01 Jan 2006

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Recommended Citation

G. K. Venayagamoorthy and T. K. Das, "Optimal Design of Power System Stabilizers using a Small Population Based PSO," *Proceedings of the IEEE Power Engineering Society General Meeting, 2006*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2006.
The definitive version is available at https://doi.org/10.1109/PES.2006.1709322

Optimal Design of Power System Stabilizers Using a Small Population Based PSO

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Abstract—**Power System Stabilizers (PSSs) are used to generate supplementary control signals to excitation systems in order to damp out local and inter-area oscillations. In this paper, a modified Particle Swarm Optimization (PSO) algorithm with a small population is presented for the design of optimal PSSs. The Small Population based PSO (SPPSO) is used to determine the optimal parameters of several PSSs simultaneously in a multi-machine power system. In order to maintain a dynamic search process, the idea of particle regeneration in the population is also proposed. Optimal PSS parameters are determined for the power system subjected to small and large disturbances. The effectiveness of the PSSs parameters determined by the SPPSO algorithm is observed in damping out the power system oscillations fast after a disturbance. The advantage of the proposed approach is its convergence in fewer evaluations and lesser computations are required per evaluation. Results obtained with the SPPSO optimized PSSs parameters are compared against published PSS parameters for the Kundur's two area power system.**

Index Terms--**Multi-machine Power System, Particle Swarm Optimization, PSCAD, Power System Stabilizers, Regeneration, Small Population, Transient Stability.**

I. Introduction

TRANSIENT and dynamic stability considerations are among the most important issues in the reliable and efficient operation of power systems. The generators are equipped with Power System Stabilizers (PSSs), as supplementary control devices, to provide extra damping and the dynamic performance. PSSs are primarily used to damp low frequency oscillations in the range of 0.2 Hz to 2.5 Hz. These oscillations result when rotors of generators oscillate with respect to each other using the transmission lines between them to exchange power. These oscillations are generally categorized into three main oscillation modes – local mode, inter-area mode and intra-area mode. Depending on their location in the system, some generators participate in only one oscillation mode, while others participate in more than one mode.

Conventional power system stabilizers (CPSS) are designed using the theory of phase compensation in the frequency domain and are introduced as a lead-lag compensator. The parameters of CPSS are determined based on a linearized model of the power system. To have the CPSS provide good damping over a wide operating range, its parameters need to be fine tuned in response to all modes of oscillations present in the system. Since power systems are highly nonlinear systems, with configurations and parameters that change with time, the CPSS design based on a linearized model of the power system cannot guarantee its performance in a practical operating environment. Thus, it is important to determine the parameters of the PSSs and similar controllers using power system simulation models and tools where the nonlinear behavior of the power system is realizable but this becomes a challenge as size of the system studied becomes larger.

Several PSS design techniques are reported in literature, a few are listed here [1]-[9]. Kundur et al [3] have presented a comprehensive approach for conventional tuning of PSS parameters and its effect on the dynamic performance of the power system. The stabilizers designed to damp one particular mode of oscillation can produce adverse effects in the other modes. Thus, the multimodal nature of oscillations and the mutual interaction among generating units should be considered in PSS designs. Local optimization techniques like gradient descent method [6] failed to provide the optimum PSS parameters. Heuristic techniques such as Genetic Algorithms (GAs) [7], tabu search algorithm [8] and simulated annealing [9] have been applied earlier to PSS design. Studies have revealed that GA has a degraded performance if the function to be optimized is epistatic (where parameters to be optimized are highly co-related) [10]. The GA algorithm has also the demerits of premature convergence.

A modified Particle Swarm Optimization (PSO) algorithm [11] has been proposed in this paper as a solution to the above mentioned problems and drawbacks. PSO has been shown to have great potential for single and multi-objective optimization [12]. It is a population based algorithm which does not cause individuals/particles to reproduce over generations but it simply evolves better solutions through the collective interaction of all the individuals. PSO has flexible and well balanced mechanism to carry out local and global search.

Optimization of PSS parameters using standard PSO and the evolutionary PSO, called the EPSO [14], are reported in [13], [15] and [16]. The authors in this paper propose a Small Population based PSO (SPPSO) feasible for implementation on simulation tools that allow detailed representation of the power system dynamics such as the PSCAD/EMTDC software [17]. In addition, a population regeneration concept

The support from the National Science Foundation under the grant CAREER ECS # 0348221 is gratefully acknowledged by the authors.

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1-4244-0493-2/06/$20.00 ©2006 IEEE.

is introduced with the SPPSO to overcome the drawback of a small population. The SPSPO algorithm is applied for simultaneous optimization of parameters of all PSSs in the Kundur two area-power system [3]. The PSO fitness/cost function is formulated as the sum of the transient area under all the speed response curves during a disturbance. In other words, maximize damping of all PSSs without any causing adverse affects on any one of the generating units. To the knowledge of the authors, this is first paper in literature reporting the implementation of a population based optimization algorithm in PSCAD.

The paper is organized as follows: Section II describes multimachine power system; Section III describes the PSO and SPPSO algorithm. Section IV describes how SPPSO cost functions are formulated and used in determining the optimal parameters of the PSSs; Section V presents some simulation results obtained using the SPPSO algorithm. Section VI highlights the benefits of the SPPSO approach over the standard PSO and EPSO based PSS designs in [13], [15] and [16]. Finally, conclusions and future work is given in Section VII.

II. Multi-Machine Power System

For the study in this paper, the two area multi-machine power system [18], [19] is simulated in the PSCAD/EMTDC environment [17]. The two area power system is shown in Fig. 1, consists of two fully symmetrical areas linked together by two transmission lines. Each area is equipped with two identical synchronous generators rated 20 kV/900 MVA. All the generators are equipped with identical speed governors and turbines, exciters and AVRs, and PSSs. The loads in the two areas are such that area 1 is exporting 413MW to area 2. This power network is specifically designed to study low frequency electromechanical oscillations in large interconnected power systems. Despite the small size of this power network, it mimics very closely the behavior of typical systems in actual operation [18]. It is specifically designed to study low frequency electromechanical oscillations in large interconnected power systems. Three electro-mechanical modes of oscillation are present in this system [18]; two inter-plant modes, one in each area, and one inter-area low frequency mode.

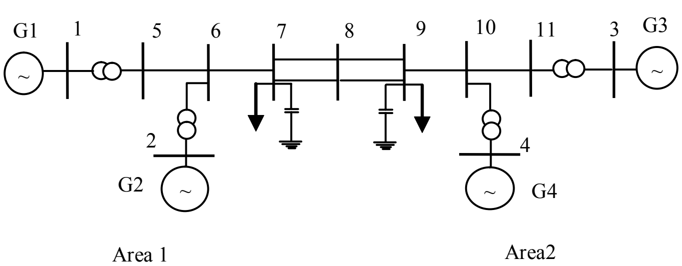

Fig. 1. Two area multi-machine power system.

The PSSs provide additional input signals (V_{pss}) to the voltage regulators/excitation systems to damp out the power oscillations. Some commonly used input signals are rotor speed deviation ($\Delta\omega$), accelerating power and frequency. A typical block diagram of a PSS is shown in Fig. 2. It consists of an amplifier block of gain constant, K, a block having washout time constant, T_W, and two lag-lead compensators with time constants T_1 to T_4. The gain K and the four time constants T_1 to T_4 are the five PSS parameters that need to be optimally selected for each generator to ensure optimal system performance under a wide range of operating conditions and disturbances.

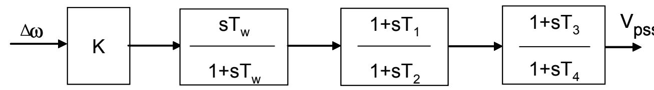

Fig. 2. Block diagram of power system stabilizer

III. PSO and SPPSO Algorithm

Particle swarm optimization is a form of evolutionary computation technique (a search method based on natural systems) developed by Kennedy and Eberhart [20]-[21]. PSO like GA is a population (swarm) based optimization tool. However, unlike in GA, individuals are not eliminated from the population from one generation to the next. One major difference between particle swarm and traditional evolutionary computation methods is that particles' velocities are adjusted, while evolutionary individuals' positions are acted upon; it is as if the "fate" is altered rather than the "state" of the particle swarm individuals [22].

The system initially has a population of random solutions. Each potential solution, called *particle*, is given a random velocity and is flown through the problem space. The particles have memory and each particle keeps track of previous best position and corresponding fitness. The previous best value is called the *pbest* of the particle and represented as p_{id}. Thus, p_{id} is related only to a particular particle *i*. The best value of all the particles' *pbests* in the swarm is called the *gbest* and is represented as p_{gd}. The basic concept of PSO technique lies in accelerating each particle towards its p_{id} and the p_{gd} locations at each time step. The amount of acceleration with respect to both p_{id} and p_{gd} locations is given random weighting.

Fig. 3 illustrates briefly the concept of PSO, where x_i is current position, x_{i+1} is modified position, v_{ini} is initial velocity, v_{mod} is modified velocity, v_{pid} is velocity considering p_{id} and v_{pgd} is velocity considering p_{gd}. The following steps explain the procedure in the standard PSO algorithm.

(i) Initialize a population of particles with random positions and velocities in *d* dimensions of the problem space.

(ii) For each particle, evaluate the desired optimization fitness function.

(iii) Compare every particle's fitness evaluation with its pbest value, p_{id}. If current value is better than p_{id}, then set p_{id} value equal to the current value and the p_{id} location equal to the current location in *d*-dimensional space.

(iv) Compare the updated pbest values with the population's previous gbest value. If any of pbest values is better than p_{gd}, then update p_{gd} and its parameters.

(v) Compute the new velocities and positions of the particles according to (1) and (2) respectively. v_{id} and x_{id} represent the velocity and position of i^{th} particle in d^{th} dimension respectively and, $rand_1$ and $rand_2$ are two uniform random functions.

$$v_{id} = w \times v_{id} + c_1 \times rand_1 \times (p_{id} - x_{id}) + c_2 \times rand_2 \times (p_{gd} - x_{id}) \quad (1)$$

$$x_{id} = v_{id} + x_{id} \quad (2)$$

(vi) Repeat from step (ii) until a specified terminal condition is met, usually a sufficiently good fitness or a maximum number of iterations.

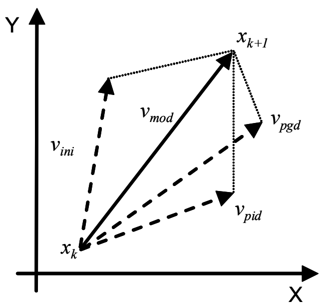

Fig. 3. Movement of a PSO particle in two dimensions from one instant k to another instant $k+1$.

The PSO parameters in (1) are: w is called the inertia weight, which controls the exploration and exploitation of the search space. Local minima are avoided by small local neighborhood, but faster convergence is obtained by larger global neighborhood and in general, global neighborhood is preferred. Synchronous updates are more costly than the asynchronous updates.

The velocity is restricted to a certain dynamic range. v_{max} is the maximum allowable velocity for the particles i.e. in case the velocity of the particle exceeds v_{max} then it is reduced to v_{max}. Thus, resolution and fitness of search depends on v_{max}. If v_{max} is too high, then particles will move beyond good solution and if v_{max} is too low, then particles will be trapped in local minima. c_1 *and* c_2 termed as cognition and social components respectively are the acceleration constants which changes the velocity of a particle towards p_{id} and p_{gd} (generally somewhere between p_{id} and p_{gd}). Velocity determines the tension in the system. A swarm of particles can be used locally or globally in a search space. In the local version of the PSO, the p_{id} is replaced by the l_{id} and the entire procedure is same.

The modification proposed to the standard PSO in this paper are mainly two ideas. The first idea is the use of a small population of particles, few as five or lesser; calling this algorithm the SPPSO. This idea is synonymous to the Micro GA (µGA) algorithm [23]. The second idea is regeneration concept where new particles are randomly created every N iterations to replace all but the gbest particle in the swarm. In the addition to keeping the gbest's particle parameters, the population pbest attributes are also transition from one set of population to the next every N iterations. The concept of PSO with regeneration is incorporated to make the convergence faster like it would with a large population of PSO. Randomize the positions and velocities of the particles helps the particles move out of local minima and find the global optimum.

IV. Optimal Design Of PSS Using SPPSO

This section describes how the SPPSO algorithm is used to determine the parameters of the PSSs on the four generating units in Fig. 1 and the procedure is applicable to any more of PSSs on any power system. For the each PSS, the optimal setting of five parameters is determined by the SPPSO, i.e. 20 parameters in total for the two area system. The objective of the optimization is to maximize damping; this means minimize overshoots and settling times in system oscillations. For this study, the total area of the four generators' speed response curves under transient is minimized by the SPPSO.

The time response performance is used as the fitness function for the SPPSO to improve the transient stability of the power system. The optimization is carried out for different disturbances applied to the system. The following three cases described the optimization process.

A. Case 1

The optimal parameters of the PSSs are determined for a large disturbance such a three phase short circuit applied at a bus. The transient area under the speed response of each generating unit for the short circuit disturbance is given by J_{Gn}^{Sh} in (3) where Gn is the generating unit number.

$$J_{Gn}^{Sh} = \sum_{t=t_0}^{t_2/\Delta t} (\Delta\omega_{Gn}(t)) \times (A \times (t - t_0) \times \Delta t) \quad (3)$$

Where $\Delta\omega_{Gn}$ is the speed deviation of the generator Gn, A is weighting factor, t_0 is the time the fault is cleared, $t_2 - t_0$= transient period time considered for area calculation, Δt is the speed signal sampling period and t = simulation time in seconds.

The SPPSO algorithm minimizes the following cost function.

$$J1 = \sum_{Gn=1}^{m} J_{Gn}^{Sh} \quad (4)$$

where m is the number of PSSs or generators equipped with PSS in the system and is 4 for Fig. 1.

B. Case 2

The optimal parameters of the PSSs are determined for a transmission line outage for a period of time which is not as severe disturbance as a three phase short circuit in Case 1. The transient area under the speed response of each generating unit for a line outage disturbance is given by J_{Gn}^{Ln} in (5).

$$J_{Gn}^{Ln} = \sum_{t=t_0}^{t_2/\Delta t} (\Delta\omega_{Gn}(t)) \times (A \times (t - t_0) \times \Delta t) \quad (5)$$

The SPPSO algorithm minimizes the following cost function.

$$J1 = \sum_{Gn=1}^{m} J_{Gn}^{Ln} \quad (6)$$

C. Case 3

Here the SPPSO optimization is carried out to determine the PSS parameters that give optimal performance for multiple faults and disturbances. The SPPSO algorithm minimizes the following cost function given by (7).

$$J2 = \sum_{fault=1}^{s} \sum_{Gn=1}^{m} J_{Gn}^{fault} \qquad (7)$$

Where s is the number of faults applied.

In this study, two faults are applied; and these are the three phase short circuit and the transmission line outage. The SPPSO minimizes J2 given by (8).

$$J2 = \sum_{Gn=1}^{4} J_{Gn}^{sh} + \sum_{Gn=1}^{4} J_{Gn}^{Ln} \qquad (8)$$

D. *Case 4 (Referred to as Kundur in the Results Figures)*

The PSSs parameters in this case are those directly taken from the Kundur's text book [24]. These parameters are as follows: K = 20.0, T_1 = 0.05 s, T_2 = 0.02 s, T_3 = 3.0 s and T_4 = 5.4 s; and are used to compare the effectiveness of SPPSO determined parameters in Section V.

V. Simulation Results

The entire power system and SPPSO simulation is carried out in the PSCAD/EMTDC/FORTRAN environment. Each particle is a two area power system case in PSCAD. The number of particles in the SPPSO is five, this five PSCAD cases. The regeneration of the particles is carried out every 16 iterations. The multiple run feature in PSCAD is used to carry out a set of SPPSO iterations.

The gbest particle's fitness for Cases 1, 2 and 3 are shown in Fig 4. Case 1 is for a 200 ms three phase short circuit applied at bus 8 in Fig. 1. Case 2 is for a 200 ms transmission line outage between buses 8 and 9. Case 3 is for faults in Cases 1 and 2 applied sequentially. The fitness of the gbest particle is found to decrease over the iterations. The regeneration concept is applied twice resulting in total of 48 SPPSO iterations.

The SPPSO algorithm for Cases 1 and 3 are started with random p_{gd} parameters whereas for Case 2, the SPPSO algorithm is started with p_{gd} parameters from Kundur's PSS settings [24]. Thus the initial cost J1/J2 in Cases 1 and 3 are higher than that in Case 2, as shown in Table I.

TABLE I
COMPARISON OF FITNESS WITH PSS PARAMETERS OBTAINED FROM KUNDUR [24] AND USING THE SPPSO ALGORITHM

Case	Cost with Kundur's parameters [24]	Final cost with the SPPSO after 48 iterations
1	1.11	0.40
2	0.18	0.08
3	1.30	0.59

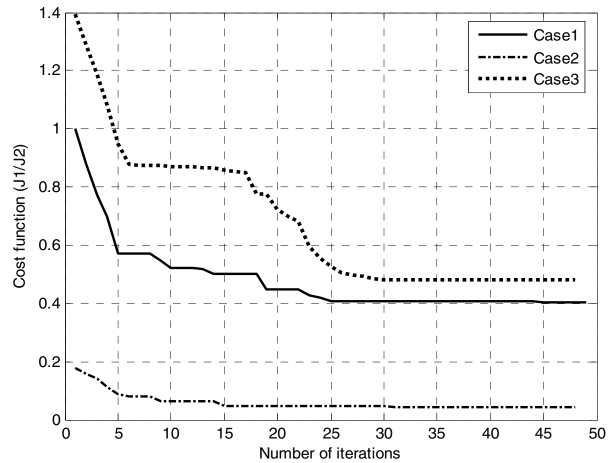

Fig. 4. Fitness of the best particle in the different cases.

The performances of the PSS parameters determined by the SPPSO algorithm in the three cases above (Cases 1 to 3) is compared with the Case 4 parameters for different disturbances below.

A. *Test 1*

A three phase 200 ms short circuit test is applied at bus 8 in Fig. 1. The four PSSs parameters are the gbest (p_{gd}) values obtained from Cases 1, 2, 3 and 4. Figs. 5 and 6 show the speed of generators G1 and G3 for the short circuit fault. It can be seen that the damping with Cases 1 to 3 is better than with Case 4 and the best is Case 1, which is expected, followed by Case 3.

B. *Test 2*

A 200 ms transmission line outage test is carried out between buses 8 and 9 in Fig. 1. The four PSSs parameters are the gbest (p_{gd}) values obtained from Cases 1, 2, 3 and 4. Figs. 7 and 8 show the speed of generators G2 and G4 for the line outage fault. It can be seen that the damping with Cases 1 to 3 is better than with Case 4 and the best is Case 2, which is expected, followed by Case 3.

C. *Test 3*

A 100 ms three phase short circuit fault is applied at bus 8 followed immediately by a 100 ms transmission line outage between buses 8 and 9 in Fig. 1 is carried out. The four PSSs parameters are the gbest (p_{gd}) values obtained from Cases 1, 2, 3 and 4. Figs. 9 and 10 show the speed of generators G1 and G3. It can be seen that the damping with Cases 1 to 3 is better than with Case 4 and the best is Case 3, which is expected.

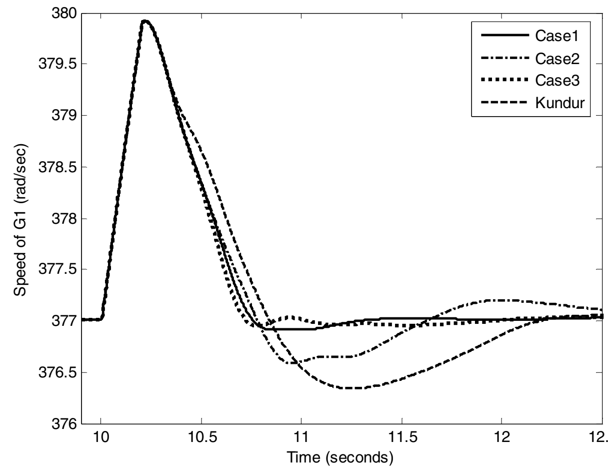

Fig. 5. Speed response of generator G1 for a 3 phase 200 ms short circuit applied at bus 8.

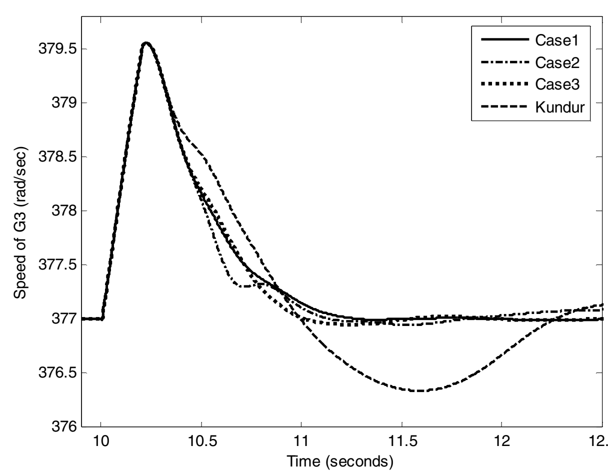

Fig. 6. Speed response of generator G3 for a 3 phase 200 ms short circuit applied at bus 8.

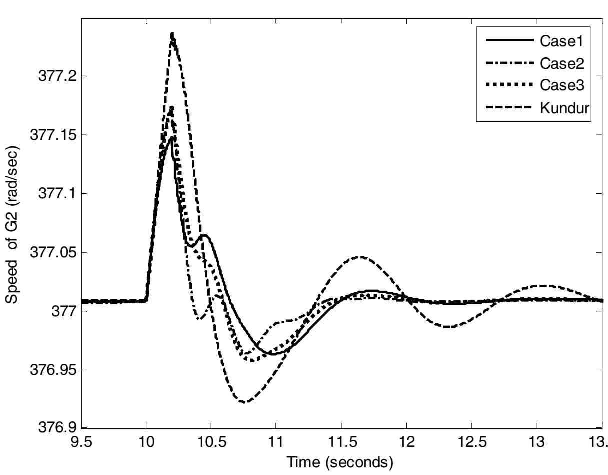

Fig. 7. Speed response of generator G2 for a 200 ms transmission line outage between buses 8 and 9.

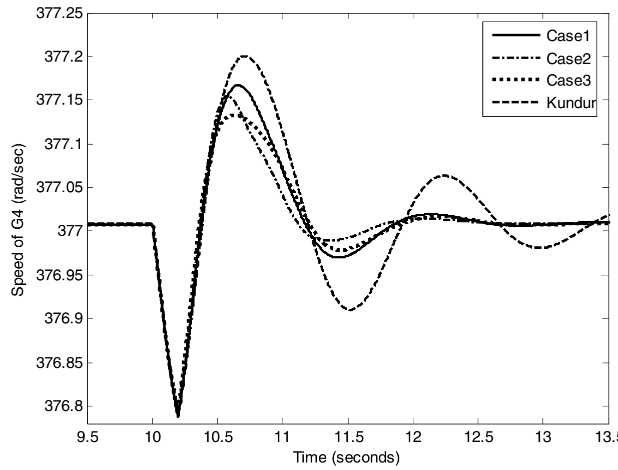

Fig. 8. Speed response of generator G4 for a 200 ms transmission line outage between buses 8 and 9.

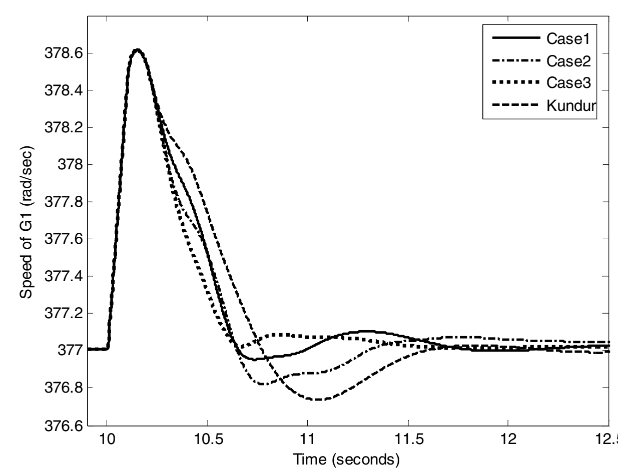

Fig. 9. Speed response of generator G1 for a 3 phase 100 ms short circuit applied at bus 8, followed by immediate 100 ms transmission line outage between buses 8 and 9.

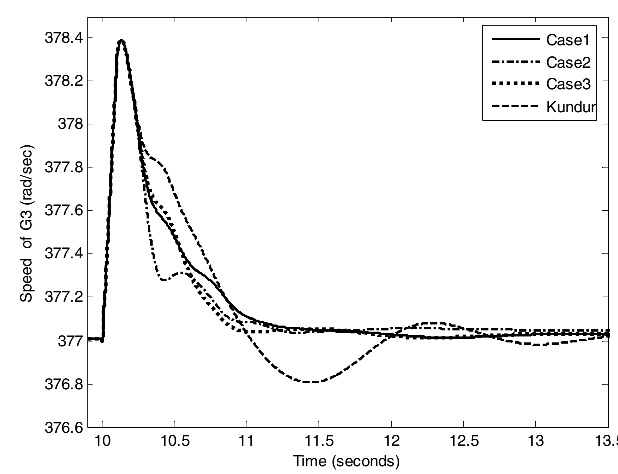

Fig. 10. Speed response of generator G1 for a 3 phase 100 ms short circuit applied at bus 8, followed by immediate 100 ms transmission line outage between buses 8 and 9.

VI. Discussions

Abido [13] reported the application of the standard PSO algorithm for optimal PSS design and presented results for a small and large power system. Papers [15] and [16] using EPSO report on simultaneous tuning of PSS parameters. The frequency response of the system is used as fitness function (eigenvalues) in the search processes here. The major differences between the PSO algorithm in [13]-[16] and the SPPSO algorithm proposed in this paper for optimal PSS design is given in Table II below. The small power system studied in [13] is a three machine power system with two PSS (optimizing only 3 parameters in each PSS). The EPSO approach has been implemented in the two area power system with two PSSs (on G1 and G3 generators). The parameters optimized by the EPSO algorithm in this case are 3 (the two time constants for each of the lag lead compensator is the same). In this paper, the authors have studied the two area power system with four PSSs (optimizing five distinct parameters in each PSS). The dramatic improvement is in the number of fitness evaluations required by the SPPSO algorithm, much lesser compared to the standard PSO and EPSO algorithms even though the number of parameters optimized by SPPSO is at least three times more.

Table II
Comparison between PSO appproach [13], EPSO approach [15], [16] and the SPPSO approach

	PSO Abido [13]	EPSO [15], [16]	SPPSO
No. of particles in the population	50	20	5
No. of parameters optimized per PSS	3	3	5
No. of PSSs	2	2	4
No. of iterations	500	200	48
Fitness evaluations	25000	4000	240

VII. Conclusion

The simultaneous optimal design of multiple power system stabilizers is presented with a modified particle swarm optimization algorithm. The small population based PSO (SPPSO) with the regeneration concept is shown to have fast convergence and requiring far less number of computations and evaluations in comparison to the standard PSO and the EPSO based PSS designs. The SPPSO algorithm is implemented in a commercial power system simulation tool with detailed nonlinear models of the power system elements. The PSSs designed by the SPPSO have better damping than that reported in literature for the two area power system in [24]. The SPPSO algorithm remains to be tried out on large power systems for optimal design of PSS and other damping controllers including their coordinated tuning to avoid adverse affects.

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IX. Biographies

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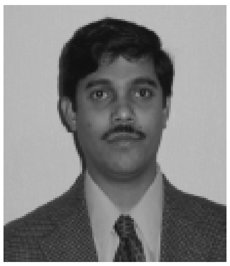

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