Enhancement of Power System Stability by Means of SSSC and STATCOM: A Comparative Study

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Abstract

In this paper the ability of the SSSC and STATCOM to enhance the dynamical stability of a single-machine infinite-bus (SMIB) power system using linearized Phillips-Heffron model is compared. The design problem of these FACTS devises is formulated as an optimization problem and Particle Swarm Optimization (PSO) technique is employed to search for optimal controller parameters. By minimizing the frequency-domain based objective function, in which the deviation in the oscillatory rotor angle of the generator is involved, dynamical stability performance of the system is improved. Simulation results have been carried out using MATLAB/SIMULINK show that the SSSC performance is better than STATCOM and it provides higher damping than that of the STATCOM.

1. Introduction

Damping of a power system oscillation is one of the main concerns in the power system operation since many years [1-2]. Nowadays, the conventional power system stabilizer (CPSS) is widely used by power utilities.In recent years, the fast progress in the field of power electronics had opened new opportunities for the application of the FACTS devices as one of the most effective ways to improve power system operation controllability and power transfer limits [3, 4].

Static synchronous compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) are two of the important members of FACTS family. STATCOM maintains the bus voltage by supplying the required reactive power even at low bus voltages and improves the power swing damping. Assessment study of STATCOM on stability enhancement has been introduced in. STATCOM model has been incorporated in to the Phillips-Heffron model and its AC/DC voltage regulators controllers interaction has been studied [5]. SSSC is installed in series in the transmission lines. With the capability to change its reactance characteristic from capacitive to inductive, the SSSC is very effective in controlling power flow in power systems [6]. An auxiliary stabilizing signal can also be superimposed on the power flow control function of the SSSC so as to improve power system oscillation stability [7]. The applications of SSSC for power oscillation damping, stability enhancement and frequency stabilization can be found in several references [6, 9].

In this paper, using the PSO technique, the potential of the STATCOM and SSSC supplementary controllers to enhance the dynamic stability of a power system under different loading conditions is compared. PSO is a useful tool for engineering optimization. Unlike the other heuristic techniques, it has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. Also, it suffices to specify the objective function and to place finite bounds on the optimized parameters. This algorithm has also been found to be robust in solving problems featuring non-linearity, non-differentiability and high-dimensionality [11, 13].

In this comparative study, a SMIB system equipped with STATCOM & SSSC controllers is used seperately. The problems of robust STATCOM and SSSC based damping controllers design are formulated as a multi-objective optimization problem. The multi-objective problem is concocted to optimize a composite set of two eigenvalue based objective functions comprising the desired damping factor, and the desired damping ratio of the lightly damped and undamped electromechanical modes. The controllers are automatically tuned with optimization an eigenvalue based multi-objective function by PSO to simultaneously shift the lightly damped and undamped electromechanical modes to a prescribed zone in the s-plane

2. Particle Swarm Optimization

Particle Swarm Optimization (PSO) approach, was introduced first in [11]. This approach features many advantages; it is simple, fast and can be coded in few lines. Also, its storage requirement is minimal. Moreover, this approach is advantageous over evolutionary and genetic algorithms in many ways. First, PSO has memory. That is, every particle remembers its best solution (local best) as well as the group best solution (globalbest). PSO starts with a population of random solutions ‘‘particles’’ in a D-dimension space. The *i*th particle is represented by $X_i = (x_{i1}, x_{i2}, ..., x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution. The value of the fitness for particle i (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, …, p_{iD})$. The global version of the PSO keeps track of the overall best value (gbest), and its location, obtained thus far by any particle in the population [11, 12]. PSO consists of, at each step, changing the velocity of each particle toward its pbest and gbest according to Eq. (1). The velocity of particle i is represented as $V_i = (v_{i1}, v_{i2}, …, v_{iD})$. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest. The position of the *i*th particle is then updated according to Eq. (2) [11, 12]:

$$v_{id} = w * v_{id} + c_1 * rand() * (p_{id} - x_{id}) + c_2 * rand() * (p_{gd} - x_{id}) \quad (1)$$

$$x_{id} = x_{id} + v_{id} \tag{2}$$

where, p_{id} = pbest and p_{gd} = gbest. Several modifications have been proposed in the literature to improve the PSO algorithm speed and convergence toward the global minimum. One modification is to introduce a local-oriented paradigm (lbest) with different neighborhoods. It is concluded that gbest version performs best in terms of median number of iterations to converge. However, pbest version with neighborhoods of two is most resistant to local minimal [13]. PSO Algorithm is:

1. Initialize an array of particles with random positions and their associated velocities to satisfy the inequality constraints.
2. Check for the satisfaction of the equality constraints and modify the solution if required.
3. Evaluate the fitness function of each particle.
4. Compare the current value of the fitness function with the Compare the current value of the fitness function with the value is less, then assign the current fitness value to pbest and assign the current coordinates (positions) to pbestx.
5. Determine the current global minimum fitness value among the current positions.
6. Compare the current global minimum with the previous global minimum (gbest). If the current global minimum is better than gbest, then assign the current global minimum to gbest and assign the current coordinates (positions) to gbestx.
7. Change the velocities according to Eq. (1).
8. Move each particle to the new position according to Eq. (2) and return to Step 2.
9. Repeat Step 2–8 until a stopping criterion is satisfied or the maximum number of iterations is reached.

3. Power System Model

A SMIB power system installed with SSSC is investigated, as shown in Fig. 1 [8]. The SSSC typically has the same power electronics topology as STATCOM. However, it is incorporated into the ac power system through a series coupling transformer as opposed to shunt transformer found in the STATCOM. The dynamic model of the SSSC can be modeled as [8]:

$$\bar{I}_{tL} = I_{tLd} + jI_{tLq} = I_{TL}\angle\varphi \tag{3}$$

$$\begin{aligned} \bar{V}_{INV} &= mkV_{DC}(\cos\psi + j\sin\psi) = mkV_{DC}\angle\psi \\ \psi &= \varphi \pm 90^o \end{aligned} \tag{4}$$

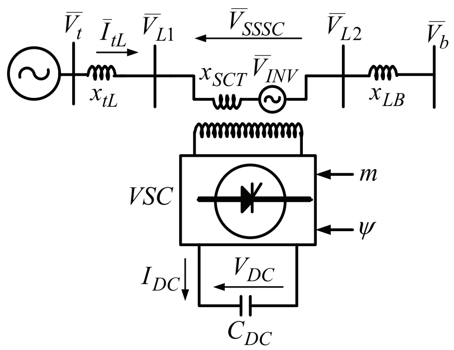


Fig. 1. Single-machine infinite-bus power system with SSSC.

$$\dot{V}_{DC} = \frac{dV_{DC}}{dt} = \frac{I_{DC}}{C_{DC}} \tag{5}$$

$$\dot{V}_{DC} = \frac{mk}{C_{DC}}(I_{tLd}\cos\psi + I_{tLq}\sin\psi) \tag{6}$$

where k is the ratio between AC and DC voltages and is dependent on the inverter structure.

The non-linear dynamic model of the power system of Fig. 1 is:

$$\dot{\delta} = \omega_b\omega \tag{7}$$

$$\dot{\omega} = (P_m - P_e - D\omega)/M \tag{8}$$

$$\dot{E}'_q = (-E_q + E_{fd})/T'_{do} \tag{9}$$

$$\dot{E}_{fd} = -\frac{1}{T_A}E_{fd} + \frac{K_A}{T_A}(V_{to} - V_t) \tag{10}$$

Where

$$P_e = E'_q I_{tLq} + (x_q - x'_d)I_{tLd}I_{tLq} \quad ,$$

$$E_q = E'_q + (x_d - x'_d)I_{tLd} \quad ,$$

$$V_t = \sqrt{(E'_q - x'_d I_{tLd})^2 + (x_q I_{tLq})^2} \quad .$$

A linear dynamic model is obtained by linearizing the non-linear model around an operating condition. By linearizing (3)-(10) we can obtain:

$$\Delta\dot{\delta} = \omega_b\Delta\omega \tag{11}$$

$$\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \tag{12}$$

$$\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \tag{13}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{K_A}{T_A}\Delta V_t \tag{14}$$

$$\Delta\dot{V}_{DC} = K'_7\Delta\delta + K'_8\Delta E'_q + K'_9\Delta V_{DC} + K'_{dm}\Delta m + K'_{d\psi}\Delta\psi \tag{15}$$

where

$$\Delta P_e = K'_1\Delta\delta + K'_2\Delta E'_q + K'_{pDC}\Delta V_{DC} + K'_{pm}\Delta m + K'_{p\psi}\Delta\psi$$

$$\Delta E_q = K'_4\Delta\delta + K'_3\Delta E'_q + K'_{qDC}\Delta V_{DC} + K'_{qm}\Delta m + K'_{q\psi}\Delta\psi$$

$$\Delta V_t = K'_5\Delta\delta + K'_6\Delta E'_q + K'_{vDC}\Delta V_{DC} + K'_{vm}\Delta m + K'_{v\psi}\Delta\psi \quad .$$

K'_1, K'_2, …, K'_9, K'_{pu}, K'_{qu}, K'_{du} and K'_{vu} are linearization constants and are dependent on system parameters and the operating condition.

The state space model of power system is given by:

$$\dot{x} = Ax + Bu \tag{16}$$

where the state vector x, control vector u, A and B are :

$$x = \begin{bmatrix}\Delta\delta & \Delta\omega & \Delta E'_q & \Delta E_{fd} & \Delta V_{DC}\end{bmatrix}^T$$

$$u = \begin{bmatrix}\Delta m & \Delta\psi\end{bmatrix}^T$$

$$A=\begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1'}{M} & -\frac{D}{M} & -\frac{K_2'}{M} & 0 & -\frac{K'_{pDC}}{M} \\ -\frac{K_4'}{T'_{do}} & 0 & -\frac{K_3'}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K'_{qDC}}{T'_{do}} \\ -\frac{K_A K_5'}{T_A} & 0 & -\frac{K_A K_6'}{T_A} & -\frac{1}{T_A} & -\frac{K_A K'_{vDC}}{T_A} \\ K_7' & 0 & K_8' & 0 & K_9' \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & 0 \\ -\frac{K'_{pm}}{M} & -\frac{K'_{p\psi}}{M} \\ -\frac{K'_{qm}}{T'_{do}} & -\frac{K'_{q\psi}}{T'_{do}} \\ -\frac{K_A K'_{vm}}{T_A} & -\frac{K_A K'_{v\psi}}{T_A} \\ K'_{dm} & K'_{d\psi} \end{bmatrix}.$$

The block diagram of the linearized dynamic model of the SMIB power system with SSSC is shown in Fig. 2. The same work to SSSC is performed with STATCOM [5].

4. Power System Oscillations Damping Controller

A damping controller shown in Fig. 3 is provided to improve the damping of power system oscillations. It comprises gain block, signal-washout block and lead-lag compensator [3]. This controller is used for STATCOM & SSSC.

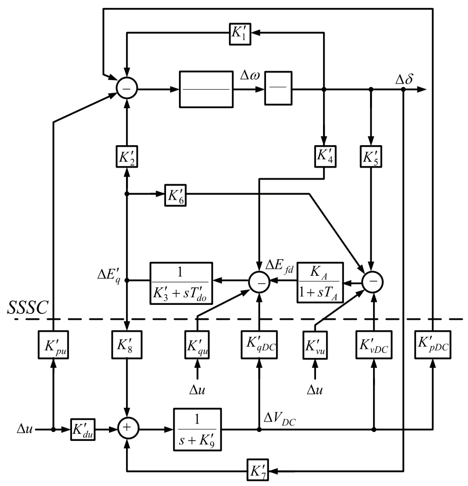


Fig. 2. Modified Phillips-Heffron model of a SMIB system with SSSC.

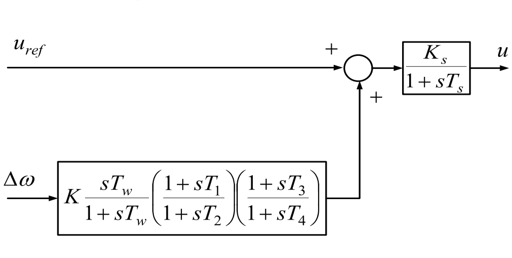


Fig. 3. STATCOM/SSSC with lead-lag controller.

5. Optimization Problem

In the proposed method, we must tune the STATCOM and SSSC controller parameters optimally to improve overall system dynamic stability in a robust way under different operating conditions. For our optimization problem, an eigenvalue based multi-objective function reflecting the combination of damping factor and damping ratio is considered as follows [14]:

$$J_3 = J_1 + aJ_2 \tag{17}$$

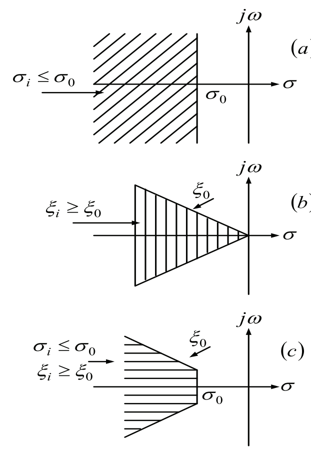


Fig.4. Region of eigenvalue location for objective functions.

where $J_1 = \sum_{\sigma_i \geq \sigma_0} (\sigma_0 - \sigma_i)^2$, $J_2 = \sum_{\zeta_i \leq \zeta_0} (\zeta_0 - \zeta_i)^2$, σ_i and ζ_i are the real part and the damping ratio of the ith eigenvalue, respectively. The value of a is chosen at 10. The value of σ_0 determines the relative stability in terms of damping factor margin provided for constraining the placement of eigenvalues during the process of optimization. The closed loop eigenvalues are placed in the region to the left of dashed line as shown in Fig. 4a, if only J_1 is considered as the objective function. Similarly, if only J_2 is considered, then it limits the maximum overshoot of the eigenvalues as shown in Fig. 4b. In the case of J_2, ζ_0 is the desired minimum damping ratio which can be achieved. When optimized with J_3, the eigenvalues are restricted within a D-shaped area as shown in Fig. 4(c).

The optimization problem can be stated as:

Minimize J_3 Subject to

$$\begin{aligned} K^{\min} &\leq K \leq K^{\max} \\ T_1^{\min} &\leq T_1 \leq T_1^{\max} \\ T_2^{\min} &\leq T_2 \leq T_2^{\max} \\ T_3^{\min} &\leq T_3 \leq T_3^{\max} \\ T_4^{\min} &\leq T_4 \leq T_4^{\max} \end{aligned} \tag{18}$$

Typical ranges of the optimized parameters are [0.01–100] for K and [0.01–1] for T_1, T_2, T_3 and T_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 methods yield optimal parameters and the method is free from the curse of local optimality. In view of the above, the proposed approach employs PSO to solve this optimization problem and search for optimal set of STATCOM and SSSC damping controller parameters.

In this study, the values of σ_0 and ζ_0 are taken as -1.5 and 0.2, respectively. In order to acquire better performance, number of particle, particle size, number of iteration, c_1 and c_2 is chosen as 30, 5, 50, 2 and 2, respectively. Also, the inertia weight, w, is linearly decreasing from 0.9 to 0.4.

5. Simulation Results

To assess the effectiveness of the proposed stabilizer, three different loading conditions given in Table 1 were considered.

Table 1. Font sizes and styles

Loading	P(pu)	Q(pu)
Nominal	0.9	0.08
Light	0.65	0.15
Heavy	1.2	0.12

The PSO algorithm has been applied to search for the optimal parameter settings of the supplementary controller so that the objective functions are optimized. It should be noted that PSO algorithm is run several times and then optimal set of STATCOM controller parameters is selected. In this comparative study, three different loading conditions given in Table 1 were considered. The values of the optimized parameters with the multi-objective function J_3 i.e. the best objective function in the nominal loading condition for STATCOM [14] and SSSC are given .

The electromechanical modes and the damping ratios obtained for all operating conditions with STATCOM and SSSC ψ-based controller by J_3 in the system are given in Table 2.

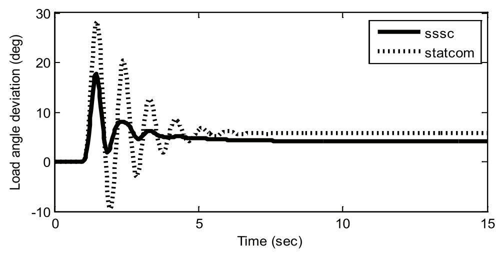
The similar single-machine infinite-bus systems shown in Fig. 1 are considered for simulation studies. A step ΔP_m =0.1 pu at t = 1s is obtained, at all loading conditions given in Table 1, to study the performance of the proposed controller. The potential of the STATCOM and SSSC supplementary controllers to enhance the dynamic stability of the power system is compared.

The load angle deviation and rotor speed deviation in different loading conditions are shown in Figs. 5.

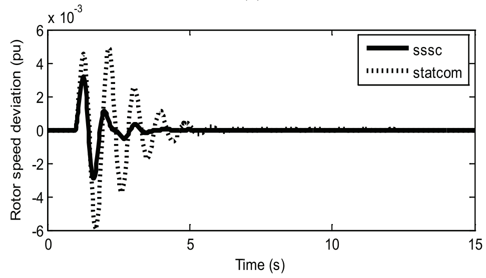
Table 2. Eigenvalues and damping ratios of electromechanical modes with STATCOM and SSSC ψ-based controller by J_3

FACTS devices type	Nominal loading condition	Light loading condition	Heavy loading condition
STATCOM	-10.68 ± 17.7i, (0.5165) -1.47 ± 5.44i, (0.2616) -1.45 ± 7.12i, (0.2) -1.02, -2.32, -118.38	-10.31 ± 18.14i, (0.494) -1.38 ± 6.78i, (0.1994) -1.47 ± 4.51i, (0.3092) -1.02, -1.83, -117.61	-11.64 ± 17.41i, (0.5558) -1.32 ± 7.11i, (0.1821) -1.28 ± 6.79i, (0.1851) -1.12, -2.12, -192
SSSC	-30.3843 ± 30.3888i, (0.7071) -1.4786 ± 10.0208i, (0.1460) -1.4732 ± 6.1988i, (0.2312) -0.2577, -1.7955 , -91.16	-19 ± 27.58i, (0.5674) -1.50 ± 9.83i, (0.1508) -1.49 ± 5.51i, (0.2606) -0.35, -4.27, -104.49	-96.3048 ± 67.66i, (0.8182) -1.4825 ± 10.8389i, (0.1355) -1.3468 ± 6.4268i, (0.2051) -9.66, -0.5134, -39.39

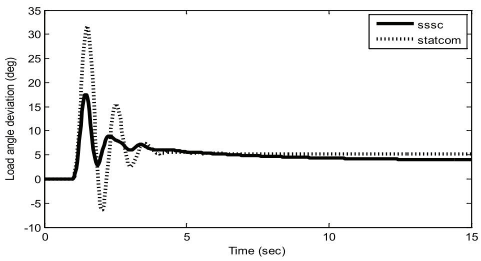
It can be seen that the PSO based SSSC controller tuned using the multi-objective function achieves good robust performance, provides superior damping in comparison with the STATCOM controller and enhance greatly the dynamic stability of power system.



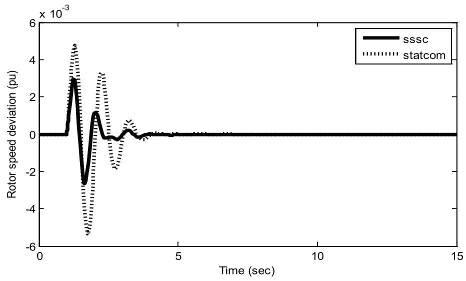
(a)



(b)



(c)



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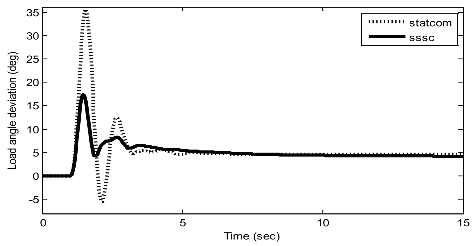
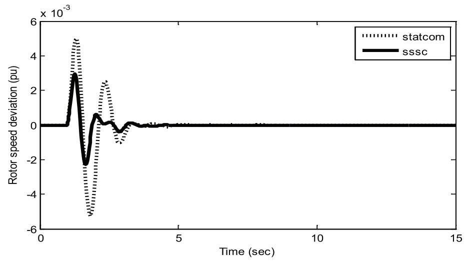


(e)



(f)

Fig. 5. Load angle and rotor speed deviation at (a),(b) heavy loading (c),(d) nominal loading (e),(f) light loading conditions.

6. Conclusions

This paper presents a design of PSO algorithm-based controller in a single-machine infinite-bus system for the STATCOM and SSSC that are two of the important members of FACTS family, and their performance comparison in terms of oscillations damping. The design problem of the controller is converted into an optimization problem which is solved by a PSO technique with the eigenvalue-based multi-objective function. Simulation results reveal that the SSSC performance is better than STATCOM and it provides higher damping than that of the STATCOM.

Appendix

The test systems parameters are:
Machine: D=0; x_d =1; x_q=0.6; x_d'=0.3; M=8; T'_{do}=5.044; f=60; V_t=1;
Excitation system: K_A=250; T_A=0.05;
Transmission line: x_{tL}=0.15; x_{LB}=0.6;
STATCOM: C_{DC}=1; V_{DC}=2; K_s=1.2; T_s=0.05; T_w=0.01; x_{SDT}=0.15.
SSSC: C_{DC}=0.25; V_{DC}=1; K_s=1.2; T_s=0.05; T_w=0.01; x_{SCT}=0.15.

7. References

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