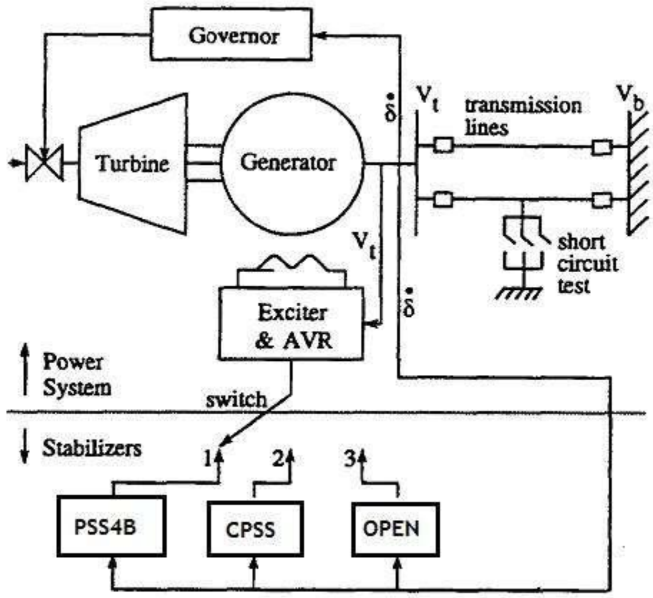

Fig. 2: Schematic diagram of SMIB with AVR & PSS4B

III. POWER SYSTEM MODELLING

A. SMIB system

The PSS optimality can be defined in various ways. In this paper, it is assumed that the PSS is optimal when it produces a damping electromagnetic torque component only, i.e. a component that is in phase with the rotor speed deviation. Providing a damping torque is indeed the main task of a PSS, although it should be noted that sometimes it may be useful for the PSS to provide a synchronizing torque too. To achieve such "optimal" PSS, let us consider a linear model of the single-machine system presented in Fig. 3 [3]. Let us also assume rotor speed Δω and electrical power ΔPe as PSS input.

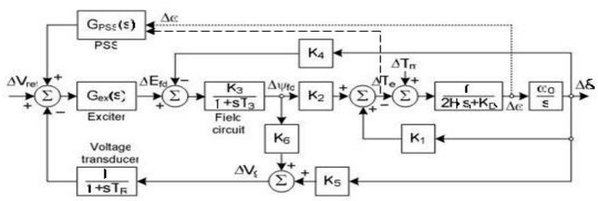

Fig. 3 Linear model of SMIB with AVR & PSS4B

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International Journal of Engineering and Innovative Technology (IJEIT)
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$$\Delta T_e = T_\delta(s).\Delta\delta + T_v(s).\Delta V_{ref} + T_{PSS}(s)(\Delta\omega + \Delta P_e) \quad (1)$$

$$T_\delta(s) = K_1 - \frac{K_2K_3(K_4(1+sT_R)+K_5G_{ex}(s))}{(1+sT_R)(1+sT_3)+K_3K_6G_{ex}(s)} \quad (2)$$

$$T_{PSS}(s) = \frac{K_2K_3G_{ex}(s)G_{PSS}(s)(1+sT_R)}{(1+sT_R)(1+sT_3)+K_3K_6G_{ex}(s)} \quad (3)$$

$$\Delta T_{PSS} = T_{PSS}(s).\Delta\omega \quad (4)$$

$$T_{PSS}(s=j\omega)=K(\omega)=K_{re}(\omega)+jK_{im}(\omega) \quad (5)$$

$$T_{PSS}(s)=K \quad (6)$$

$$G_{PSS}(s) = K.\frac{(1+sT_R)(1+sT_3)+K_3K_6G_{ex}(s)}{K_2K_3(1+sT_R)G_{ex}(s)} \quad (7)$$

There are two major loops in the fig. 3; the mechanical loop on top and the electrical loop at the bottom. The linearized equations are used because we are dealing with periodic small oscillations. The incremental torque (ΔT_m-ΔT_e) is considered as the input and the torque angle $\Delta\delta$ as the output. The mechanical loop has two transfer function blocks from left to right. The first block is based on the equation of torque equilibrium and second block shows the relation of the angle and speed for the units chosen. In these blocks, M is the inertia constant, D is the mechanical damping coefficient and 2Πf is the synchronous speed.

The electrical loop has a supplementary control U_E minus the incremental terminal voltage ΔV_t as the input and the incremental internal voltage, Δeq as the output; which is multiplied by K_2 to become part of the electrical ΔT_e of the system. It has two transfer function blocks from right to left. The first block represents an exciter and voltage regulator system of the fast response type with a time constant T_A and an overall gain K_A. This block should be expanded when the system has rotating exciter and voltage regulator. The second block represents the transfer function of the field circuit as affected by the armature reaction, with an effective time constant T_e, K_A and a gain K_3. Finally ΔV_t consists of two components K5, Δδ due to the torque angle variation Δδ and K_6Δeq. Here ΔV_t means (V_t-V_t) and the negative sign is given to ΔV_t because of the negative feedback.

B. Synchronous Generator

For a power system dynamic study, a proper and adequate power system model of a synchronous generator must be chosen. Fundamental equations of synchronous machines were derived by Park and others, years ago. Park's equations have the simplest form and are most well known. Park's synchronous machine consists of three armature phase windings on the stator of the machine, which have been replaced by two equivalent armature phase windings; d – winding on the d-axis and the q-winding of the q-axis. There are two damper windings on the rotor. D on d-axis and Q on q-axis are permanently short-circuited. The third order model is selected for the representation of synchronous generator. The torque relation is described by differential equation. The change in flux linkage of field windings cannot be neglected, although the changes in flux linkage of other windings are still negligible.

The state equation of third order may be described as follows

$$\omega = (T_m - T - T_D)/M \quad (8)$$

$$\delta = \omega \ * (\omega - 1) \quad (9)$$

$$e_q = [E_a - e_q - (X_d - X_d')*i_d]/T_{do} \quad (10)$$

The auxiliary equations are,

$$T_e \approx P_e \approx e_q * V_t * \sin\delta / X_d' + V_t^2 * (X_d' - X_d) \sin2\delta / 2 * X_d' *X_q \quad (11)$$

$$e_q' = V_t + j*X_d'*i_d + j*X_q*(j * i_q) \quad (12)$$

C. Excitation System – Type ST1A

The computer model of the Type ST1A potential-source controlled-rectifier excitation system is intended to represent systems in which excitation power is supplied through a transformer from the generator terminals (or the unit's auxiliary bus) and is regulated by a controlled rectifier. The maximum exciter voltage available from such systems is directly related to the generator terminal voltage. In this type of system, the inherent exciter time constants are very small, and exciter stabilization may not be required. On the other hand, it may be desirable to reduce the transient gain of these systems for other reasons. The model shown is sufficiently versatile to represent transient gain reduction implemented either in the forward path via time constants, T_B and T_C (in which case K_F would normally be set to zero), or in the feedback path by suitable choice of rate feedback parameters, K_F and T_F. Voltage regulator gain and any inherent excitation system time constant are represented by K_A and T_A, respectively. Simplified IEEE ST1A static excitation system is shown in Fig.4 [4]. It is the most commonly used excitation system.

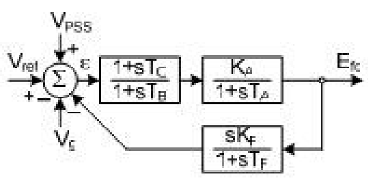

Fig. 4 - IEEE ST1A static excitation systems

D. Power System Stabilizer (PSS)

1) PSS4:The PSS4B measures the rotor speed deviation in two different ways. Δω L-I feeds the low and intermediate bands, while ΔωH is dedicated to the high-frequency band. The equivalent model of these two

ISSN: 2277-3754
International Journal of Engineering and Innovative Technology (IJEIT)
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speed transducers is shown in Fig 5 [4]. Tunable notch filters Ni(s), optionally used for turbo-generators torsional modes, are defined as shown in equation below [8].

$$N_i(s) = \frac{s^2 + \omega_{ni}^2}{s^2 + B_{wi}s + \omega_{ni}^2} \quad (13)$$

ω_{ni} = the filter frequency, B_{wi} = 3 dB bandwidth.

The PSS4B model represents a structure based on multiple working frequency bands as shown in Fig 6 [4]. Three separate bands dedicated to the low-, intermediate- and high-frequency modes of oscillations, are used in this delta-omega (speed input) PSS. The low band is typically associated with the power system global mode, the intermediate with the inter-area modes, and the high with the local modes. Each of the three bands is composed of a differential filter, a gain and a limiter. Their outputs are summed and passed through a final limiter VSTMIN/VSTMAX resulting in PSS output VST.

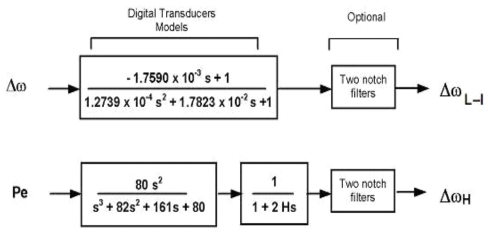

Fig. 5 - Type PSS4B—MB-PSS speed deviation transducers

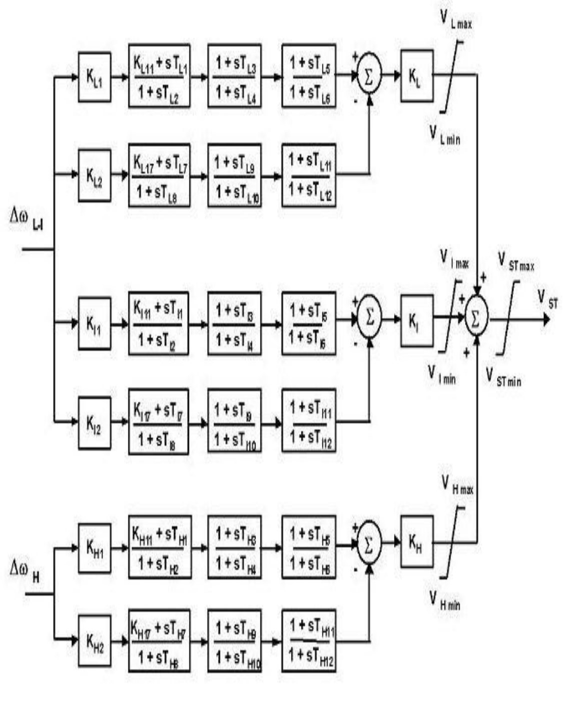

Fig. 6 - Type PSS4B—Multi-band PSS

IV. PROPOSED OBJECTIVE FUNCTION FORMULATION

The employed objective function is the integral square of error between the reference voltage and the signal produced from the terminal voltage (i.e. to minimize the overshoot of low-frequency oscillations). Every setting which can achieve this goal can optimize the power system stability.

$$J = \min\left(\int e^2(t)\, dt \right) \quad (14)$$

Where

$$e = (\Delta V_{ref} - \Delta V_t)$$

Subject to:

$$\begin{aligned} &K_{PSS1}^{min} \le K_{PSS1} \le K_{PSS1}^{max} \\ &K_{PSS2}^{min} \le K_{PSS2} \le K_{PSS2}^{max} \\ &T_0^{min} \le T_0 \le T_0^{max} \\ &T_1^{min} \le T_1 \le T_1^{max} \\ &T_2^{min} \le T_2 \le T_2^{max} \\ &T_3^{min} \le T_1 \le T_3^{max} \\ &T_4^{min} \le T_1 \le T_4^{max} \end{aligned} \quad (15)$$

V. PARTICLE SWARM OPTIMIZATION

PSO optimizes a problem by maintaining a population of candidate solutions called particles and moving these particles around in the search space according to simple formulae. The movements of the particles are guided by the best found positions in the search-space, which are continually updated as better positions are found by the particles. The PSO method is a member of wide category of Swarm Intelligence methods for solving the optimization problems. It is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also the flying experience of the other particles. In PSO each particles strive to improve themselves by imitating traits from their successful peers. Further, 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 known as *pbest* and the overall best out of all the particles in the population is called *gbest*. The modified velocity and position of each particle can be calculated using the current velocity and the distance from the *pbestjg* to *gbestg* as shown in the following formula:

vi(t + 1) = wvi(t) + c1r1[ˆxi(t) - xi(t)] + c2r2[g(t) - xi(t)] (16)

The index of the particle is represented by i. Thus, vi(t) is the velocity of particle i at time t and xi(t) is the position of particle i at time t. The parameters w, c1, and c2 ($0 \le w \le 1.2$, $0 \le c1 \le 2$, and $0 \le c2 \le 2$) are user-supplied coefficients. The values r1 and r2 ($0 \le r1 \le 1$ and $0 \le r2 \le 1$) are random values regenerated for each velocity update. The value ˆxi(t) is the

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individual best candidate solution for particle i at time t, and g(t) is the swarm's global best candidate solution at time t. Once the velocity for each particle is calculated, each particle's position is updated by applying the new velocity to the particle's previous position:

$X_i(t + 1) = X_i(t) + V_i(t + 1)$ (17)

This process is repeated until some stopping condition is met. Some common stopping conditions include a preset number of iterations of the PSO algorithm, a number of iterations since the last update of the global best candidate solution, or a predefined target fitness value. Fig. 7 shows the velocity and position updates of a particle for a two-dimensional parameter space. The flowchart for fitness function evaluation in PSO algorithm is shown in Fig.8 [1].

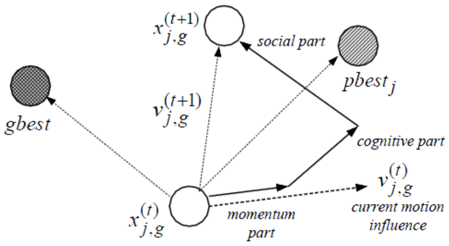


Fig.7 Description of velocity and position updates in particle Swarm optimization technique

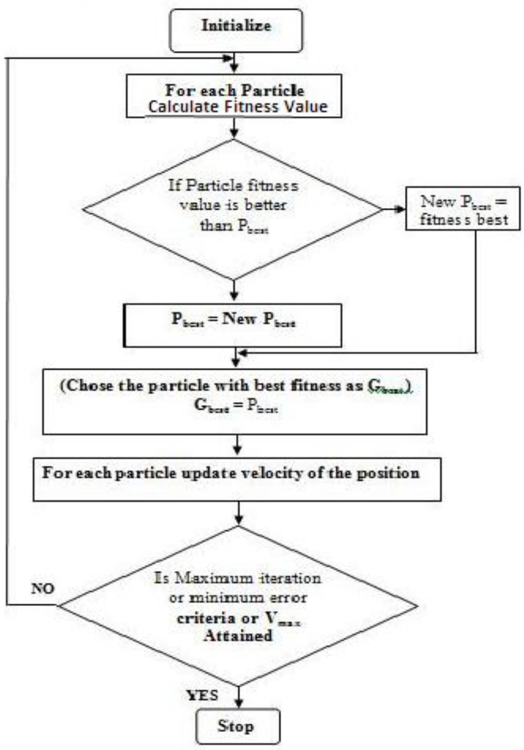


Fig. 8 Flowchart of fitness function evaluation in PSO algorithm

Table .1 Parameters used for PSO Algorithms

PSO parameters		Value
Swarm size		10
No of Generation		3
Acceleration factor	C1	0.12
	C2	0.8
Inertia		0.9

VI. SIMULATION RESULTS AND ANALYSIS

An SMIB system, as considered in the present work, is shown in the appendix. The block diagram representation of SMIB system with AVR, Exciter, synchronous generator and PSS4B is shown in fig.1 and their input parameters are given in the appendix. MATLAB – Simulink is the software used for modeling, simulating, and analyzing dynamic systems. The simulation results for the SMIB system under investigation is shown below.

1) Speed deviation, Power angle deviation, Electrical power deviation versus Time for (P=1.0,Q=0.6) is shown in Fig 9, 10 & 11.

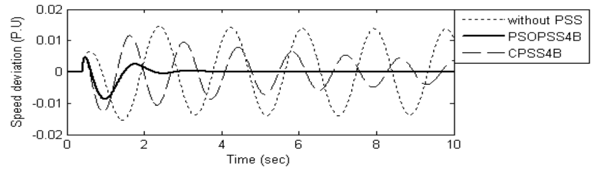


Fig. 9. Speed deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.0, Q = 0.6).

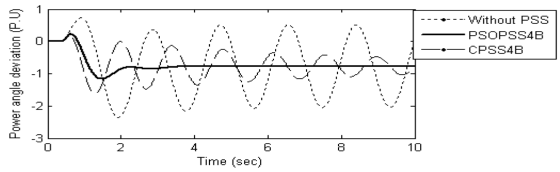


Fig. 10. Power Angle deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.0, Q = 0.6).

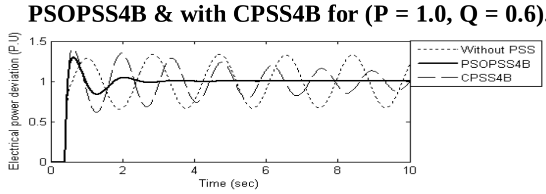
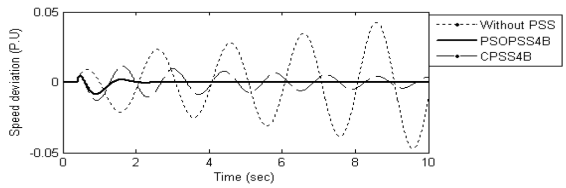


Fig. 11. Electrical power deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.0, Q = 0.6).

2) Speed deviation, Power angle deviation, Electrical power deviation versus Time for (P=1.1,Q=0.8) is shown in Fig 12, 13 & 14.



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International Journal of Engineering and Innovative Technology (IJEIT)
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Fig. 12. Speed deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.1, Q = 0.8).

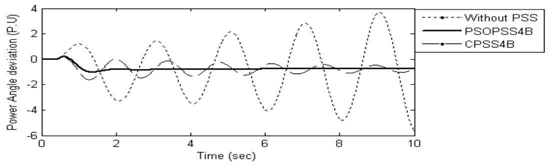

Fig .13. Power Angle deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.1, Q = 0.8).

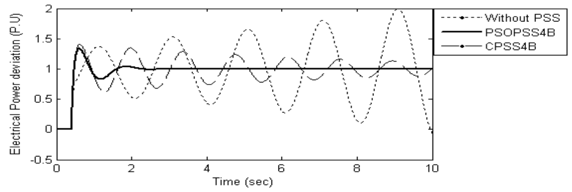

Fig. 14. Electrical power deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.1, Q = 0.8).

3) Speed deviation, Power angle deviation, Electrical power deviation versus Time for (P=1.2,Q=0.9) is shown in Fig 15, 16 & 17.

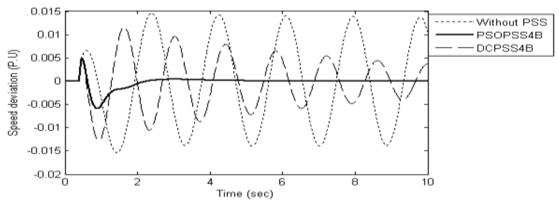

Fig . 15. Speed deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.2, Q = 0.9).

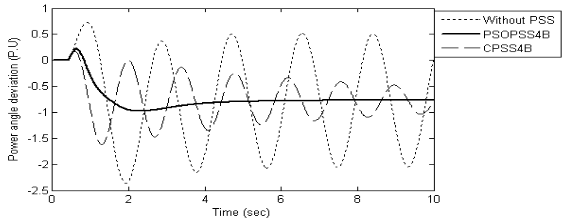

Fig . 16. Power Angle deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.2, Q = 0.9

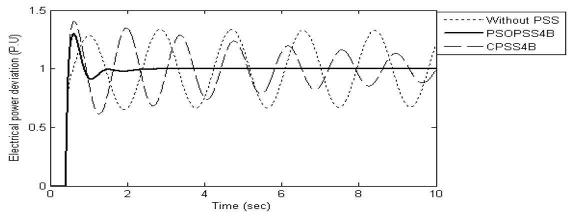

Fig. 17. Electrical power deviation without PSS, with PSOPSS4B & with CPSS4B for (P = 1.2, Q = 0.9).

Simulation results revealed that,

- The dynamic stabilization performance of PSOPSS4B equipped system model is superior to that of CPSS4B equipped system.
- PSOPSS4B equipped model settles the $\Delta\omega r$ quickly with lesser value of overshoot, lesser value of undershoot and lesser value of settling time as compared to CPSS4B based model.
- The damping ratios of PSOPSS4B equipped model are predominantly larger than those for CPSS4B based counterpart.

VII. CONCLUSION

In this paper, Damping of Low-frequency oscillations using Swarm optimized controller for Single Machine Infinite Bus (SMIB) system is presented. It is concluded that the damping performance of generator's electromechanical mode of oscillations of PSS4B is better than CPSS4B. PSS4B yield robust dynamic performance over a wide range of system operating conditions for the particular SMIB system. The objective function is defined based on the system linear model analysis around the operating point and the objective is to minimize the overshoot of low-frequency oscillations and to increase their damping. As the algorithm is employed for various operating conditions, the obtained results will be valid for a vast range of operating conditions. Comparing the simulation results of the proposed algorithm with those of a conventional-tuned controller reveal that the PSO-based setting works better even for high amplitude disturbances such as short circuits.

APPENDIX

An SMIB system, as considered in the present work, is shown in the Fig.18 [3]. All of the parameters as well as values of initial conditions for system simulation are in pu otherwise it will be mentioned.

A. Generator:

$H = 3.5$, $M = 2H$, $T_{dO}' = 7.76$, $D = 0$, $X_d = 0.973$, $X_d' = 0.19$, $X_q = 0.55$, $X_e = 1.08$.

B. Excitation system:

$K_A = 200$, $T_A = 0$.

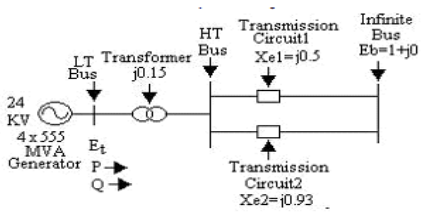

Fig.18 .Single Machine Infinite Bus system

C. Field circuit:

$K_3 = 0.4494$, $T_3 = 3.9336$.

D. SMIB K constants:

$K_1 = 0.5320$, $K_2 = 0.7858$, $K_4 = 1.0184$, $K_5 = -0.0597$, $K_6 = 0.5746$.

E. Operating points:

1) $P = 1.0$, $Q = 0.6$, $D = 0$, $E_t = 1.1$, Frequency =60 Hz.
2) $P = 1.1$, $Q = 0.8$, $D = 0$, $E_t = 1.1$, Frequency =60 Hz.
3) $P = 1.2$, $Q = 0.9$, $D = 0$, $E_t = 1.1$, Frequency =60 Hz.

F. CPSS4B:

$90 \leq K_{PSS1} \leq 200,\ 50 \leq K_{PSS2} \leq 100,\ 0.2 \leq T_0 \leq 1.0,$
$0.5 \leq T_1 \leq 1.0,\ 0.001 \leq T_2 \leq 0.005,\ 0.5 \leq T_1 \leq 1.0,$
$0.1 \leq T_1 \leq 0.5.$

G. PSOPSS4B:

$50 \leq K_{PSS1} \leq 60,\ 50 \leq K_{PSS2} \leq 60,\ 0.1 \leq T_0 \leq 0.5,$
$0.5 \leq T_1 \leq 1.0,\ 0.001 \leq T_2 \leq 0.02,\ 0.1 \leq T_1 \leq 0.5,$
$0.01 \leq T_1 \leq 0.05.$

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Publications:

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2. National Conference on “Emerging Technologies (MKCE – Confluence ’11)” held on 11th February 2011.
3. National Conference on “Computing and Communication Technologies (N3CT ’11)” held on 17th March 2011.
4. International Conference on “Adaptive Technologies for Sustainable Growth (ICATS-2011)” held on 16-18th June 2011.