Stability Improvement by SSSC and STATCOM based Damping Controller Employing Differential Evolution Algorithm

Sangram Keshori MOHAPATRA and Sidhartha PANDA

Abstract - Principal Objective of this paper is to investigate the power system stability improvement by a SSSC and STATCOM based damping controllers. The present study is considered both local and remote signals with associated time delays. The design problem of the proposed controller is formulated as an optimization problem, and Differential evolution (DE) is employed to search for the optimal controller parameters. The performances of the proposed controllers are evaluated under different disturbances for both single-machine infinite bus power system and multi-machine power system. Simulation results are presented under various operating conditions and disturbances to show the effectiveness and robustness of the proposed approach.

Keywords: Static synchronous series compensator, static synchronous compensator, Differential evolution algorithm, single-machine infinite-bus power system, multi-machine power system.

1. INTRODUCTION

Recent development of power electronics introduces the use of flexible ac transmission systems (FACTS) controllers in power systems [1]. Subsequently, within the FACTS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the lines and in improving stability [2, 3]. The voltage sourced converter-based series compensator, called static synchronous series compensator (SSSC), and provides the virtual compensation of transmission line impedance by injecting the controllable voltage in series with the transmission line. The ability of SSSC to operate in capacitive as well as inductive mode makes it very effective in controlling the power flow of the system [4,5]. 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 [6]. Applications of SSSC for power oscillation damping, stability enhancement and frequency stabilization can be found in several references [7–10]. The influence of degree of compensation and mode of operation of SSSC on small disturbance and transient stability is also reported in the literature [11,12]. Artificial intelligence-based approaches have been proposed recently to design a FACTS-based supplementary damping controller. These approaches include particle swarm optimization [13–15], genetic algorithm [16], differential evolution [17], multi-objective evolutionary algorithm [18,19],

etc. In the design of an efficient and effective damping controller, selection of the appropriate input signal is a primary issue. Input signal must give correct control actions when a disturbance occurs in the power system. Most of the available literatures on damping controller design are based on either local signal or remote signal. Also the issues related to potential time delays due to sensor time constant and signal transmission delays are hardly addressed in the literature. Recently there is a growing interest in designing the controllers in the presence of uncertain time delays [22-25]. In view of the above, this paper investigates the design of a SSSC/STATCOM-based damping controller considering the potential time delays. Despite significant strides in the development of advanced control schemes over the past two decades, the conventional lead–lag structure controller remains the controller's of choice in many industrial applications. The conventional lead–lag controller structure remains an engineer's preferred choice because of its structural simplicity, reliability and the favorable ratio between performance and cost. Beyond these benefits, it also offers simplified dynamic modeling, lower user-skill requirements and minimal development effort, which are issues of substantial importance to engineering practice. In view of the above, a lead–lag structure controller has been considered in the present study to modulate the SSSC injected voltage. A number of conventional techniques have been reported in the literature pertaining to design problems of lead-lag structure controller 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. 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. Differential evolution (DE) is a branch of evolutionary algorithms developed by Rainer Stron and Kenneth Price in 1995for optimization problems [21]. It is a population-based direct search algorithm for global optimization capable of handling non-differentiable, non-linear and multi-modal objective functions, with few, easily chosen, control parameters. It has demonstrated its usefulness and robustness in a variety of applications such as, Neural network learning, Filter design and the optimization of aerodynamics shapes. DE differs from other evolutionary algorithms (EA) in the mutation and recombination phases. DE uses weighted differences between solution vectors to change the population whereas in other stochastic techniques such as genetic algorithm (GA) and expert systems (ES), perturbation occurs in accordance with a random quantity. DE employs a greedy selection process with inherent elitist features. Also it has a minimum number of EA control parameters, which can be tuned effectively [17].

2.   SYSTEM MODEL

2.1.   Single-Machine infinite-bus power system with SSSC/STATCOM

To design and optimize the SSSC-based damping controller, a single-machine infinite-bus system with SSSC, shown in Fig. 1, is considered at the first instance. The system comprises a synchronous generator connected to an infinite-bus through a step-up transformer and a SSSC followed by a double circuit transmission line. The generator is equipped with hydraulic turbine & governor (HTG) and excitation system. 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 (SimPowerSystems 4.3 User's Guide). In Fig. 1, T/F represents the transformer; VS and VR are the generator terminal and infinite-bus voltages, respectively; $V1$ and $V2$ are the bus voltages; VDC and V_{cnv} are the DC voltage source and output
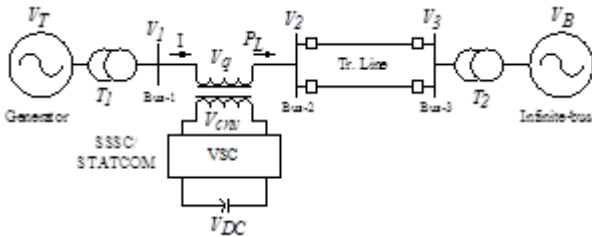
voltage of the SSSC converter, respectively; I is the line current and PL and $PL1$ are the total real power flow in the transmission lines and that in one line, respectively. All the relevant parameters are given in Appendix.

3.   THE PROPOSED APPROACH

3.1.   Structure of SSSC/STATCOM-based damping controller

The commonly used lead–lag structure are chosen in this study as SSSC/STATCOM-damping controller as shown in Fig.2 .The lead-lag structure is preferred by the power system utilities because of the ease of on-line tuning and also lack of assurance of the stability by some adaptive or variable structure techniques. The structure consists of a delay block, a gain block with gain K_S, a signal washout block and two-stage phase compensation block. The time delay introduced due to delay block depends on the type of input signal. For local input signals only the sensor time constants is considered and for remote signals both sensor time constant and the signal transmission delays are included. 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 [27]. The phase compensation blocks (time constants T_{1S}, T_{2S} and T_{3S}, T_{4S}) provide the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. In Fig. 2, V_{ref} represents the reference voltage as desired by the steady operation of the system. The steady state loop acts quite slowly in practice and hence, in the present study V_{ref} is assumed to be constant during the disturbance period. The desired value of compensation is obtained according to the change in the SSSC injected voltage ΔV_{sssc} which is added to V_{ref} to get the desired V_{sssc} . In Fig 2, the desired value of reference voltage is obtained according to the change in the STATCOM reference $\Delta V_{STATCOM}$ which is added to V_{ref} to get the desired voltage reference $V_{STATCOM\_ref}$.
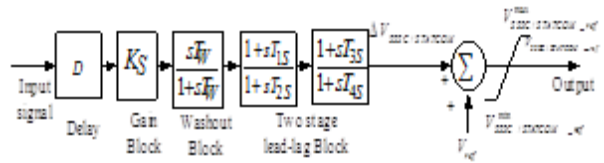

Fig. 2. Structure of proposed SSSC/TATCOM-based damping controller.

3.2.   Problem formulation

In the lead-lag structured controllers, the washout time constants T_W is usually pre-specified [1,13-15]. A washout time constant $T_W = 10s$ is used in the present study. The controller gain K_S and the time constants T_{1S}, T_{2S} , T_{3S} and T_{4S} are to be determined for both the cases. For the case of SSSC, during steady state conditions

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

$\Delta Vsssc$ and V_{ref} are constant. During dynamic conditions the series injected voltage V_{SSSC_ref} is modulated to damp system oscillations. The effective voltage V_{SSSC_ref} in dynamic conditions is given by:

$$V_{SSSC\_ref} = V_{ref} + \Delta V_{SSSC} \qquad (1)$$

For the case of STATCOM, during steady state conditions $\Delta V_{STATCOM}$ and V_{ref} are constant. During dynamic conditions the reference voltage $\Delta V_{STATCOM}$ is modulated to damp system oscillations. The effective reference voltage $V_{STATCOM\_ref}$ in dynamic conditions is given by:

$$V_{STATCOM\_ref} = V_{ref} + \Delta V_{STATCOM} \qquad (2)$$

In the design of a robust damping controller, selection of the appropriate input signal is a main issue. Input signal must give correct control actions when a disturbance occurs in the power system. Both local and remote signals can be used as control. To avoid additional costs associated with communication and to improve reliability, input signal should preferably be locally measurable. However, local control signals, although easy to get, may not contain the desired oscillation modes. So, compared to wide-area signals, they are not as highly controllable and observable. Owing to the recent advances in optical fiber communication and global positioning systems, the wide-area measurement system can realize phasor measurement synchronously and deliver it to the control center even in real time, which makes the wide-area signal a good alternative for control input. In a wide-area monitoring system, global positioning system synchronized time-stamped data are used. In today's technology, dedicated communication channels should not have more than 50-ms delay for the transmission of measured signals even in the worst scenarios [28].For local input signals, line active power, line reactive power, line current magnitude and bus voltage magnitudes are all candidates to be considered in the selection of input signals for the FACTS power oscillation damping controller [29]. Among these possible local input signals, active power and current are the most commonly employed in the literature. Similarly, generator rotor angle and speed deviation can be used as remote signals. However rotor speed seems to be a better alternative as input signal for FACTS based controller [30] In view of the above, both line active power and speed deviations are considered and compared as candidate input signals for the SSSC/STATCOM based controller. For local signals a sensor time constant of 15 ms is considered. For remote signals a signal transmission delay of 50 ms is considered along with the sensor time constant of 15 ms. In the present study, an integral time absolute error of the speed deviations is taken as the objective function J expressed as:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| \cdot t \cdot dt \qquad (3)$$

Where, $\Delta\omega$ is the speed deviation in 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. The problem constraints are the SSSC/STATCOM controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Minimize J $\qquad (4)$

Subject to

$$K_S^{\min} \leq K_S \leq K_S^{\max}$$

$$T_{1S}^{\min} \leq T_{1S} \leq T_{1S}^{\max}$$

$$T_{2S}^{\min} \leq T_{2S} \leq T_{2S}^{\max}$$

$$T_{3S}^{\min} \leq T_{3S} \leq T_{3S}^{\max}$$

$$T_{4S}^{\min} \leq T_{4S} \leq T_{4S}^{\max} \qquad (5)$$

4. DIFFERENTIAL EVOLUTION (DE)

Differential Evolution (DE) algorithm is a stochastic, population-based optimization algorithm recently introduced [20]. DE works with two populations; old generation and new generation of the same population. The size of the population is adjusted by the parameter N_P. The population consists of real valued vectors with dimension D that equals the number of design parameters/control variables. The population is randomly initialized within the initial parameter bounds. The optimization process is conducted by means of three main operations: mutation, crossover and selection. In each generation, individuals of the current population become target vectors. For each target vector, the mutation operation produces a mutant vector, by adding the weighted difference between two randomly chosen vectors to a third vector. The crossover operation generates a new vector, called trial vector, by mixing the parameters of the mutant vector with those of the target vector. If the trial vector obtains a better fitness value than the target vector, then the trial vector replaces the target vector in the next generation. The evolutionary operators are described below [17];

4.1. Initialization

For each parameter j with lower bound X_j^L and upper bound X_j^U, initial parameter values are usually randomly selected uniformly in the interval [X_j^L, X_j^U].

4.2. Mutation

For a given parameter vector $X_{i,G}$, three vectors ($X_{r1,G}$ $X_{r2,G}$ $X_{r3,G}$) are randomly selected such that the indices i, $r1$, $r2$ and $r3$ are distinct. A donor vector $V_{i,G+1}$ is created by adding the weighted difference between the two vectors to the third vector as:

$$V_{i,G+1} = X_{r1,G} + F.(X_{r2,G} - X_{r3,G}) \qquad (6)$$

Where F is a constant from (0, 2)

4.3. Crossover

Three parents are selected for crossover and the child is a perturbation of one of them. The trial vector $U_{i,G+1}$ is developed from the elements of the target vector ($X_{i,G}$) and the elements of the donor vector ($X_{i,G}$). Elements of the donor vector enter the trial vector with probability CR as:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & if \quad rand_{j,i} \le CR \quad or \quad j = I_{rand} \\ X_{j,i,G+1} & if \quad rand_{j,i} > CR \quad or \quad j \ne I_{rand} \end{cases}$$
$$(7)$$

With $rand_{j,i} \sim U$ (0,1), I_{rand} is a random integer from (1,2,….D) where D is the solution's dimension i.e number of control variables. I_{rand} ensures that $V_{i,G+1} \ne X_{i,G}$.

4.4. Selection

The target vector $X_{i,G}$ is compared with the trial vector $V_{i,G+1}$ and the one with the better fitness value is admitted to the next generation. The selection operation in DE can be represented by the following equation:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & if \quad f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & otherwise. \end{cases} \qquad (8)$$

where $i \in [1, N_P]$. Fig. 3 shows the vector addition and subtraction necessary to generate a new candidate solution.
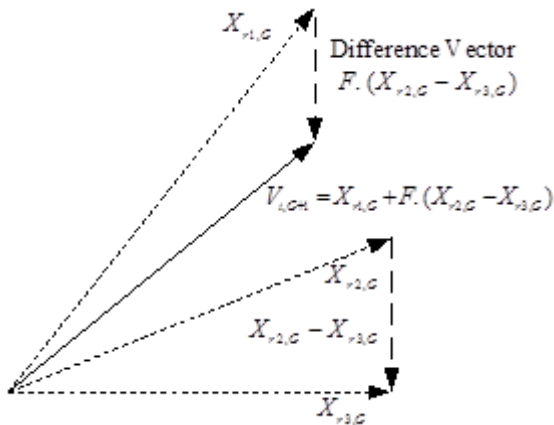

Fig. 3. Shows the vector addition and subtraction necessary to generate a new candidate solution.

The flow chart of the DE algorithm employed in the present study is given in Fig. 4

5. RESULTS AND DISCUSSIONS

The optimization of the proposed SSSC/STATCOM based damping controller parameters is carried out by minimizing the fitness given in Eq. (4)
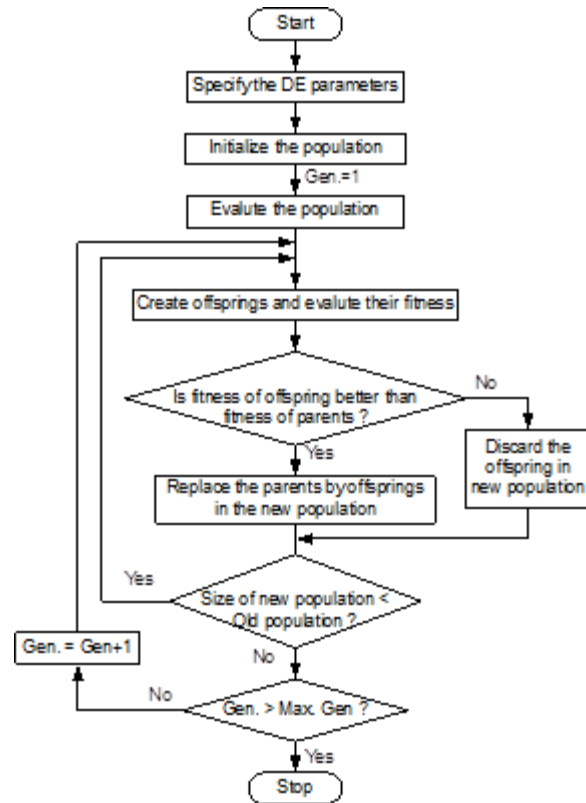

Fig. 4. Flow chart of proposed DE optimization approach.

employing DE. The model of the system under study has been developed in MATLAB/SIMULINK environment and DE programme has been written in .mfile. For objective function calculation, the developed model is simulated in a separate programme (by another .m file using initial population/controller parameters) considering a disturbance. Form the SIMULINK model the objective function value is evaluated and moved to workspace. The process is repeated for each individual in the population. The optimization was repeated 20 times and the best final solution among the 20 runs is chosen as proposed controller parameters. The best final solutions obtained in the 20 runs are given in Table 1.

Table 1. SSSC AND STATCOM based controller parameters for SMIB power system.

Signal/ Parameters	SSSC /STATCOM Controller				
	Ks	T$_{1S}$	T$_{2S}$	T$_{3S}$	T$_{4S}$
Remote	181.2617	2.1993	2.0446	0.6526	1.4863
Local	72.4925	1.9705	1.9510	1.6716	0.3346
Remote	197.7727	2.3244	1.0297	0.0109	1.3568
Local	49.5691	1.5243	0.8222	2.2033	0.3422

5.1. Simulation results

During normal operating condition there is complete balance between input mechanical power and output electrical power and this is true for all operating points. During disturbance, the balance is disturbed and the difference power enters into/drawn from the rotor. Hence the rotor speed deviation and subsequently all other parameters (power, current, voltage etc.) change. As the input to the SSSC/STATCOM controller is the

speed deviation/electrical power, for the case of SSSC injected voltage and for the case of STATCOM reference voltage is suitable modulated and the power balanced is maintained at the earliest time period irrespective of the operating point. So, with the change in operating point also the SSSC/STATCOM controller parameters remain fixed. To assess the effectiveness and robustness of the proposed controller, three different operating conditions as given in Table II are considered. At the first instance the remote speed deviation signal is considered as the input signal to the proposed SSSC/STATCOM-based controller. The following cases are considered.

Table 2. Loading conditions considered.

Loading conditions	Pe in per unit (pu)	δ_0 in Degree
Nominal	0.85	51.51^0
Light	0.5	29.46^0
Heavy	1	60.72^0

Case 1: Nominal loading, 3-phase fault

The behavior of the proposed controller is verified at nominal loading condition under severe disturbance condition. A 5 cycle, 3-phase self clearing fault is applied at the middle of one transmission line connecting bus 2 and bus 3, at $t = 1.0$ s. The system response under this severe disturbance is shown in Figs. 5-7 where, the response with Local signal with STATCOM is shown with dotted line, the response with proposed approach Remote signal with time delay in STATCOM is shown with dash line, Local signal with SSSC shown with dash-dotted line and time delay with Remote signal in SSSC are considered with solid line respectively. For comparison, it can be seen from Figs. 5-7 that when potential time delays are considered the proposed approach remote signal is better than local signal.
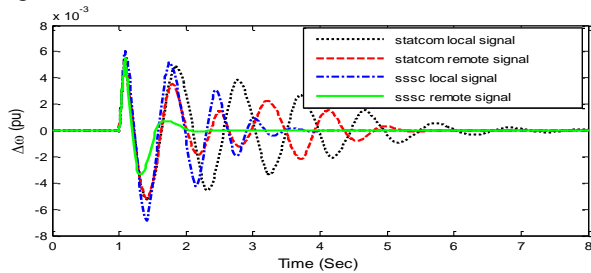

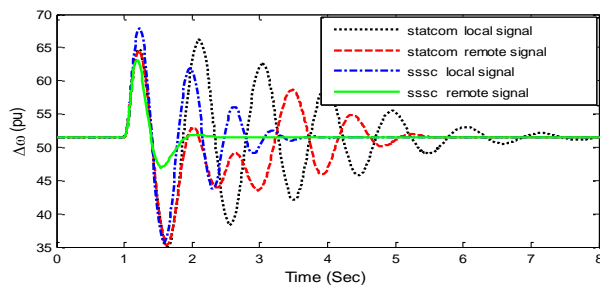**Fig. 5.** Speed deviation response for 5 cycle 3-ph fault in transmission line with nominal loading.

Fig. 6. Rotor angle response for 5cycle 3-ph fault in transmission line with nominal loading.
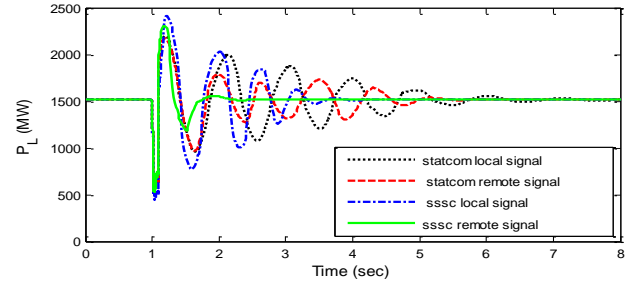

Fig. 7. Tie-line power flow response for 5 cycle 3-ph fault in transmission line with nominal loading.

Case 2: Light loading, 3-phase fault cleared by line outage

To test the robustness of the controller to the operating condition and type of disturbance, the generator loading is changed to light loading condition as given in Table 2. A 5 cycle 3-phase fault is assumed in one of the parallel transmission line near bus 2 at t=1.0 s. The fault is cleared by tripping the faulted line and the lines are reclosed after 5 cycles. The system response under this contingency is shown in Figs.8-9 which clearly depicts the robustness of the proposed controller for changes in operating condition and fault location. It can be seen that the proposed design approach remote signal is better than local signal.
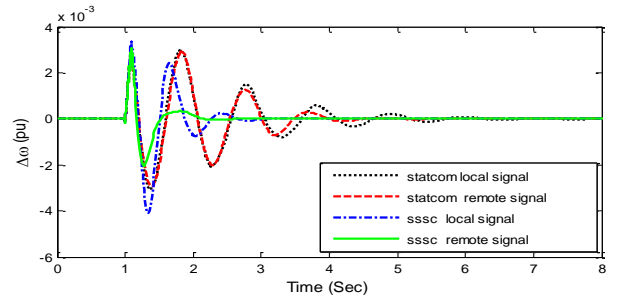

Fig. 8. Speed deviation response for 5 cycle 3-ph fault in transmission line with Light loading.
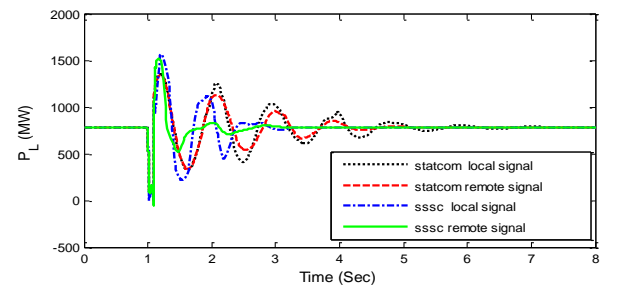

Fig. 9. Tie-line power flow response for 5 cycle 3-ph fault in transmission line with Light loading.

Case-3: Heavy loading, small disturbance

The robustness of the proposed controller is also verified at heavy loading condition under small disturbance by disconnecting the load near bus 1 at t =1.0 s for 5 cycle with generator loading being changed to heavy loading condition. The system Response under this contingency is shown in Figs 10-11 from which it
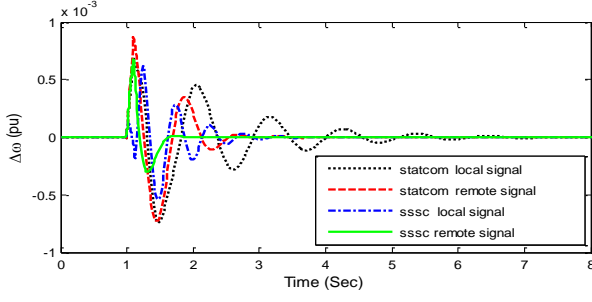
Fig. 10. Speed deviation responses for 5 cycle 3-ph fault in transmission line with Heavy loading.
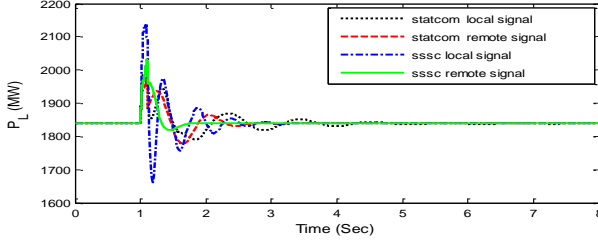

Fig. 11. Tie-line power flow response for 5 cycle 3-ph fault in transmission line with Heavy loading.

is clear that local signals are more unstable than under this severe disturbance and the stability of the system is maintained with the proposed approach remote signal with time delay.

Case-4: Effect of signal transmission delay

To study the effect of variation in signal transmission delay on the performance of controller, the transmission delay is varied and the response is shown in Fig. 14. In this case, nominal loading condition with 5 cycle, 3-phase, self clearing fault is assumed at the middle of one transmission line for the analysis purpose. It is evident from Fig. 12 that the performances of the proposed controllers are hardly affected by the signal transmission delays.
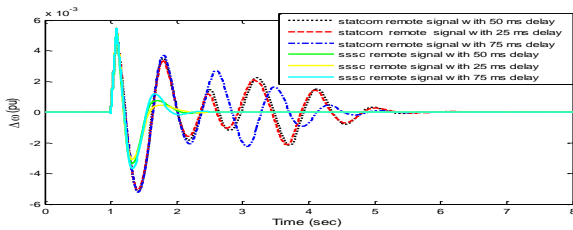

Fig. 12. Speed deviation response showing for case-4.

5.2. Extension to multi-machine power system with SSSC/ STATCOM

The proposed approach of designing and optimizing the parameters of a SSSC/STATCOM based damping controller is further extended to a multi-machine power system shown in Fig. 13. It is similar to the power system used in references [14, 18, 32, 33]. 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
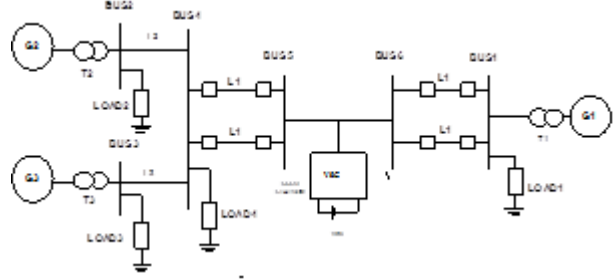

Fig. 13. Three machine power system with SSSC/STATCOM.

the stability the line is sectionalized and a SSSC/STATCOM is assumed on the mid-point of the tie line. The relevant data for the system are given in Appendix. For remote input signal speed deviation of generator G1 and G2 is chosen as the control input of SSSC/STATCOM based damping controller and for local signal real power flow at the nearest bus (bus5) is selected.

The objective functions J is defined as:

$$J = \int_{t=0}^{t=t_{sim}} (\sum | \Delta\omega_L | + \sum | \Delta\omega_I |) \cdot t \cdot dt \qquad (9)$$

Where $\Delta\omega_I$ and $\Delta\omega_L$ are the speed deviations of inter-area and local modes of oscillations respectively and t_{sim} is the time range of the simulation. The same approach as explained for SMIB case is followed to optimize the SSSC/STATCOM-based damping controller parameters for three-machine case (i.e. for remote signal a delay of 50 ms has been considered and for local signal the delay is neglected). The best among the 20 runs for both the input signals are shown in Table3.

Table 3. SSSC/STATCOM based controller parameters for multi-machine power system.

Signal/ Parameters	SSSC /STATCOM Controller				
	K_S	T_{1S}	T_{2S}	T_{3S}	T_{4S}
Remote	184.2195	1.9869	1.4439	1.1006	0.6448
Local	100.8801	0.8688	0.2313	0.3705	0.4962
Remote	154.1656	2.4880	0.4672	1.9531	0.4903
Local	156.1155	1.4540	2.3209	1.4506	0.0434

A self clearing 3-phase fault is applied near bus 1 at t = 1 s. The fault is cleared after 5 cycles and the original system is restored after the fault clearance.

Figs. 14-16 show the variations of the inter-area and local mode of oscillation against time respectively for both the control inputs. In these Figs. the response with Local signal with STATCOM is shown with dotted line, the response with proposed approach Remote signal with time delay in STATCOM is shown with dash line, Local signal with SSSC shown with dash-dotted line and time delay with Remote signal in SSSC are considered with solid line respectively. It is clear from Fig. 14 that inter-area modes of oscillations of the proposed SSSC/STATCOM based damping controller are significantly improves the power system stability with both local and remote signals. However, remote signal seems to be a better choice compared to

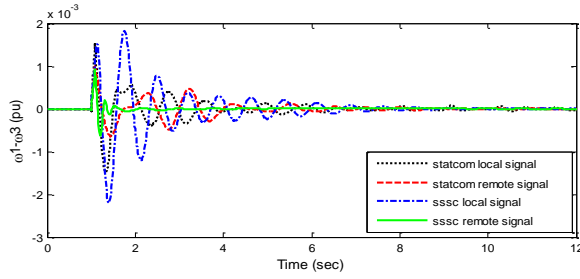the local signal as the power system oscillations are quickly damped out with remote signal.

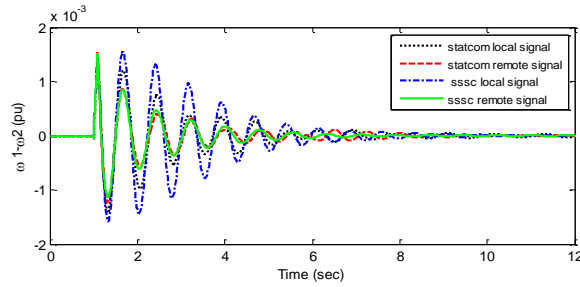**Fig. 14.** Inter-area mode of oscillation for 5 cycle 3-phase fault disturbance.

Fig. 15. Local mode of oscillation for self clearing three phase fault disturbance.
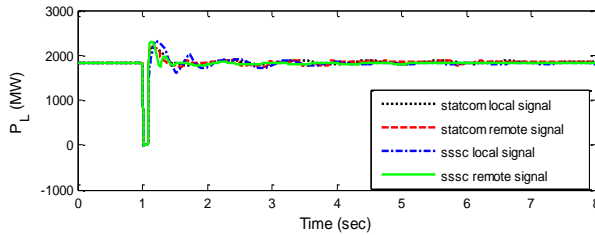

Fig. 16. Tie line power flow for self clearing three phase fault disturbance.

To show the robustness of the proposed approach, another disturbance is considered. The transmission line between bus 5 and bus 1 is tripped at t=1.0 sec and reclosed after 5 cycles.
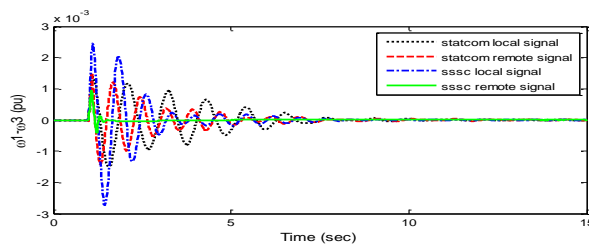

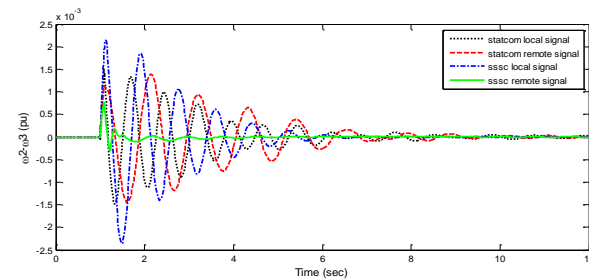**Fig. 17.** Inter-area mode of oscillation for line outage disturbance.

Fig. 18. Local mode of oscillation for line outage disturbance.

The system response is shown in Figs. 17-18 from which it is clear that remote signal with time delay is a better choice than local signal for stability improvement. For completeness, the load at bus 1 is disconnected for 100 ms and the system response is shown in Figs. 19-20. It is clear from these Figs. that the proposed controllers are robust and damps power system oscillations even under small disturbance conditions. Further, the performance with remote speed deviation signal is better than that with local signal.
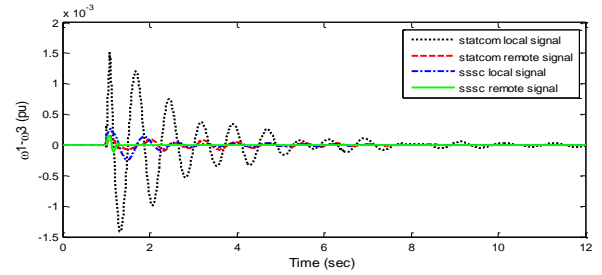

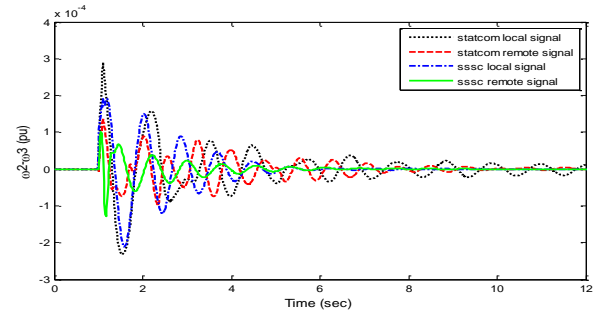**Fig. 19.** Inter-area mode of oscillation for small disturbance.

Fig. 20. Local mode of oscillation for small disturbance.

6. CONCLUSION

In this study, power system stability improvement by a static synchronous series compensator (SSSC) and static synchronous compensator (STATCOM) based damping controller is thoroughly investigated. For the controller design, potential time delays due to sensor time constant and signal transmission delays are considered. The design problem is formulated as an optimization problem, Differential evaluation (DE) algorithm is employed to search for the optimal controller parameters. The performance of the proposed controller is evaluated under different disturbances for both single-machine infinite bus power system and multi-machine power system using both local and remote signals. Results show that remote signal with time delay is a better choice than the local signal.

APPENDIX

System data: All data are in pu unless specified otherwise. The variables are as defined in [26].

(i) Single-machine infinite-bus power system Generator:
S_B = 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.,
Load at Bus2: 250MW

Transformer: 2100 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, $L_1 = 0.9337e\text{-}3$ H/km, $L_0 = 4.1264e\text{-}3$ H/ km, $C_1 = 12.74e\text{-}9$ F/ km, $C_0 = 7.751e\text{-}9$ 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, $\beta = 0$, $T_w = 2.67$ 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, $E_{fmin} = 0$, $E_{fmax} = 7$, $K_p = 0$

SSSC:Converter rating: Snom=100 MVA, System nominal voltage: Vnom=500 kV, Frequency: f=60 Hz, Maximum rate of change of reference voltage ($Vqref$)=3 pu/s, Converter impedances: R=0.00533, L=0.16, DC link nominal voltage: VDC=40 kV, DC link equivalent capacitance CDC=375_10ÿ6 F, Injected Voltage regulator gains: KP=0.00375, Ki=0.1875, DC Voltage regulator gains: KP=0.1_10ÿ3, Ki=20_10ÿ3, Injected voltage magnitude limit: Vq=70.2

STATCOM parameters: 500 KV, ±100 MVAR, R = 0.071, L = 0.22, Vdc = 40 KV, Cdc = 375 ± µ F, Vref = 1.0, Kp = 50, Ki = 1000

(ii) Multi-machine power system

Generators:
$S_{B1} = 4200$ MVA, $S_{B2} = S_{B2} = 2100$ MVA, $V_B = 13.8$ kV, $f = 60$ Hz, $X_d = 1.305$, $X_d' = 0.296$, $X_d'' = 0.252$, $X_q = 0.474$, $X_q' = 0.243$, $X_q'' = 0.18$, $T_d' = 1.01$s, $T_d'' = 0.053$s, $T_{q0}'' = 0.1$s, $R_s = 2.8544$ e -3, $H = 3.7$ s, $p = 32$

Transformers:
$S_{B1} = 4200$ MVA, $S_{B2} = S_{B3} = 2100$ MVA, D_1/Y_g, $V_1 = 13.8$ kV, $V_2 = 500$ kV, $R_1 = R_2 = 0.002$, $L_1 = 0$, $L_2 = 0.12$, $R_m = 500$, $L_m = 500$

Transmission lines: 3-Ph, $R_1 = 0.02546$ Ω/ km, $R_0 = 0.3864$ Ω/ km, $L_1 = 0.9337 \times 10^{-3}$ H/km, $L_0 = 4.1264 \times 10^{-3}$ H/ km, $C_1 = 12.74 \times 10^{-9}$ F/ km, $C_0 = 7.751 \times 10^{-9}$ F/ km, $L_1 = 175$ km, $L_2 = 50$ km, $L_3 = 100$ km

Loads: Load 1=7500 MW+1500 MVAR, Load 2=Load 3=25 MW, Load 4=250 M

REFERENCES

1. N.G. Hingorani, L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems (IEEE Press, New York, 2000).
2. L. Gyugyi, 1998. Solid-state control of electric power in ac transmission systems, in: Proceedings of the International Symposium on Electric Power and Energy Conversion Systems, Invited Paper, No. T-IP4.
3. L. Gyugyi, Dynamic compensation of ac transmission lines by solid-state synchronous voltage sources (IEEE Trans. Power Deliv. 9, 1994) pp. 904–911.
4. L. Gyugyi, et al., Static synchronous series compensator: a solid state approach to the series compensation of transmission lines (IEEE Trans. Power Deliv. 12, 1997) pp.406–417.
5. K.K. Sen, SSSC-static synchronous series compensator: theory, modeling, and applications (IEEE Trans.Power Deliv. 13, 1998) pp. 241-246.
6. H.F. Wang, Static synchronous series compensator to damp power system oscillations (Electr. Power Syst.Res. 54, 2000) pp.113-119.
7. D. Menniti, et al., Using a FACTS device controlled by a decentralised control law to damp the transient frequency deviation in a deregulated electric power system (Electr. Power Syst. Res. 72, 2004) pp. 289–298.
8. F.A.R. Al Jowder, B.T. Ooi, Series compensation of radial power system by a combination of SSSC and dielectric capacitors (IEEE Trans. Power Deliv. 20, 2005) pp. 458–465.
9. I. Ngamroo, et al., Robust decentralised frequency stabilisers design of static synchronous series compensators by taking system uncertainties into consideration (Int. J. Electr. Power Energy Syst. 28, 2006) pp.513–52.
10. R. Mihalic, I. Papic, Static synchronous series compensator-a mean for dynamic power flow control in electric power systems (Electr.PowerSyst.Res. 45, 1998) pp.65-71.
11. F.A.R. Al Jowder, Influence of mode of operation of the SSSC on the small disturbance and transient stability of a radial power system (IEEE Trans. Power Syst. 20, 2005) pp. 935–942.
12. M.S. Castro, et al., Impacts of the SSSC control modes on small-signal transient stability of a power system (Electr.Power Syst. Res.77, 2007) pp. 1–9.
13. S. Panda, N.P. Padhy, Comparison of particle swarm optimization and genetic algorithm for FACTS based controller design (Appl.SoftComput.8, 2008) pp.1418-1427.
14. S. Panda, et al., Power system stability improvement by PSO optimized SSSC-based damping controller (Electr. Power Comput.Syst.36, 2008) pp.468-490.
15. S. Panda, N.P. Padhy, Optimal location and controller design of STATCOM using particle swarm optimization. (J. Franklin Inst. 345, 2008) pp.166–181.
16. M.A. Abido, Analysis and assessment of STATCOM-based damping stabilizers for power system stability enhancement (Int. J. Electr. Power Energy Syst. 73, 2005) pp. 177–185.
17. S. Panda, Differential evolutionary algorithm for TCSC-based controller design, Simulation Modelling (Pract. Theory 17, 2009) pp. 1618–1634.
18. S. Panda, Multi-objective evolutionary algorithm for SSSC-based controller design (Electr. Power Syst. Res.79, 2009) pp.937–944
19. S. Panda, Application of non-dominated sorting genetic algorithm-II technique for optimal FACTS-based controller design (J. Franklin Inst. 347, 7, 2009) pp. 1047–1064.
20. H.M. Soliman, A. Dabroum, M.S. Mahmoud, M. Soliman, Guaranteed-cost reliable control with regional pole placement of a power system (J. Franklin Inst. 348, 2011) pp. 884–898.
21. R. Stron, K. Price, Differential evolution—a simple and efficient adaptive scheme for Global Optimization over continuous spaces (J. Global Optim. 11, 1995) pp. 341–359.
22. L. Eriksson, T. Oksanen, K. Mikkola, PID controller tuning rules for integrating processes with varying timedelays (J. Franklin Inst. 346 ,2009)pp. 470–487.
23. P.L. Liu, Stabilization criteria for neutral time delay systems with saturating actuators (J. Franklin Inst. 347, 2010) pp. 1577–1588.
24. H. Li, Qi. Zhou, B. Chen, H. Liu, Parameter-dependent obust stability for uncertain Markovian jump systems with time delay (J. Franklin Inst. 343, 2011) pp. 738–748.
25. D. Fei-Peng, H. Shuai-Tian, Exponential stability analysis and controller design of fuzzy systems with time delay (J. Franklin Inst.348, 2011) pp.865-883.
26. SimPowerSystems 4.3 User's Guide.
27. P. Kundur, Power System Stability and Control, McGraw-Hill, New York, 1994.
28. S. Ray, et al., A computational approach to optimal damping controller design for a GCSC (IEEE Trans. Power Deliv. 23, 2008) pp. 1673–1681.
29. A.D. Del Rosso, et al., A study of TCSC controller design for power system stability improvement (IEEE Trans. Power Syst. 18, 2003) pp. 1487–1496.
30. Y. Chang, Z. Xu, A novel SVC supplementary controller based on wide area signals (Electr. Power Syst. Res.77, 2007) pp.1569–1574.
31. P. Kundur, et al., Definition and classification to power system stability, IEEE Trans. Power Syst. 19 (2004) 1387–1401.
32. M. Noroozian, et al., Robust near-optimal control of power system oscillation with fuzzy logic, IEEE Trans. Power Deliv. 11 (1996) 393–400.
33. S. Mishra, et al., Genetically optimized neuro-fuzzy IPFC for damping modal oscillations of power system,IEEE Trans. Power Syst. 17 (2002) 1140–1147.

Assist.Prof. Sangram Keshori MOHAPATRA
Department of Electrical Engineering
CVRCE, Bhubaneswar, Odisha, India
E-mail: sangram_muna@rediffmail.com

Prof. Sidhartha PANDA
Department of Electrical & Electronics Engineering
VSSUT, Burla, Odisha, India
E-mail: panda_sidhartha@rediffmail.com

Sangram Keshori MOHAPATRA received M.tech degree from KIIT, University, Orissa, Bhubaneswer, India in 2008. Presently he is working as an Assistant Professor in the Department of Electrical Engineering, C.V. Raman College of Engineering, Bhubaneswar, Odisha, India. He worked in various reputed organizations for 12 years. His research interest is in the area of Power System Stability, FACTS and Optimization techniques.

Sidhartha PANDA is working as a Professor at VSSUT, Burla (erstwhile UCE, Burla). He received Ph.D. degree from IIT, Roorkee and M.E. degree from UCE, Burla in Electrical Engineering. Earlier he worked in various reputed organizations for 18 years. He has published about 65 papers in various International Journals. His areas of research include MATLAB/SIMULINK, Flexible AC Transmission Systems (FACTS), Modeling of Machines, Power Systems and FACTS, Controller Design, Power System Stability, Genetic Algorithm, Particle Swarm Optimization, Differential Evolution, Multi-objective Optimization, Economic Operation of Power System, Fuzzy Logic, Model Order Reduction, Distributed Generation and Wind Energy.