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Coordinated Design of SVC Internal and External Controllers with Power System Stabilizer using Particle Swarm Optimization Technique

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Abstract

Power system stability enhancement by simultaneous tuning of a Power System Stabilizer (PSS) and a Static Var Compensator (SVC)-based controller is thoroughly investigated in this paper. The coordination among the proposed damping stabilizers and the SVC internal voltage regulators has also been taken into consideration. The design problem is formulated as an optimization problem with a time-domain simulation-based objective function and Particle Swarm Optimization (PSO) technique is employed to search for optimal controller parameters. The proposed stabilizers are tested on a weakly connected power system with different disturbances and loading conditions. The nonlinear simulation results are presented to show the effectiveness and robustness of the proposed control schemes over a wide range of loading conditions and disturbances. Further, the proposed design approach is found to be robust and improves stability effectively even under small disturbance and unbalanced fault conditions.

Keywords: Static var compensator, power system stabilizer, power system stability, particle swarm optimization.

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 power system oscillations [2-4]. However, during some operating conditions, this device may not produce adequate damping, and other effective alternatives are needed in addition to PSS. With the advent of Flexible AC Transmission System (FACTS) technology, shunt FACTS devices play an important role in controlling the reactive power flow in the power network and hence the system voltage fluctuations and stability [5-7]. Static Var Compensator (SVC) is member of FACTS family that is connected in shunt with the system [8, 9]. Even though the primary purpose of SVC is to support bus voltage by injecting (or absorbing) reactive power, it is also capable of improving the power system stability [10]. When a SVC is present in a power system to support the bus voltage, a supplementary damping controller could be designed to modulate the SVC bus voltage in order to improve damping of system oscillations [11, 12].

The interaction among PSS and SVC-based controller may enhance or degrade the damping of certain modes of rotor's oscillating modes. To improve overall system performance, many researches were made on the coordination between PSSs and FACTS power oscillation damping controllers [13-15]. Also, the controllers 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 stabilise 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 [16, 17].

The problem of PSS and FACTS controllers parameter tuning is a complex exercise as uncoordinated local control of FACTS devices and PSS may cause destabilising interactions. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers namely: the pole placement technique [18], phase compensation/root locus technique (Larsen and Swann [19], residue compensation [20], and also the modern control theory. Unfortunately, the conventional techniques are time consuming 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. 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 evolutionary technique for handling the optimization problems [21]. PSO has been popular in academia and the industry mainly because of its intuitiveness, ease of implementation, and the ability to effectively solve highly nonlinear, mixed integer optimisation problems that are typical of complex engineering systems. In view of the above, this paper proposes to use PSO technique for the simultaneous tuning of PSS and SVC-based controller. To improve the interactions between PSS and SVC-based controller, PSO based optimal tuning approach is employed to simultaneous and coordinately design the proposed damping controllers.

The reminder of the paper is organized in five major sections. An overview of SVC and its control system is presented in Section II. The structures of the PSS and

SVC-based controller and the objective function are described in Section III. In Section IV a brief introduction about PSO is provided. Results are given and discussed in Section V.

Overview of SVC and its control system

To SVC is basically a shunt connected Static Var Generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables. Fig. 1 shows the single-line diagram of a SVC and a simplified block diagram of its control system.

The control system consists of [22]

- A measurement system measuring the positive-sequence voltage to be controlled.
- A voltage regulator that uses the voltage error (difference between the measured voltage V_m and the reference voltage (V_{ref}) to determine the SVC susceptance needed to keep the system voltage constant.
- A distribution unit that determines the Thyristor Switched Capacitors (TSC) and eventually Thyristor Switched Reactors (TSR) that must be switched in and out, and computes the firing angle α of TCRs.
- A synchronizing system using a phase-locked loop (PLL) synchronized on the secondary voltages and a pulse generator that send appropriate pulses to the thyristors.

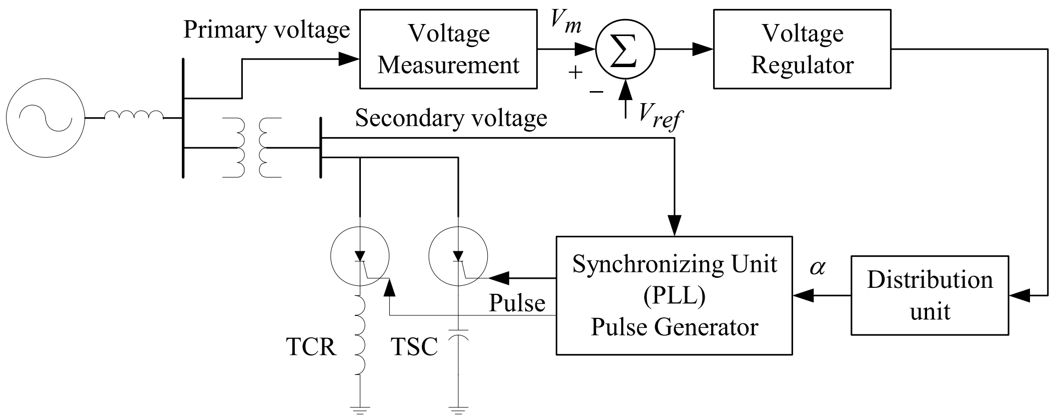

Figure 1: Single-line diagram of a Static Var Compensator and its control system.

Proposed approach

Structure of the PSS and SVC-based controllers

The commonly used lead–lag structure is chosen in this study as SVC-based controller as shown in Fig. 2. Fig. 3 shows the structure of the power system stabilizer used in the present study. The input signal to both the controller is the speed deviation $\Delta\omega$. Each structure consists of: a gain block; a signal washout block and two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter which allows signals associated with oscillations in input signal to pass unchanged. Without it steady changes in input would modify the output.

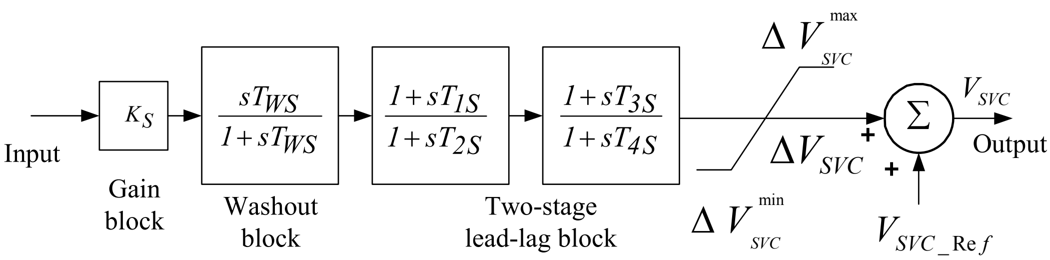

Figure 2: Structure of the SVC-based controller.

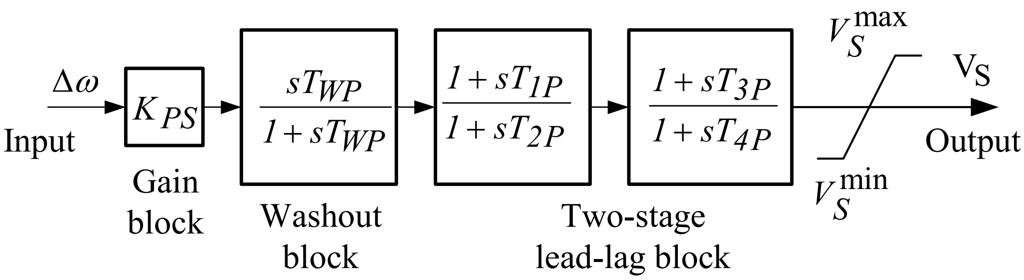

Figure 3: Structure of the power system stabilizer.

Problem formulation

In lead-lag structured controllers from the viewpoint of the washout function the value of washout time constant is not critical and may be in the range 1 to 20 seconds [1] and generally the washout time constant is prespecified. In the present study, washout time constant of $T_{WS} = T_{WP} = 10$ s is used. The controller gains K_S and K_{PS} ; and the time constants T_{1S}, T_{2S}, T_{3S} and T_{4S} , T_{1P}, T_{2P}, T_{3P} and T_{4P} are to be determined.

For the internal voltage regulator of the SVC, the PI structure is used. The parameters of the PI controller are: KP_{VR}, and KI_{VR}. These controllers are designed in coordination with the SVC-based controller and PSS.

It is worth mentioning that the proposed controllers 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 deviations is taken as the objective function.

The objective function is expressed as:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| \cdot t \cdot dt \tag{1}$$

Where, $\Delta\omega$ is the speed deviation and t_{sim} is the time range of the simulation.

For objective function calculation, the time-domain simulation of the power system model is carried out for the simulation period. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots.

Particle swarm optimization

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 *gbes*t [23, 24].

The features of the searching procedure can be summarized as follows:

- 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. 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 [25]:

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

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

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 number. Fig. 4 shows the velocity and position updates of a particle for a two-dimensional parameter space. The computational flow chart of PSO is shown in Fig. 5.

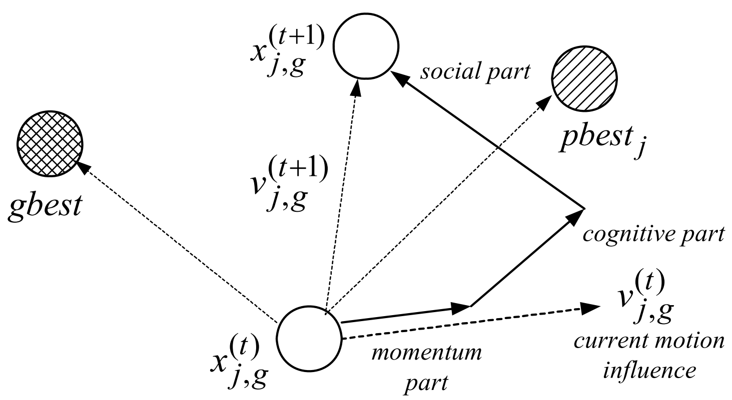

Figure 4: Description of velocity and position updates in particle swarm optimization technique.

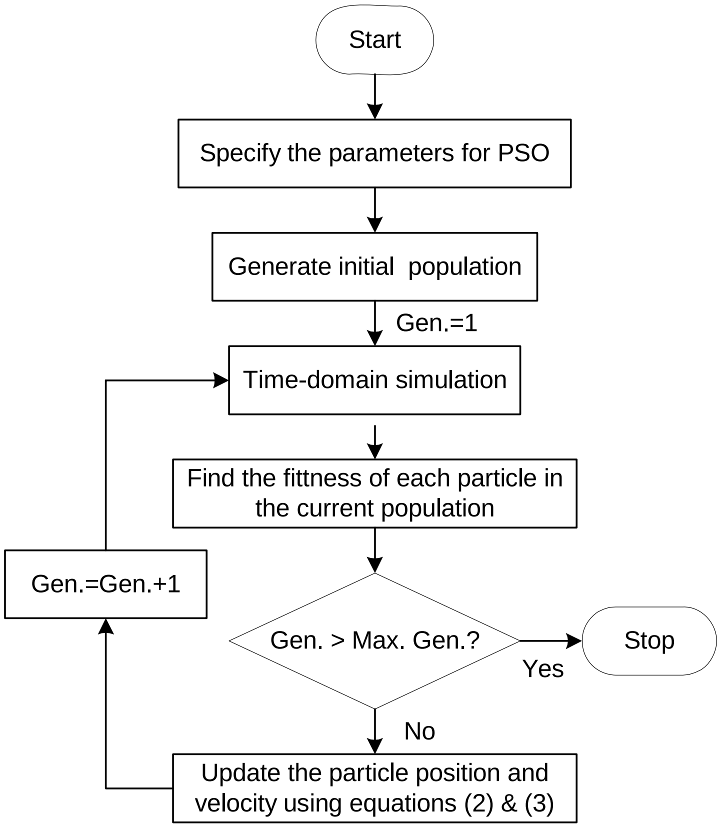

Figure 5: Flowchart of particle swarm optimization algorithm.

Results and discussions

The SimPowerSystems (SPS) toolbox is used for all simulations and PSS 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 [22].

In power system stability study, the fast oscillation modes In order to optimally tune the parameters of the proposed controllers, as well as to assess their performance and robustness under wide range of operating conditions with various fault disturbances and fault clearing sequences, the model of the example power system shown in Fig. 5, is developed using SimPowerSystems blockset. The system consists of a of 2100 MVA, 13.8 kV, 60Hz hydraulic generating unit, connected to a 300 km long double-circuit transmission line through a 3-phase 13.8/500 kV step-up transformer and a 100 MVA SSSC. The relevant parameters are given in appendix.

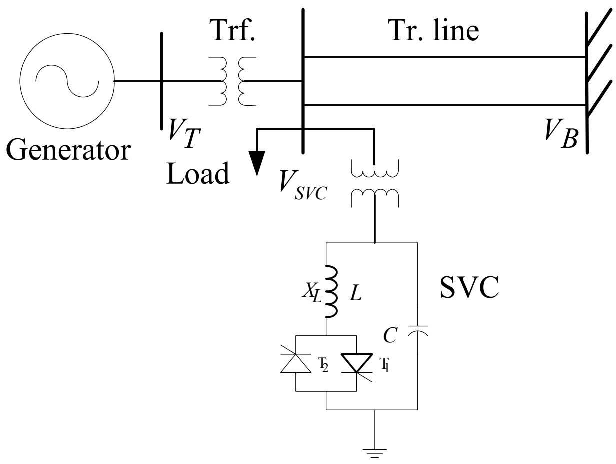

Figure 6: Single-machine infinite-bus power system with SVC.

Application of PSO

For In order to coordinately design PSS and SVC-based controller, as well as to assess their performance, a single-machine infinite- bus power system with SVC depicted in Fig. 5 is considered at the first instance. The model of example power system shown in Fig. 5 is developed using SimPowerSystems blockset. The system consists of a of 500 MVA, 13.8 kV, 60 Hz hydraulic generating unit, connected to an infinite bus through a 300 km long double-circuit transmission, 3-phase 13.8/500 kV step-up transformer and a 100 MVA STATCOM. The generator is equipped with hydraulic turbine and governor (HTG), excitation system and a power system stabilizer. 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. All the relevant parameters are given in Appendix. The objective function is evaluated for each individual by simulating the example power system, considering a severe disturbance. For objective function calculation, a 3-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.

Simulations were conducted on a Pentium 4, 3 GHz, 504 MB RAM computer, in the MATLAB 7.0.1 environment and the optimisation process is repeated 20 times. As three-phase non-linear models of power system components are used in the present study. The best final solutions obtained in the 20 runs are given below.

For SVC-based controller:

K_S = 179.8219, T_{1S} = 0.1036, T_{2S} = 0.1576, T_{3S} = 0.2679, T_{4S} = 0.3224 s

For SVC voltage regulator:

KP_{VR}, =5.8975, KI_{VR} =766.7665,

For power system stabilizer:

K_{PS} =10.2799, T_{1P} = 0.1818, T_{2P} = 0.2982, T_{3P} = 0.2894, T_{4P}=0.1142 s

Table I: Parameters Used for PSO Algorithm.

PSO parameters	Value/Type
Swarm size	20
No. of Generations	100
c1, c2	2.0, 2.0
w_{start}, w_{end}	0.9, 0.4

Table II: Loading Conditions Considered.

Loading Conditions	P (pu)	δ_0 (deg.)
Nominal	0.8	33.8^0
Light	0.5	21.5^0
Heavy	1.0	41.5^0

Simulation results

To assess the effectiveness and robustness of the proposed controller various loading conditions given in Table II are considered. 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 under different operating conditions. In all the Figs., the response without control is shown with dotted line (with legend WC); the response with conventionally designed power system stabilizer [22] with dashed lines (with legend PSS) and the response with proposed PSO optimized PSS and SVC-based controllers are shown with solid line (with legend Coordinated) respectively.

Case I: Nominal loading, 3-phase fault disturbance

The behavior of the proposed controllers is verified at nominal loading condition under severe disturbance. A 5-cycle, 3-phase fault is applied at the infinite-bus terminal at t = 1.0 sec. The original system is restored upon the fault clearance. The system response under this severe disturbance is shown in Figs. 7-10. It can be observed from Figs.7-10 that with out control the system is highly oscillatory for the above contingency. It is also clear that, coordinately designed PSS and SVC-based controller outperform the CPSS and power system oscillations are quickly damped out.

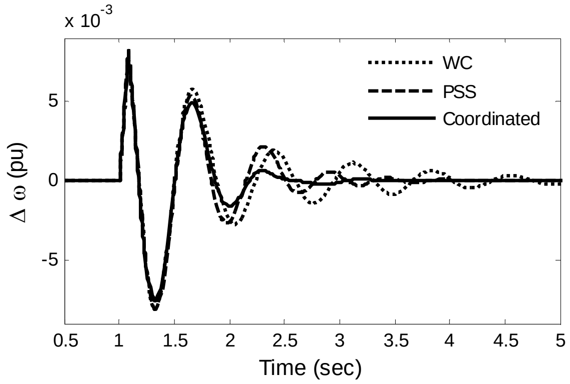

Figure 7: Speed deviation response for Case-I.

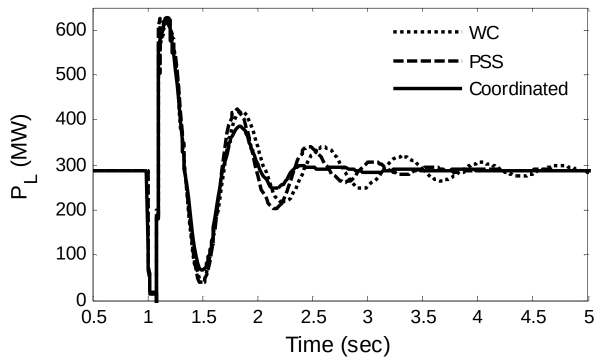

Figure 8: Tie-line power flow response for Case-I.

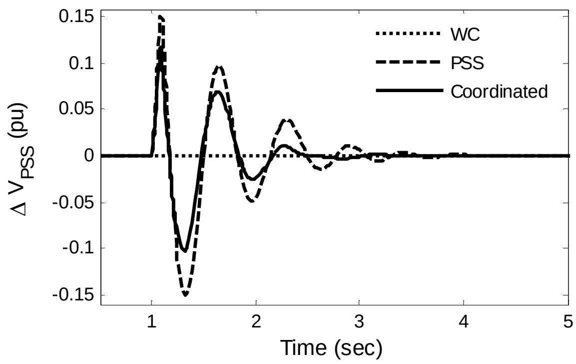

Figure 9: Stabilising signal of PSS for Case-I.

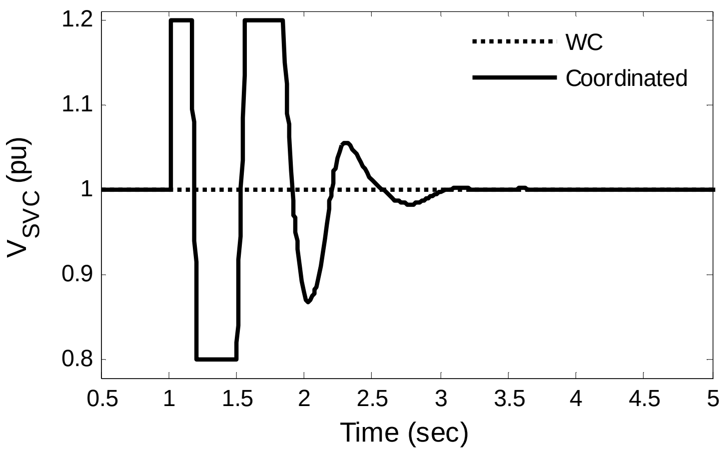

Figure 10: SVC reference voltage signal for Case-I.

Case II: Light loading, 3-phase fault and line outage disturbance

To test the robustness of the controller to operating condition and fault clearing sequence, the generator loading is changed to light loading condition and a 5-cycle, 3-phase fault is applied at the middle of the one transmission line at t = 1.0 sec. The fault is cleared by opening of the faulty line and the line is reclosed after 5-cycles. The system responses for the above contingency are shown in Figs. 11-13. It can be seen from Figs. 11-13 that without control, the system is poorly damped for the above contingency. It can also be seen from Figs. 11-13 that with proposed design approach, power system oscillations are quickly damped out and also the response is superior to that with CPSS.

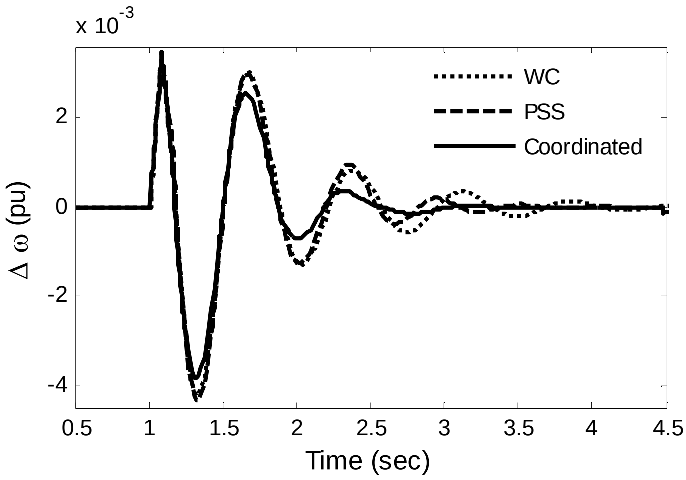

Figure 11: Speed deviation response for Case-II.

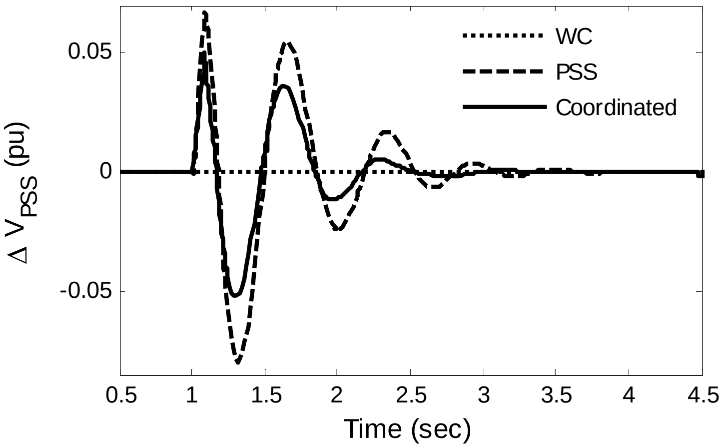

Figure 12: Stabilising signal of PSS for Case-II.

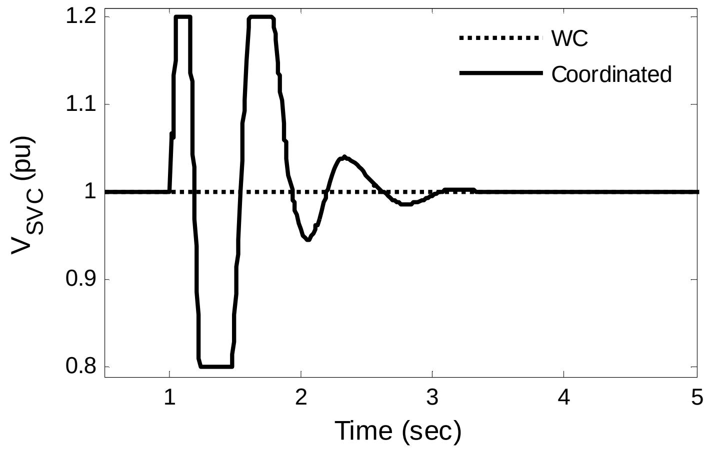

Figure 13: SVC reference voltage signal for Case-II.

Case III: Heavy loading and line outage disturbance

To test the robustness of the controller to operating condition and type of disturbance, the generator loading is changed to heavy loading condition and a line outage disturbance is simulated. Both the transmission lines are tripped at t = 1.0 sec and reclosed after 5-cycles. The original system is restored after the line reclosure. The system response for the above severe disturbance is shown in Figs. 14-16. It can be clearly seen from Figs. 14-16 that for the given operating condition and contingency, the system is highly oscillatory without control. Stability of the system is maintained and power system oscillations are effectively damped out with the application of conventional PSS. It can also be seen from Figs. 14-16 that with proposed design approach, power system oscillations are quickly damped out and also the response is superior to that with CPSS.

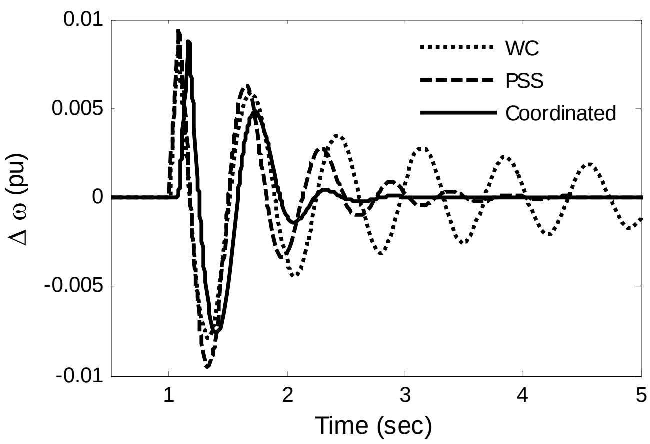

Figure 14: Speed deviation response for Case-III.

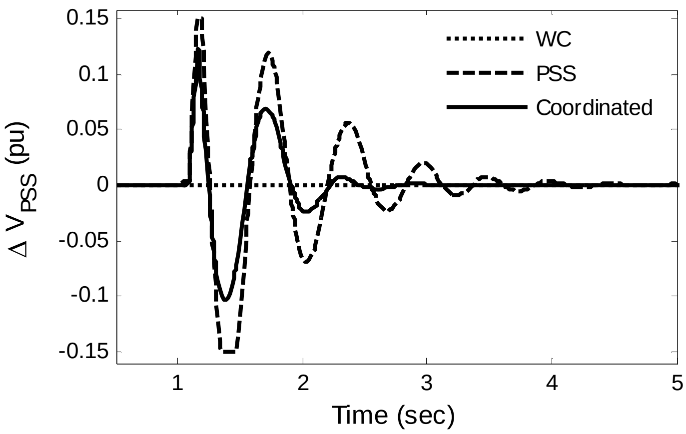

Figure 15: Stabilising signal of PSS for Case-III.

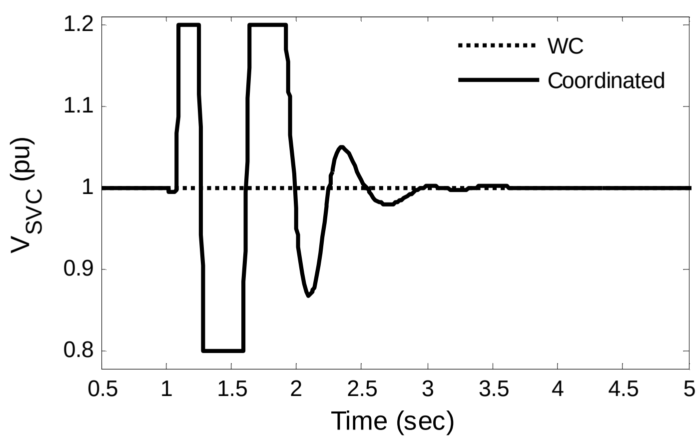

Figure 16: SVC reference voltage signal for Case-III.

Case IV: Small disturbance

The effectiveness of the proposed controllers is also tested under small disturbance. The load at generator bus is disconnected at t=1.0 s for 100 ms at nominal loading condition. The system speed deviation response for the above contingency is shown in Fig. 17. It can be seen from Fig. 17 that the proposed controllers which are designed under large disturbance work effectively under small disturbance condition also.

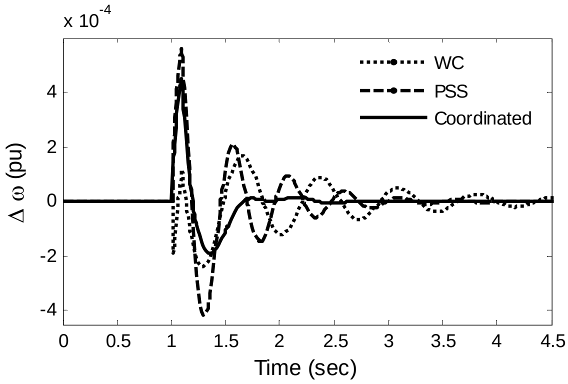

Figure 17: Speed deviation response for Case-IV.

Case V: Unbalanced fault disturbance

The effectiveness of the proposed controller on unbalanced faults is also examined by applying self-clearing type unsymmetrical faults, namely L-L-G and L-G faults, each of 5-cycle duration at the infinite-bus terminal at t = 1.0 sec. The system speed deviation responses for the above contingencies are shown in Fig. 16. The uncontrolled system response for the least-severe single L-G fault is also shown in Fig. 18 with dotted line. It is clear from Fig. 18 that the power-system oscillations are poorly damped in the uncontrolled case, even for the least-severe L-G fault, and the proposed damping controllers effectively stabilizes the power system oscillations under various unbalanced fault conditions.

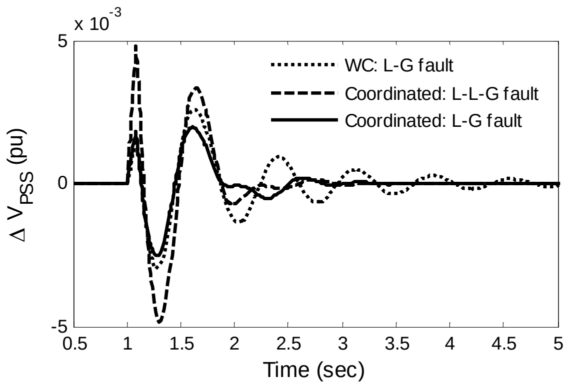

Figure 18: Speed deviation response for Case-V.

Conclusion

In this study, particle swarm optimization technique is employed for the simultaneous tuning of a PSS and a SVC-based controller. The coordination among the proposed damping stabilizers and the SVC internal voltage regulator has also been taken into consideration. For the design problem, a non-liner, time-domain simulation-based objective function, to increase the power system stability is used and particle swarm optimization technique is employed to optimally tune the parameters of the proposed controllers. The effectiveness of the proposed coordinated design approach in improving the power system stability is demonstrated for variation in loading conditions and under different disturbances and compared with a conventional power system stabilizer. It is observed that the proposed controllers generate suitable variation of the control signals and provide efficient damping to power system oscillations following any disturbance. Further, the proposed design approach is robust and improves stability effectively even under small disturbance and unbalanced fault conditions.

Appendix

A complete list of parameters used appears in the default options of SimPowerSystems in the User's Manual [22]. All data are in pu unless specified otherwise.

Generator: S_B = 500 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., P_e=0.8 pu, δ_0=48.48^0

Load at Bus2: 100MW

Transformer: 500 MVA, 13.8/500 kV, 60 Hz, R_1 =R_2= 0.002, L_1 = 0, L_2=0.12, D_1/Y_g connection, R_m = 500, L_m = 500

Transmission line: 3-Ph, 60 Hz, Length = 300 km each, 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, Ta = 0.001 s, K_e =1, T_e =0, T_b = 0, Tc =0, K_f = 0.001, Tf = 0.1 s, E_{fmin} = 0, E_{fmax} = 7, K_p = 0

Conventional power system stabilizer: T_S=15 ms, T_W= 10 s, T_1=0.05 s, T_2=0.02 s T_3=3 s, T_4=5.4 s, Output limits of V_S = ± 0.15

Static Var Compensator: 500KV, ±100 MVAR, Droop=0.03

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