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Robust Coordinated Design of Multiple Power System Stabilizers Using Particle Swarm Optimization Technique

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***Abstract*—**Power system stabilizers (PSS) are now routinely used in the industry to damp out power system oscillations. In this paper, particle swarm optimization (PSO) technique is applied to coordinately design multiple power system stabilizers (PSS) in a multi-machine power system. The design problem of the proposed controllers is formulated as an optimization problem and PSO is employed to search for optimal controller parameters. By minimizing the time-domain based objective function, in which the deviation in the oscillatory rotor speed of the generator is involved; stability performance of the system is improved. The non-linear simulation results are presented for various severe disturbances and small disturbance at different locations as well as for various fault clearing sequences to show the effectiveness and robustness of the proposed controller and their ability to provide efficient damping of low frequency oscillations.

***Keywords*—**Low frequency oscillations, Particle swarm optimization, power system stability, power system stabilizer, multi-machine power system.

I. Introduction

LOW frequency oscillations are observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1]. Power system stabilizers (PSS) are now routinely used in the industry to damp out oscillations. An appropriate selection of PSS parameters results in satisfactory performance during system disturbances [2].

The problem of PSS parameter tuning is a complex exercise. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers namely: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory [3]. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal [4]. Most of the proposals on PSS parameter tuning are based on small disturbance analysis that required linearization of the system involved. However, linear methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for tuning the PSS in that the controller tuned to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances. Also, the controller should provide some degree of robustness to the variations loading conditions, and configurations as the machine parameters change with operating conditions. A set of controller parameters which stabilize the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations [5]. In, [6], three-phase non-linear models of power system components have been used to optimally tune the PSS parameters in a single-machine infinite-bus power system. In this paper, the same approach has been extended to a multi-machine power system to coordinately design multiple power system stabilizers.

The evolutionary methods constitute an approach to search for the optimum solutions via some form of directed random search process. A relevant characteristic of the evolutionary methods is that they search for solutions without previous problem knowledge. Recently, Particle Swarm Optimization (PSO) technique appeared as a promising algorithm for handling the optimization problems. PSO is a population based stochastic optimization technique, inspired by social behaviour of bird flocking or fish schooling [7]. PSO shares many similarities with Genetic Algorithm (GA); like initialization of population of random solutions and search for the optimal by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. One of the most promising advantages of PSO over GA is its algorithmic simplicity as it uses a few parameters and easy to implement. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles [8]. In view of the above, PSO is employed in the present work to optimally tune the parameters of the PSS.

In this paper, a comprehensive assessment of the effects of

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PSS-based damping controller has been carried out. The design problem of the proposed controller is transformed into an optimization problem. The design objective is to improve the stability of a multi-machine power system, subjected to severe disturbances. PSO based optimal tuning algorithm is used to optimally tune the parameters of the PSSs. The proposed controllers have been applied and tested on a weakly connected power system under various disturbances at different locations as well as for various fault clearing sequences to show the effectiveness and robustness of the proposed controller and their ability to provide efficient damping of low frequency oscillations.

This paper is organized as follows. In Section II, the power system under study, which is a multi-machine power system is presented. The proposed controller structure and problem formulation is described in Section III. A short overview of PSO is presented in Section IV. Simulation results are provided and discussed in Section V and conclusions are given in Section VI.

II. Power System Under Study

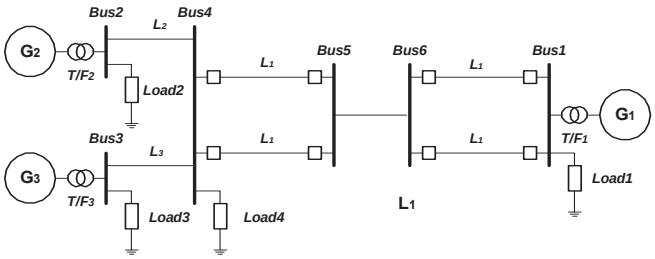


Fig. 1 Multi-machine power system

To coordinately design multiple power system stabilizers, multi-machine system shown in Fig. 1, is considered. It is similar to the power systems used in references [9, 10]. The system consists of three generators divided in to two subsystems and are connected via an intertie. Following a disturbance, the two subsystems swing against each other resulting in instability. To improve the reliability the line is sectionalized. In Fig. 1, G_1, G_2 and G_3 represent the generators; T/F_1 - T/F_3 represent the transformers and L_1, L_2 and L_3 represent the line sections respectively. The generators are equipped with hydraulic turbine & governor (HTG), excitation system and power system stabilizer. All the relevant parameters are given in appendix.

III. The Proposed Approach

A. *Structure of Power System Stabilizer*

The structure of PSS, to modulate the excitation voltage is shown in Fig. 2. The structure consists of a sensor, a gain block with gain K_P, a signal washout block and two-stage phase compensation blocks as shown in Fig. 2. The input signal of the proposed controller is the speed deviation ($\Delta\omega$), and the output is the stabilizing signal V_S which is added to the reference excitation system voltage. The signal washout block serves as a high-pass filter, with the time constant T_W, high enough to allow signals associated with oscillations in input signal to pass unchanged. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range of 1 to 20 seconds [1]. The phase compensation block (time constants T_1, T_2 and T_3, T_4) provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

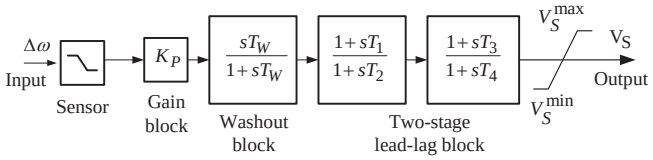


Fig. 2 Structure of power system stabilizer

B. *Problem Formulation*

In case of above lead-lag structured PSS, the sensor and the washout time constants are usually specified. In the present study, a sensor time constant T_{SN} = 15 ms and washout time constant T_W =10s are used. Also, in lead-lag structured controllers the denominator time constants are usually specified [#]. In the present study, T_2, = T_4 = 0.1 s are used. The controller gain K_P and the time constants T_1, and T_3 are to be determined.

It is worth mentioning that the PSSs are designed to minimize the power system oscillations after a large disturbance so as to improve the power system stability. In the present study, an integral time absolute error of the speed signals corresponding to the local and inter-area modes of oscillations is taken as the objective function. The objective function is expressed as:

$$J = \int_{t=0}^{t=t_{sim}} (\sum \Delta\omega_L + \sum \Delta\omega_I) \cdot t \cdot dt \qquad (1)$$

Where, $\Delta\omega_L$ and $\Delta\omega_I$ are the speed deviations of inter-area and local modes of oscillations respectively and t_{sim} is the time range of the simulation. In the present three-machine study, the local mode $\Delta\omega_L$ is (ω_2- ω_3), and the inter-area mode $\Delta\omega_I$ is [(ω_2- ω_1) + (ω_3- ω_1)], where ω_1 , ω_2 and ω_3 are the speed deviations of machines, 1 2 and 3 respectively.

IV. Overview Of Particle Swarm Optimization (PSO)

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

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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 *gbes*t [8].

The features of the searching procedure can be summarized as follows [11, 12]:

- Initial positions of *pbest* and *gbest* are different. However, using the different direction of *pbest* and *gbest*, all agents gradually get close to the global optimum.
- The modified value of the agent position is continuous and the method can be applied to the continuous problem. However, the method can be applied to the discrete problem using grids for XY position and its velocity.
- There are no inconsistency in searching procedures even if continuous and discrete state variables are utilized with continuous axes and grids for XY positions and velocities. Namely, the method can be applied to mixed integer nonlinear optimization problems with continuous and discrete state variables naturally and easily.
- The above concept is explained using only XY axis (2 dimensional space). However, the method can be easily applied to n dimensional problem.

The modified velocity and position of each particle can be calculated using the current velocity and the distance from the $pbest_{j,g}$ to $gbest_g$ as shown in the following formulas [13]:

$$v_{j,g}^{(t+1)} = w * v_{j,g}^{(t)} + c_1 * r_1(\ \ ) * (pbest_{j,g} - x_{j,g}^{(t)}) + c_2 * r_2(\ \ ) * (gbest_g - x_{j,g}^{(t)}) \quad (2)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \quad (3)$$

Where $j = 1,2,...,n$ and $g = 1,2,...,m$

n =number of particles in a group;
m = number of members in a particle;
t = number of iterations (generations);
$v_{j,g}^{(t)}$ =velocity of particle j at iteration t,

with $v_g^{min} \le v_{j,g}^{(t)} \le v_g^{max}$;

w = inertia weight factor;
c_1 , c_2 = cognitive and social acceleration factors respectively;
r_1 , r_2 = random numbers uniformly distributed in the range (0, 1);
$x_{j,g}^{(t)}$ = current position of j at iteration t;
$pbest_j$ = *pbest* of particle j;
gbest = *gbest* of the group.

The j-th particle in the swarm is represented by a g-dimensional vector $x_j = (x_{j,1}, x_{j,2}, \ldots\ldots, x_{j,g})$ and its rate of position change (velocity) is denoted by another g-dimensional vector $v_j = (v_{j,1}, v_{j,2}, \ldots\ldots, v_{j,g})$. The best previous position of the j-th particle is represented as $pbest_j = (pbest_{j,1}, pbest_{j,2}, \ldots\ldots, pbest_{j,g})$. The index of best particle among all of the particles in the group is represented by the $gbest_g$. In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. The velocity update in a PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO algorithm. The parameters c_1 & c_2 determine the relative pull of *pbest* and *gbest* and the parameters r_1 & r_2 help in stochastically varying these pulls. In the above equations, superscripts denote the iteration

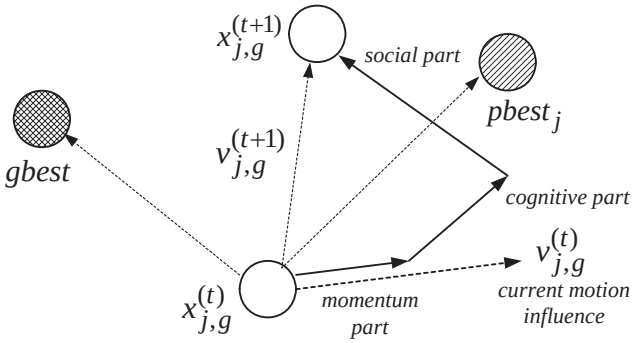


Fig. 3 Description of velocity and position updates in particle swarm optimization technique

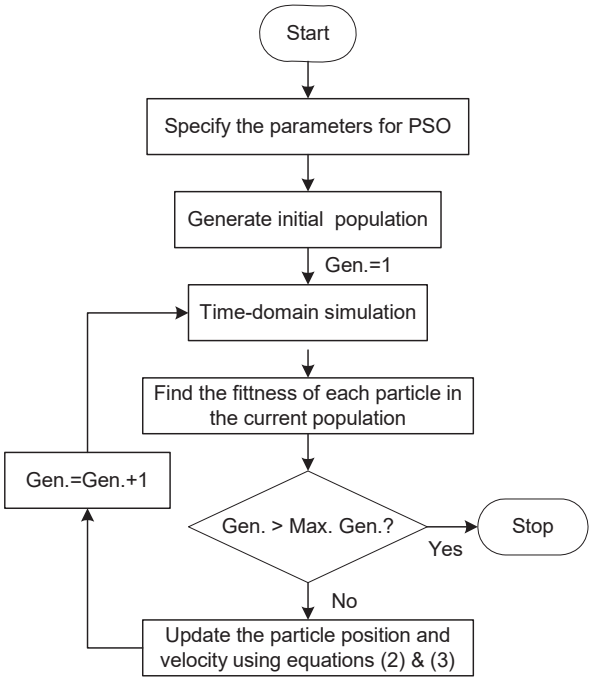


Fig. 4 Flowchart of particle swarm optimization algorithm

number. Fig. 3 shows the velocity and position updates of a particle for a two-dimensional parameter space. The

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computational flow chart of PSO is shown in Fig. 4.Tuning a controller parameter can be viewed as an optimization problem in multi-modal space as many settings of the controller could be yielding good performance. Traditional method of tuning doesn't guarantee optimal parameters and in most cases the tuned parameters needs improvement through trial and error. In PSO based method, the tuning process is associated with an optimality concept through the defined objective function and the time domain simulation. The designer has the freedom to explicitly specify the required performance objectives in terms of time domain bounds on the closed loop responses. Hence the PSO method yields optimal parameters and the method is free from the curse of local optimality.

V. Results And Discussions

The SimPowerSystems (SPS) toolbox is used for all simulations and SSSC-based damping controller design. SPS is a MATLAB-based modern design tool that allows scientists and engineers to rapidly and easily build models to simulate power systems using Simulink environment. The SPS's main library, *powerlib*, contains models of typical power equipment such as machines, governors, excitation systems, transformers, and transmission lines. The library also contains the Powergui block that opens a graphical user interface for the steady-state analysis of electrical circuits. The Load Flow and Machine Initialization option of the Powergui block performs the load flow and the machines initialization [14].

In order to optimally tune the parameters of the PSSs, as well as to assess their performance and robustness the test system depicted in Fig. 1 is considered for analysis. The model of the example power system shown in Fig. 1 is developed using SimPowerSystems blockset. The system consists of three hydraulic generating units divided into two subsystems. The ratings of the generators are taken as 1400 MVA each (G_2 and G_3) in one subsystem and 4200 MVA (G_1) in the other subsystem. The generators are equipped with Hydraulic Turbine and Governor (HTG) and Excitation systems. The HTG represents a nonlinear hydraulic turbine model, a PID governor system, and a servomotor. The excitation system consists of a voltage regulator and DC exciter, without the exciter's saturation function [14]. The generators with output voltages of 13.8KV are connected to an intertie through 3-phase step up transformers. The machines are equipped with Hydraulic Turbine and Governor (HTG) and Excitation system. All the relevant parameters are given in appendix.

A. Application of PSO

For the purpose of optimization of equation (1), routines from PSO toolbox [15] are used. The objective function is evaluated for each individual by simulating the example power system, considering a severe disturbance. For objective function calculation, a three phase short-circuit fault in one of the parallel transmission lines is considered. The fitness function comes from time-domain simulation of power system model. Using each set of controllers' parameters, the time-domain simulation is performed and the fitness value is determined.

While applying PSO, a number of parameters are required to be specified. An appropriate choice of these parameters affects the speed of convergence of the algorithm. Table I shows the specified parameters for the PSO algorithm. Although the chances of PSO giving a local optimal solution are very few, sometimes getting a suboptimal solution is also possible. For different problems, it is possible that the same parameters for PSO do not give the best solution, and so these can be changed according to the situation. One more important point that affects the optimal solution more or less is the range for unknowns. For the very first execution of the programme, a wider solution space can be given and after getting the solution one can shorten the solution space nearer to the values obtained in the previous iteration. Optimization is terminated by the prespecified number of generations. The optimization was performed with the total number of generations set to 100. The convergence rate of objective function *J* for *gbest* with the number of generations is shown in Fig. 5. Table II shows the optimal values of parameters of power system stabilizers obtained by the PSO algorithm.

TABLE I
PARAMETERS USED FOR PSO ALGORITHM

PSO parameters	Value/Type
Swarm size	20
No. of Generations	200
c1, c2	2.0, 2.0
w_{start}, w_{end}	0.9, 0.4

TABLE II
OPTIMIZED PSS PARAMETERS

Parameters	K_P	T_1	T_3
PSS-1	20.3089	0.0564	0.0399
PSS-2	3.2909	0.0429	0.0831
PSS-3	19.8976	0.0965	0.0831

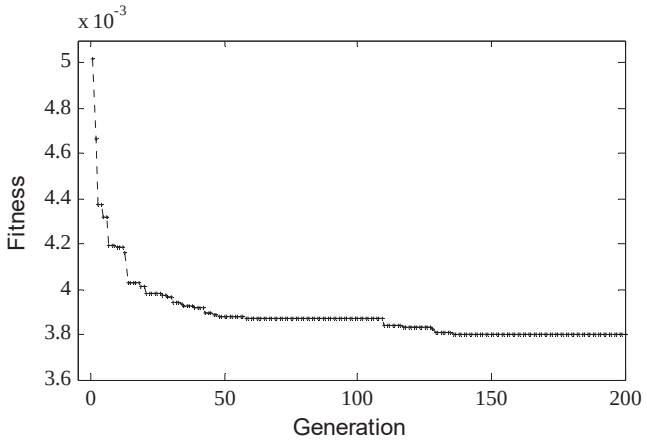


Fig. 5 Convergence of fitness value

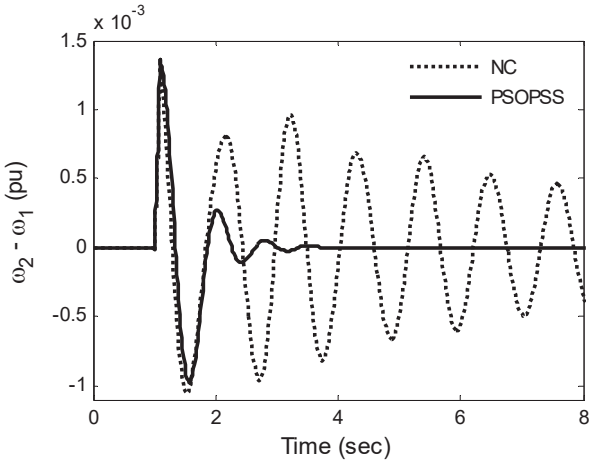


Fig. 6 Inter-area mode of oscillation for 3-phase fault near bus6 cleared by line tripping

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B. Simulation Results

To assess the effectiveness and robustness of the proposed controller, simulation studies are carried out for various fault disturbances and fault clearing sequences. The behavior of the proposed controller under transient conditions is verified by applying various types of disturbances. In all the Figs., the responses without control (no control) are shown with legend NC; the response with response with proposed PSO optimized PSS are shown with legend PSOPSS respectively. The following cases are considered:

Case I: Three-phase fault disturbance

A 3-phase fault is applied at one of the line sections between *Bus1* and *Bus6* near *Bus6* at t = 1 sec. The fault is cleared after 3-cycles by opening of the faulty line. The line is reclosed after 3-cycles and the original system is restored. The system response under this severe disturbance is shown in Figs. 6-10. It is clear from the Figs. that, the system is unstable without control under this disturbance. Stability of the system is maintained and power system oscillations are effectively suppressed with the application of proposed power system stabilizer. From these Figs. it can also be seen that, inter-area modes of oscillations are highly oscillatory in the absence of proposed controllers and the controllers significantly improves the power stability by damping these oscillations. Further, the proposed controllers are also effective in suppressing the local mode of oscillations.

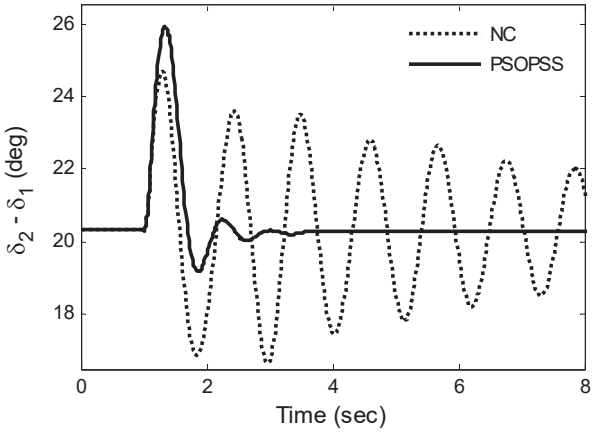


Fig. 7 Inter-area mode of oscillation for 3-phase fault near bus6 cleared by line tripping

To show the robustness of proposed approach another severe disturbance is considered. A self clearing type 3-phase fault is applied near bus-5 and removed after 3-cycles. The system response for the above fault disturbance is shown in Figs. 11-13. It is clear fro these Figs. That the proposed controllers are robust to fault location fault clearing sequence and provide efficient damping to oscillations.

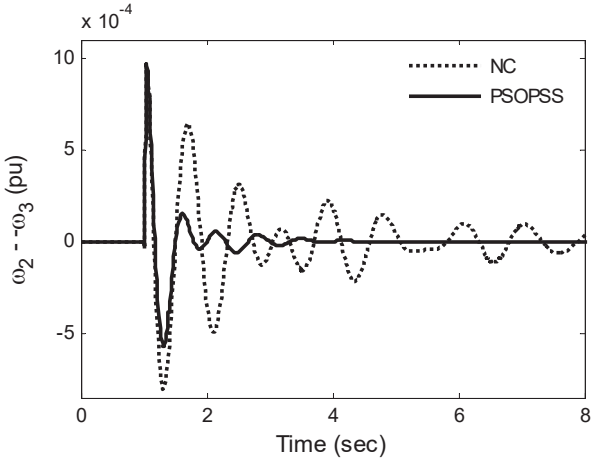


Fig. 8 Local mode of oscillation for 3-phase fault near bus6 cleared by line tripping

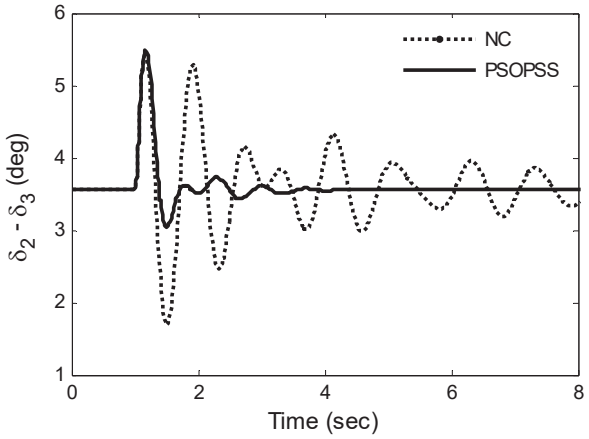


Fig. 9 Local mode of oscillation for 3-phase fault near bus6 cleared by line tripping

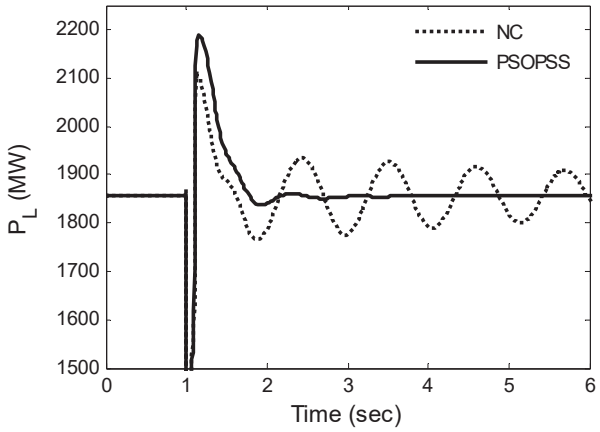


Fig. 10 Tie-line power flow for 3-phase fault near bus6 cleared by line tripping

Case II: Small disturbance

The effectiveness of the proposed controllers under small disturbance is also verified. The load at *Bus4* is disconnected at t = 1 sec for 50 ms (this simulates a small disturbance).

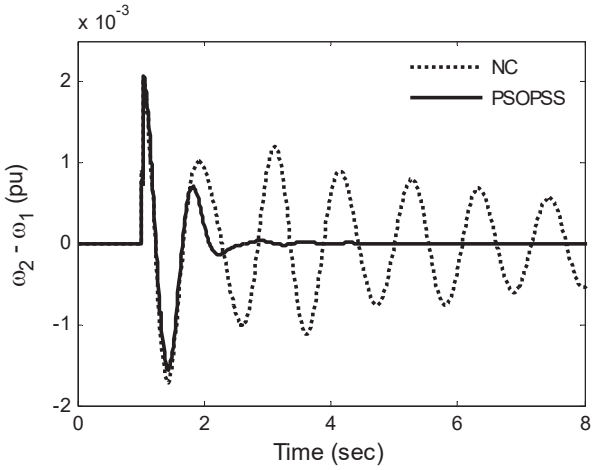


Fig. 11 Inter-area mode of oscillation for self clearing 3-phase fault near bus5

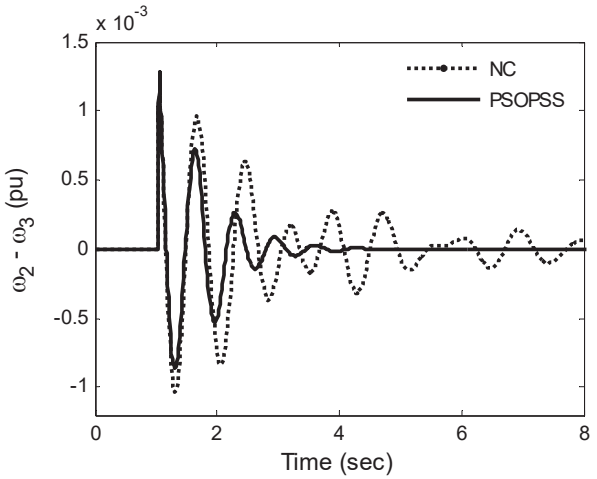


Fig. 12 Local mode of oscillation for self clearing 3-phase fault near bus5

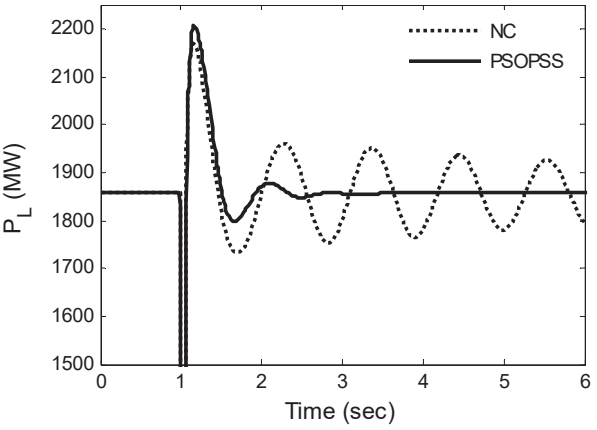


Fig. 13 Tie-line power flow for self clearing 3-phase fault near bus5.

Figs. 14-16 show the variations of the inter-area mode and local mode of oscillations and power flow in the tie-line under assumed small disturbance, from which it is clear that the proposed controllers damps the modal oscillations effectively even for small disturbance.

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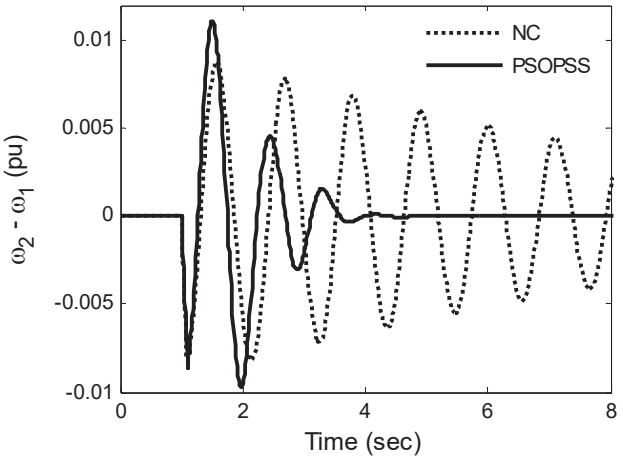


Fig. 14 Inter-area mode of oscillation under small disturbance

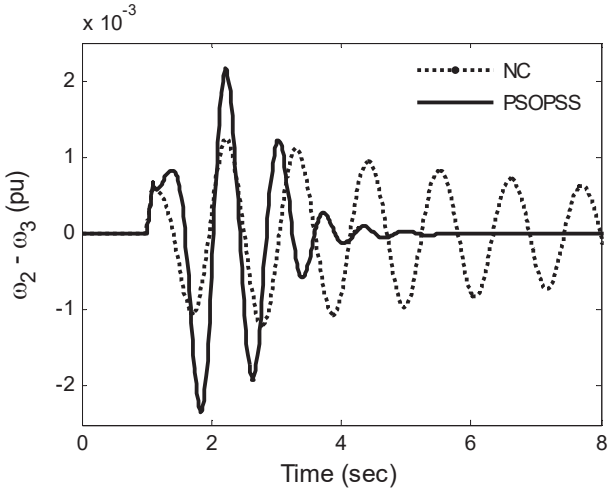


Fig. 15 Local mode of oscillation under small disturbance

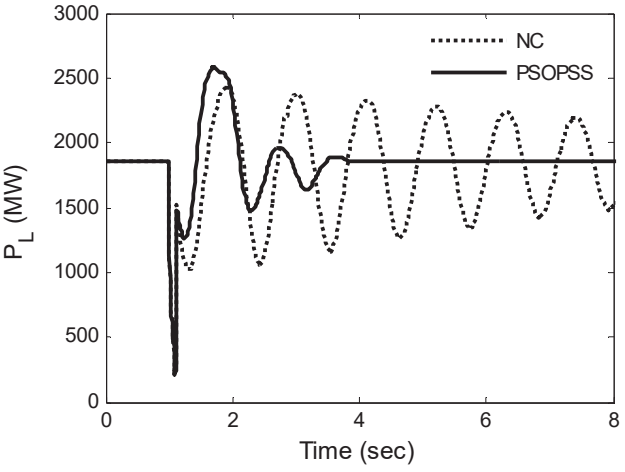


Fig. 16 Tie-line power flow under small disturbance

Case II: Unbalanced fault disturbance

The effectiveness of the proposed controller to unbalanced faults is also examined by applying self clearing type unsymmetrical faults, namely line-to-line-to-ground (L-L- G), and single line-to-ground (L-G), each of 3-cycle duration, at *Bus1*. The local and inter-area modes of oscillations against time are shown in Figs. 17 and 18 respectively. In these Figs., the uncontrolled system response for least severe single line-to-ground fault is also shown with dotted lines (with legend NC L-G). It is clear from the Figs. that the power system oscillations are poorly damped in uncontrolled case even for the least severe fault and the proposed controllers effectively stabilizes the power angle under various unbalanced fault conditions.

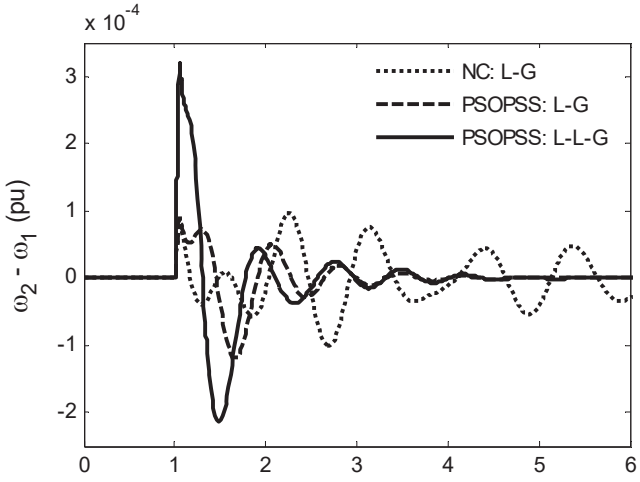


Fig. 17 Inter-area mode of oscillation under unbalanced fault disturbance

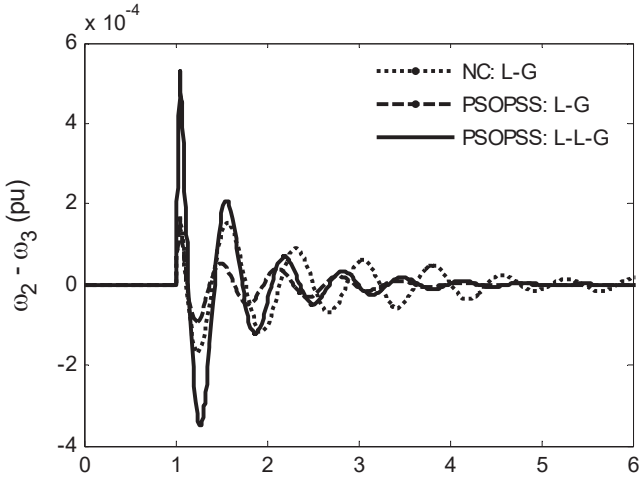


Fig. 18 Local mode of oscillation under unbalanced fault disturbance

VI. Conclusions

This paper presents a systematic procedure for simultaneous tuning of multiple power system stabilizers in a multi-machine system for enhancing power system stability. For the proposed controllers design problem, a parameter-constrained, time-domain based, objective function, is developed to improve the performance of power system subjected to a disturbance. Then, PSO is employed to search for the optimal parameters of the controllers. The controllers are tested on

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example power system subjected to various types of disturbances. The simulation results show that, proposed controllers improves the stability performance of the power system and power system oscillations are effectively damped out under various severe disturbance conditions. Further it is observed that the proposed power system stabilizers are effective in damping the modal oscillations resulting from unbalanced fault and small disturbance conditions. It can be concluded that, the local and inter-area modes of oscillations of power system can be effectively damped for various disturbances by using the proposed controllers.

The example power systems studied in this paper are simple two-area examples. By studying simple systems the basic characteristics of the controllers can be assed and analyzed and conclusions can be drawn to give an insight for larger systems. Further, since all the essential dynamics required for the power system stability studies have been included, and the results have been obtained using three-phase models, general conclusions can be drawn from the results presented in the paper so as to implement the proposed approach in a large realistic power system.

APPENDIX

A complete list of parameters used appears in the default options of SimPowerSystems in the User's Manual [14]. All data are in pu unless specified otherwise.

Generators: S_{B1} = 4200 MVA, S_{B2} = S_{B3} = 2100 MVA, H =3.7 s, V_B = 13.8 kV, f = 60 Hz, R_S = 2.8544 e -3, X_d =1.305, $X_d^{'}$= 0.296, $X_d^{''}$= 0.252, X_q = 0.474, $X_q^{'}$ = 0.243, $X_q^{''}$ = 0.18, T_d = 1.01 s, $T_d^{'}$ = 0.053 s, $T_{qo}^{''}$= 0.1 s.

Loads:Load1=7500MW+1500MVAR, Load2=Load3=25MW, Load4=250MW

Transformers:S_{BT1}=2100MVA, S_{BT2}= S_{BT2}=2100MVA, 13.8/500 kV, f = 60 Hz, R_1 =R_2= 0.002, L_1 = 0, L_2=0.12, $D1/Y_g$ connection, R_m = 500, L_m = 500

Transmission lines: 3-Ph, 60 Hz, Line lengths: $L1$ = 175 km, $L2$=50 km, $L3$=100 km, R_1 = 0.02546 Ω/ km, R_0= 0.3864 Ω/ km, L_1= 0.9337e-3 H/km, L_0 = 4.1264e-3 H/ km, C_1 = 12.74e-9 F/ km, C_0 = 7.751e-9 F/ km

Hydraulic Turbine and Governor: K_a = 3.33, T_a = 0.07, G_{min} = 0.01, G_{max} = 0.97518, V_{gmin} = - 0.1 pu/s, V_{gmax} = 0.1 pu/s, R_p = 0.05, K_p = 1.163, K_i = 0.105, K_d = 0, T_d = 0.01 s,β =0, T_w = 2.67 s

Excitation System: T_{LP} = 0.02 s, K_a =200, T_a = 0.001 s, K_e =1, T_e =0, T_b = 0, T_c =0, K_f = 0.001, T_f = 0.1 s, E_{fmin} = 0, E_{fmax} = 7, K_p = 0

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