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Optimal Design of SVC Damping Controllers with Wide Area Measurements Using Small Population based PSO

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Abstract—**Static Var Compensator (SVC) are employed for providing better voltage regulation and transient stability especially for increased power transfer through the transmission lines. In this paper, two SVC damping controllers with single and dual inputs respectively are designed based on wide area measurements of generator speed deviations. A Small Population based Particle Swarm Optimization algorithm (SPPSO) is applied to determine the optimal parameters of the damping controllers for small and large disturbances. Simulation results are provided to show that the effectiveness of the optimal damping controllers on the Kundur's two-area benchmark power system. Results show the dual input controller further improves the damping provided by the single input controller.**

I. INTRODUCTION

Large power systems like the North American power grid has many interconnections and bulk power transmissions over long distances. Due to this there are low frequency inter-area oscillations which make system vulnerable to cascading failures. Devices like Power System Stabilizers (PSSs) and Flexible AC Transmission Systems (FACTS) devices have been used for damping local and inter-area oscillations.

Static Var Compensator (SVC), a shunt FACTS device has been widely used in power systems. They can increase the transmittable power by regulating the voltage and damping the power oscillations [1]. While the main purpose of SVC is for voltage control, a proper supplementary control signal to SVC voltage control loop can provide damping to inter-area oscillations [2]. In literature, SVC damping controller has been designed using locally measured transmission line-current magnitude [3] and locally measured active power [4], [5] and generator angular speed [6]-[8]. But no considerable effort has been made to use wide area signals as the inputs. The major advantages to have wide area signal inputs are the following:

- Information about the system-wide dynamics.
- The possibility of a coordinated control for system wide disturbance.
- Transmission capacity can be increased by on-line monitoring of the system stability limits and capabilities.

Almost all of the above referred methods for designing SVC damping controller are based on a nominal operating point that is selected from a wide range of operating conditions. However, the high degree of nonlinearity of power systems and presence of uncertainty, such as changes of operating conditions or unknown system parameters/models, makes it very difficult to achieve an optimal controller design using only one single nominal operating point. Controllers designed for the optimal performance at some operating conditions do not guarantee the system stability and performance under other operating conditions.

PSO has been shown to have great potential for single and multi-objective optimization [9]. PSO has flexible and well balanced mechanism to carry out local and global search. A Small Population based Particle Swarm Optimization (SPPSO) algorithm has been used in this paper as a technique to optimize the parameters of SVC damping controllers in a two area power system. The effectiveness of the SPPSO algorithm to optimize parameters of PSSs has been reported in [10]. It is a population based algorithm which does not require individuals/particles to reproduce at every generation but keeps evolving better solutions. The implementation of SPPSO on simulation tools that allow detailed representation of the power system dynamics such as the PSCAD/EMTDC software is possible [11]. Further, two SVC damping controllers are developed, with single and dual wide area measurements based generator speed deviations respectively as controller inputs.

The paper is organized as follows: Section II describes SVC damping controllers; Section III describes the PSO and SPPSO algorithm. Section IV describes how SPPSO cost functions are formulated for determining the optimal parameters of the SVC damping controllers; Section V presents simulation results with and without the SVC damping controllers. Finally, conclusions are given in Section VI.

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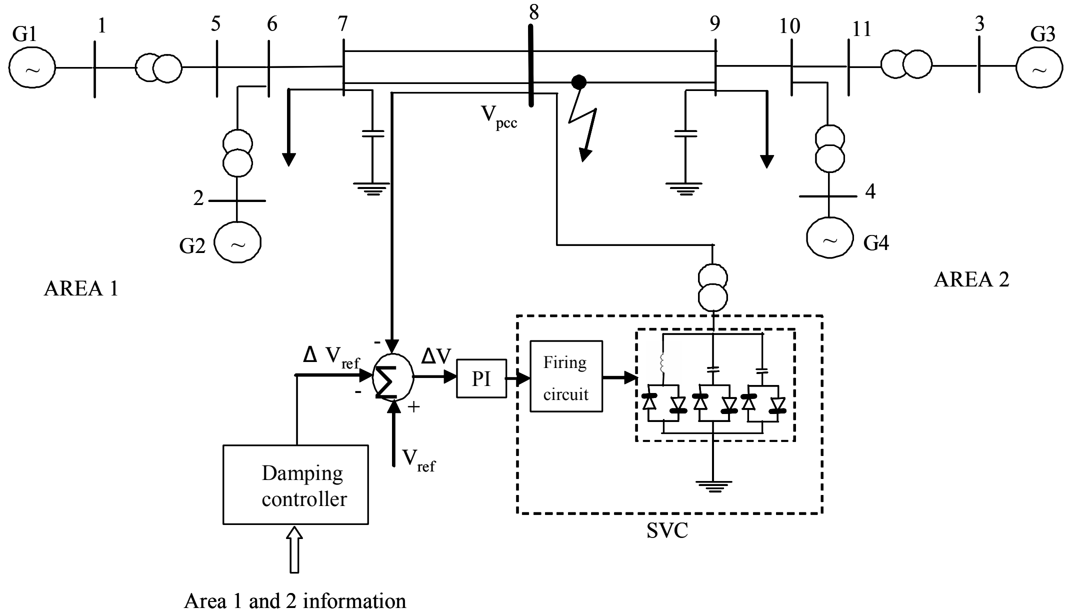

Fig. 1. Two area multi-machine power system with a SVC installed at bus 8.

II. SVC DAMPING CONTROLLERS

For the study in this paper, the two area multi-machine power system [12], [13] is simulated in the PSCAD/EMTDC environment [11]. 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 about 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 [12]. Three electro-mechanical modes of oscillation are present in this system [12]; two inter-plant modes, one in each area, and one inter-area low frequency mode.

Fig. 2 shows the block diagram of the SVC damping controller structure used in this study, referred to as *Controller 1*. A similar structure has been proposed in [14] as an external controller for a series capacitive reactance compensator. The controller proposed in this paper consists of a filter and a damping controller. The input to this controller is the speed deviation of generator G3 ($\Delta\omega_3$). The time constant (T) and the gain (K) of Controller 1 are important in influencing the stability of the system. The SPPSO algorithm is applied to determine the optimal values of these two parameters.

Fig. 3 shows the block diagram of the second SVC damping controller referred to as *Controller 2* in this paper, where the inputs are the speed deviations of generators G1 and G3, one signal from each area of the power system. The SPPSO algorithm is applied to determine the optimal values of the four parameters (K_1, K_2, T_1 and T_2).

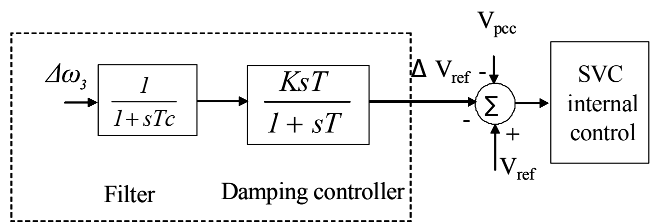

Fig. 2. Block diagram of SVC damping controller –Controller 1.

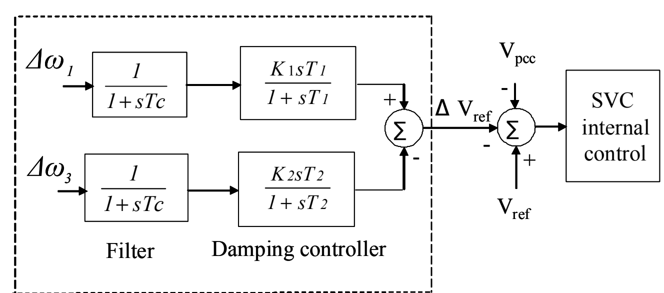

Fig. 3. Block diagram of SVC damping controller- Controller 2.

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 [15]-[16]. PSO like any other evolutionary algorithm 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 [17].

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. 4 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 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.

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

(iv) 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.

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

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

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

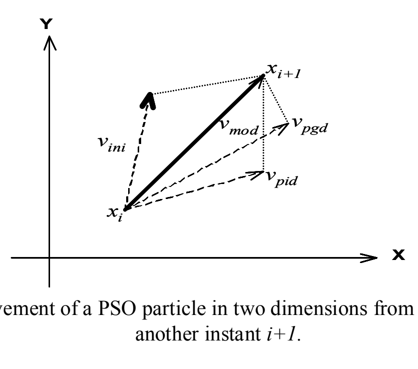

Fig. 4 . Movement of a PSO particle in two dimensions from one instant *i to* another instant *i+1*.

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.

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 Small Population based PSO (SPPSO). This idea is synonymous to the Micro-GA (µGA) algorithm [18]. The second idea is the 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's pbest attributes are also transitioned 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. Randomizing the positions and velocities of the particles aids the particles to move out of local minima and find the global optimum.

IV. Optimal Design Of SVC Damping Controller Using SPPSO

The task of SVC damping controllers is damp out oscillations during small and large disturbances in the power network. In other words, the objectives are to minimizing the overshoots and reduce the settling time of generator speed oscillations under different faults. The cost function *J* to be optimized by the SPPSO is therefore formulated for two faults as follows:

$$J = A_1 J_{fault1} + A_2 J_{fault2} \quad (3)$$

Fault 1 is a 200ms three phase short circuit fault. The three phase short circuit is applied between bus 8 and 9, 25 km away from bus 8. Fault 2 is a 200ms transmission line outage applied between buses 5 and 6.

In (3), A_1 and A_2 are the weighing factors;

$$J_{fault1} = \sum_{i=1}^{n} J_{1i} \quad (4)$$

$$J_{1i} = \sum_{t_1}^{t_2} (\Delta\omega_i(t)) \times (100 \times (t - t_0) \times 0.00005) \quad (5)$$

n is Number of areas in the system.
J_i is the cost as a function of any generator output in the i^{th} area of particular interest.
$\Delta\omega_i$ is the speed deviation of any generator in the i^{th} *area*.
t_0 is the time at which the fault is cleared.
t is the simulation time in seconds.
t_1 to t_2 is the transient period in seconds (3 seconds in this case).

$$J_{fault2} = \sum_{i=1}^{n} J_{2i} \quad (6)$$

$$J_{2i} = \sum_{t_1}^{t_2} (\Delta\omega(t)) \times (100 \times (t - t') \times 0.00005) \quad (7)$$

t' is the time at which the line re-closes after an outage.

V. Simulation Results

The simulation study and the optimization of the controller parameters are carried out in the PSCAD environment. The SPPSO algorithm consists of 4 particles. Each particle is a PSCAD case. The regeneration process is carried out on three particles every 16 PSO iterations.

The parameters are obtained by optimizing the cost function (3) which takes into account both the short circuit and the line outage (multi-objective function). The optimal parameters given by the SPPSO's global best, p_{gd}, for Controller 1 are K = 391.3770 and T = 10.0000 .The optimal values obtained for Controller 2 are K_1 = 0.0100, T_1 = 0.0100, K_2 = 391.2720 and T_2 = 0.0533. Instead of using a controller as shown in Fig.3, difference between the speed deviations of G1 and G3 can be given as an input to the control structure of Fig. 2. But then equal emphasis is given to both the speeds of G1 and G3 which may not be appropriate in a system where power flows from one area to another. Therefore, Controller 2 structure is considered allowing the SPPSO to find optimized parameters with respect to each speed deviations.

The following tests are carried out to demonstrate the effectiveness of Controller 1 and 2 for different disturbances.

Test 1

The system is subjected to a three phase short circuit fault 25 km away from bus 8 with Controller 1 output added to the SVC voltage reference. The speed responses of the generators G2 and G3, in area 1 and 2 respectively, are shown in Figs. 5 and 6. The responses are improved with the Controller 1.

Test 2

The system is subjected to a 200ms line 5-6 outage Controller 1 output added to the SVC voltage reference. The speed responses of the generators G1 and G3, in area 1 and 2 respectively, are shown in Figs. 7 and 8. The speed responses of the generators with the Controller 1 are better than speed responses without it. The settling time and oscillations are less with the Controller 1.

Test 3

This test involves comparison of performance of Controller 1 (with single input, the speed deviation of G1) and Controller 2 (with dual inputs, the speed deviations of G1 and G3). The performance of the controllers is compared by subjecting the power system to 200ms short circuit applied 25 km away from bus 8. The speed responses of the generators G1 and G3 are shown in Figs. 9 and 10 respectively. It can be observed from these figures that the dual input controller (Controller 2) provides better damping than the single input controller (Controller 1). The given tables also compare the performance of the controller shown in Figs. [5] – [10] based on their area under the speed responses.

TABLE I
COMPARISON OF THE AREA UNDER THE SPEED RESPONSES OF MACHINES WHEN SUBJECTED TO 200MS SHORT CIRCUIT: TEST 1

	Area under the speed response of G2	Area under the speed response of G3
Without Controller	0.3491	0.1945
With Controller 1	0.2991	0.1742

TABLE II
COMPARISON OF THE AREAS UNDER SPEED RESPONSES OF MACHINES WHEN SUBJECTED TO 200MS LINE OUTAGE: TEST 2

	Area under the speed response of G1	Area under the speed response of G3
Without Controller	6.3478	9.5069
With Controller 1	3.632	5.151

TABLE III
COMPARISON OF THE AREA UNDER SPEED RESPONSES OF MACHINES WHEN SUBJECTED TO 200MS SHORT CIRCUIT WITH CONTROLLER 1 AND CONTROLLER 2: TEST 3

	Area under the speed response of G1	Area under the speed response of G3
With Controller1	0.2981	0.1742
With Controller 2	0.1693	0.1140

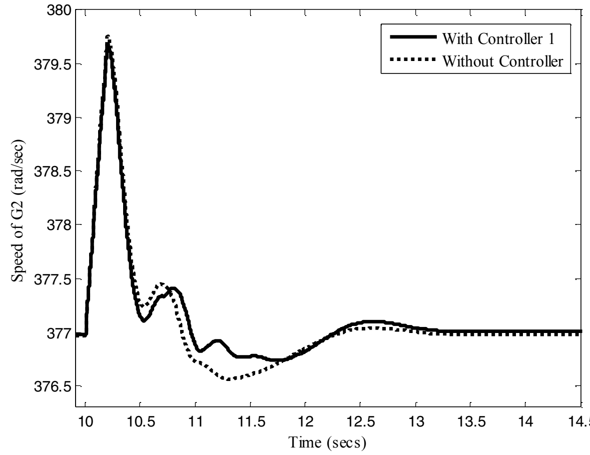

Fig. 5. Speed responses of G2 when subjected to 200ms short circuit fault applied at bus 8 with and without a SVC damping controller.

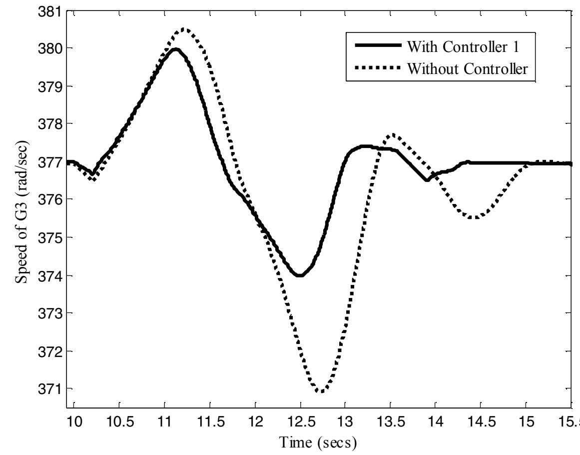

Fig 8. Speed responses of G3 when subjected to 200ms of line 5-6 outage with and without a SVC damping controller.

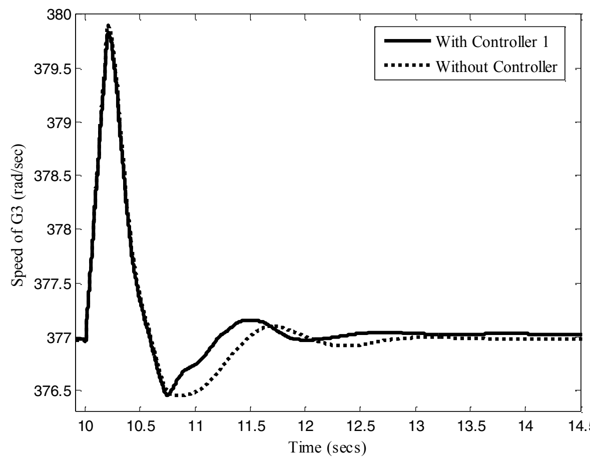

Fig. 6. Speed responses of G3 when subjected to 200ms short circuit fault applied at bus 8 with and without a SVC damping controller.

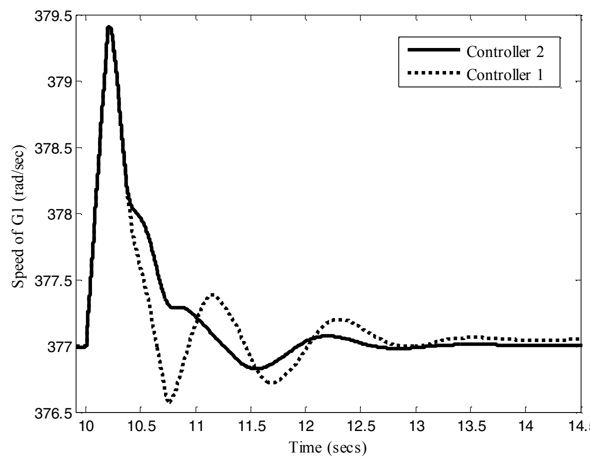

Fig 9. Speed responses of G1 when subjected to 200ms short circuit applied at bus 8 with Controller 1 and Controller 2.

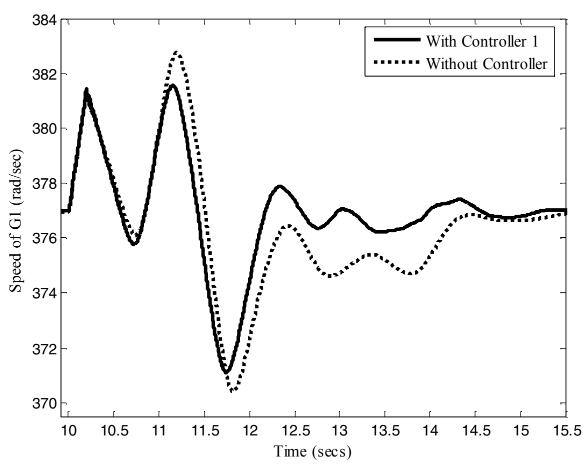

Fig. 7. Speed responses of G1 when subjected to 200ms of line 5-6 outage with and without a SVC damping controller.

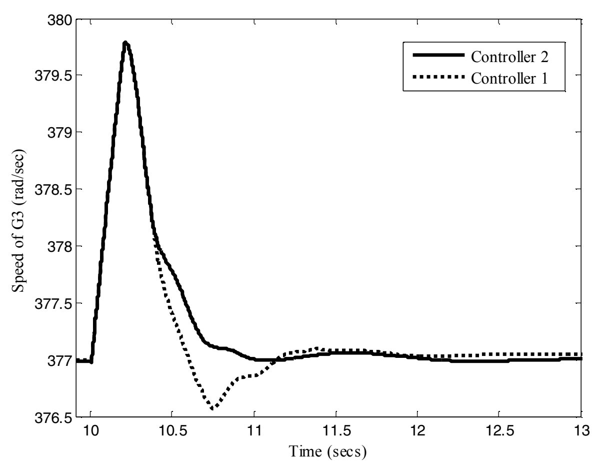

Fig. 10. Speed responses of G3 when subjected to 200ms short circuit applied at bus 8 with Controller 1 and Controller 2.

VI. CONCLUSIONS

This paper had presented the design of optimal SVC damping controllers using the small population based PSO algorithm. Results show that the SVC damping controller provides damping to the system for small and large disturbances, and speed oscillations are minimized and damped out faster. The use of multiple wide area signals to the SVC provides additional information to the damping controller thus improving its performance. Future work involves real-time experiments whereby online optimization of the SVC damping controller parameters can be carried out to accommodate changes in system operating operations.

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