Power System Stability Improvement Using Differential Evolution Algorithm based Controller for STATCOM

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Abstract- This paper describes the power-system stability improvement by a static synchronous compensator (STATCOM) based damping controller with Differential evolution (DE) algorithm is used to find out the optimal controller parameters. The present study considered both local and remote signals with associated time delays. The performances of the proposed controllers have been compared with different disturbances for both single-machine infinite bus power system and multi-machine power system. The performance of the proposed controllers with variations in the signal transmission delays has also been investigated. To show the effectiveness and robustness of the proposed controller the Simulation results are presented under different disturbances and loading conditions.

Index Terms- Static synchronous compensator, controller design, time delay, power system stability, Differential evolution algorithm, single-machine infinite-bus power system

I. 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 shunt compensation is highly effective in both controlling power flow in the lines and in improving stability [2, 3]. 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 [4]. 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 [1,6-7] Static synchronous Compensator (STATCOM) is member of FACTS family that is connected in shunt with the system [8, 9]. In order to increase of the system and damping response which makes the inverter in the STATCOM to inject voltage or current to compensate the three phase fault [10].Even though the primary purpose of STATCOM is to support bus voltage by injecting (or absorbing) reactive power, it is also capable of improving the power system stability [11]. When a STATCOM is present in a power system to support the bus voltage, a supplementary damping controller could be designed to modulate the STATCOM bus voltage in order to improve damping of system oscillations [12,13].Artificial intelligence-based approaches have been proposed recently to design a FACTS-based supplementary damping controller. These approaches include particle swarm optimization [14, 16], genetic algorithm [15], differential evolution [16], multi-objective evolutionary algorithm [17] 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. Despite significant strides in the development of advanced control schemes over the past two decades, the conventional lead-lag structure controller remains the controllers 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 STATCOM reference voltage. A number of conventional techniques have been reported in the literature pertaining to design problems of lead-lag structure controller, namely the eigen value assignment, mathematical programming, gradient procedure for optimization, and also the modern control theory. 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 1995 for optimization problems [19]. 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]. In recent years, the fast development of communication technology, low price communication devices and various communication media makes it possible to provide the control center with the real time signals from remote areas. However, the use of centralized controller entails inputs that may arrive after a certain time delay. Time delays can make the control system have less damping features. In order to satisfy specifications for wide-area control systems, the design of a controller should take into account this time delay in order to provide a controller that is robust, not only for the range of operating conditions desired, but also for the uncertainty in delay. Recently there is a growing interest in designing the controllers in the presence of uncertain time delays [20-21]. In view of the above, this paper investigates the design of a STATCOM-based damping controller considering the potential time delays. Line active power as local signal and speed deviation as remote signal are considered as candidate input signals for the proposed STATCOM based damping controller. For controller design, differential evolution algorithm is employed to tune controller parameters. To show the robustness of the proposed design approach, simulation results are presented under various disturbance and faults for single-machine infinite-bus.

II. SYSTEM MODEL

To design and optimize the STATCOM-based damping controller, a single-machine infinite-bus system with STATCOM, 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 STATCOM 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 [18]. In Fig. 1, *T*rf represents the transformer; V_T and V_B are the generator terminal and infinite-bus voltages respectively. All the relevant parameters are given in Appendix. STATCOM is basically a synchronous voltage source generating controllable AC behind a transformer leakage reactance. The voltage source converter is connected to an energy storage unit, usually a DC capacitor. The voltage difference across the reactance produces the reactive power exchange between the STATCOM and the power system.

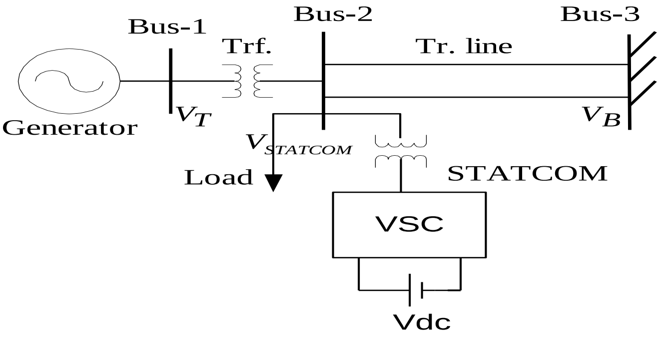

Fig.1 Single-machine infinite-bus power system with STATCOM

III. THE PROPOSED APPROACH

A. Structure of STATCOM-based damping controller

Here lead–lag structure shown inFig.2 is considered as a STATCOM-based damping controller. 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 [3]. 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 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 $V_{STATCOM\_ref}$.

B. Problem formulation

In the lead-lag structured controllers, the washout time constants T_W is usually pre-specified [1]. 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. 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:

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

In the present study, an integral time absolute error of the speed deviations is taken as the objective function J expressed as:

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| \cdot t \cdot dt \qquad (2)$$

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 STATCOM controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

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Minimize J (3)

Subject to

$$K_S^{\min} \le K_S \le K_S^{\max}$$
$$T_{1S}^{\min} \le T_{1S} \le T_{1S}^{\max}$$
$$T_{2S}^{\min} \le T_{2S} \le T_{2S}^{\max}$$
$$T_{3S}^{\min} \le T_{3S} \le T_{3S}^{\max}$$

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

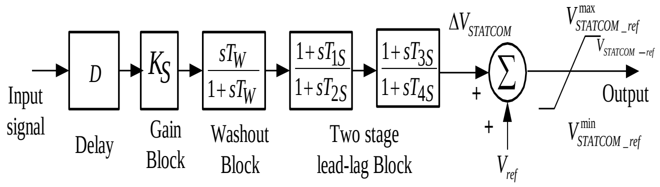

Fig. 2 Structure of proposed STATCOM-based damping controller

IV. DIFFERENTIAL EVOLUTION

Differential Evolution (DE) algorithm is a stochastic, population-based optimization algorithm recently introduced [19]. 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];

A. 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].

B. 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:

$$V_{i,G+1} = X_{r1,G} + F.(X_{r2,G} - X_{r3,G}) \qquad (5)$$

Where *F* is a constant from (0, 2)

C. 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:

$$U_{j,i,G+1} = \begin{cases} V_{j,i,G+1} & if \quad rand_{j,i} \le CR \quad or \quad j = I_{rand} \\ X_{j,i,G+1} & if \quad rand_{j,i} > CR \quad or \quad j \ne I_{rand} \end{cases} \qquad (6)$$

With $rand_{j,i}$ ~ 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 $V_{i,G+1} \ne X_{i,G}$.

D. 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:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & if \;\; f(U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G} & otherwise. \end{cases} \qquad (7)$$

where $i \in [1, N_P]$.

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

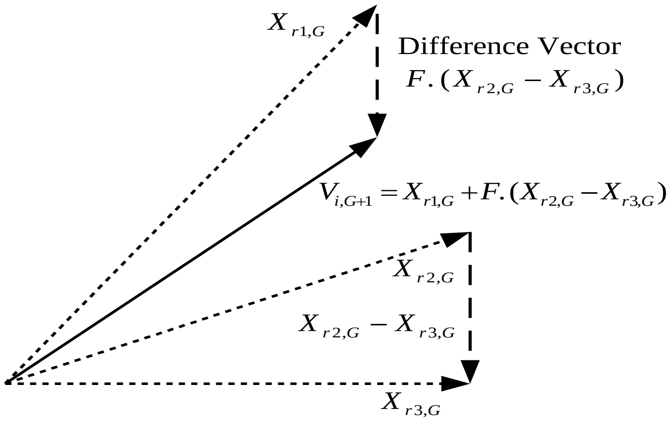

Fig. 3 Vector addition and subtraction in DE to generate a new candidate solution

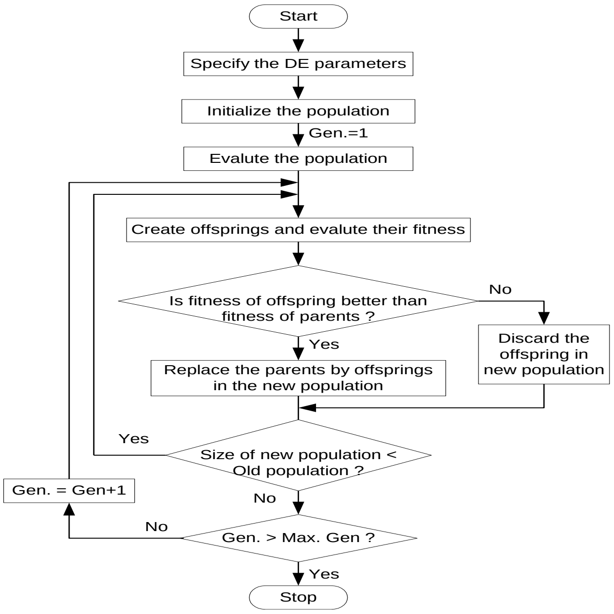

Fig. 4: Flow chart of proposed DE optimization approach

V. RESULTS AND DISCUSSIONS

The optimization of the proposed SVC-based damping controller parameters is carried out by minimizing the fitness given in Eq. (2) employing Differential Evolution algorithm.

The model of the system under study has been developed in MATLAB/SIMULINK environment and RCGA programme has been written in .m file. 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 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. Simulations were conducted on a Pentium 4, 3 GHz, 1 GB RAM computer, in the MATLAB 7.8.4 environment. 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-I.

Table I .STATCOM based controller parameters for SMIB power system

Signal/parameters	Ks	T_{1s}	T_{2s}	T_{3s}	T_{4s}
Remote	197.7727	2.3244	1.0297	0.0109	1.3568
Local	49.5691	1.5243	0.8222	2.2033	0.3422

Table II Loading conditions consider

Loading conditions	Pe in per unit (pu)	δ_0 in Degree
Nominal	0.85	51.51^0
Light	0.5	29.33^0
Heavy	1	60.73^0

A. 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 STATCOM controller is the speed deviation/electrical power, the 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 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 STATCOM-based controller. The following cases are considered:

Case I: Nominal loading:

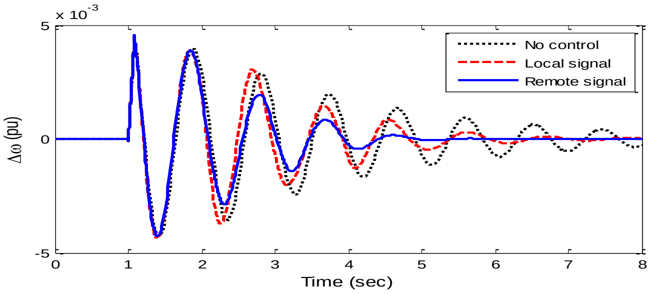

Fig. 5 Speed deviation response for 5 cycle 3-ph fault in transmission line with nominal loading

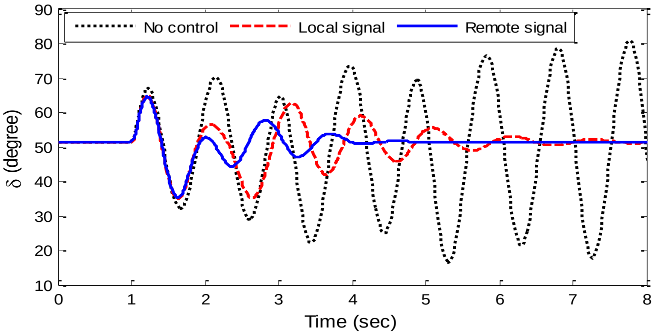

Fig. 6 Rotor angle response for 5cycle 3-ph fault in transmission line with nominal loading

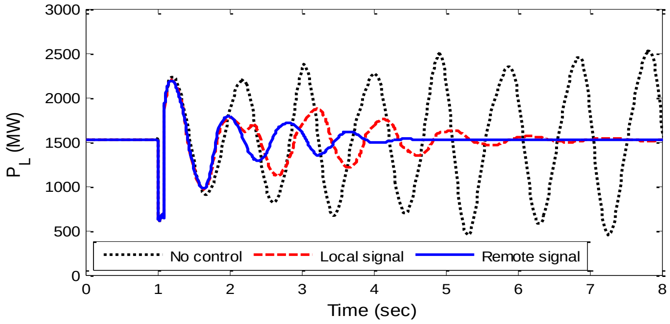

Fig.7 Tie-line power flow response for 5 cycle 3-ph fault in transmission line with nominal loading.

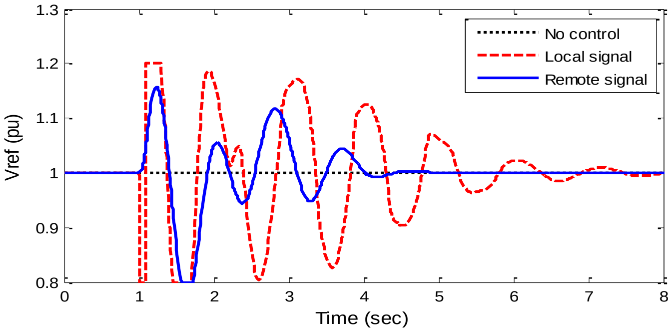

Fig. 8 Vref voltage with nominal loading

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. 5-8 where, the response without control (no control) is shown with dotted line, and the response with proposed approach with Local signal are considered is shown with dash line and time delay with Remote signal are considered with solid line respectively. For comparison, It can be seen from Figs. 5-8 that when potential time delays are considered the proposed approach Remote signal with time delay is better than Local signal.

Case II: Light loading:

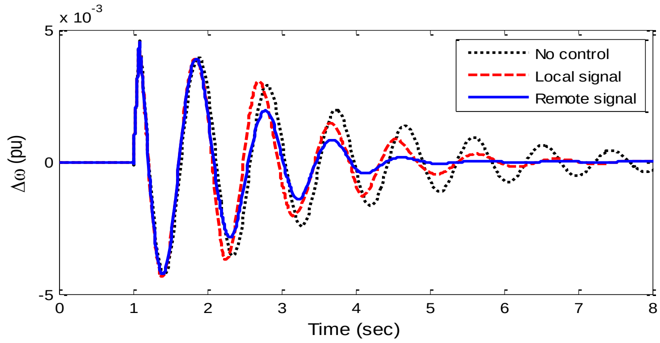

Fig. 9 Speed deviation response for 5 cycle 3-ph fault in transmission line with Light loading

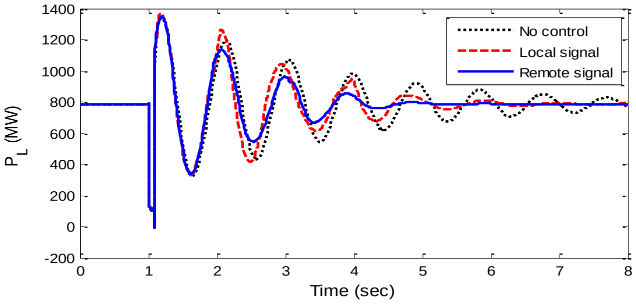

Fig. 10 Tie-line power flow response for 5 cycle 3-ph fault in transmission line with Light loading

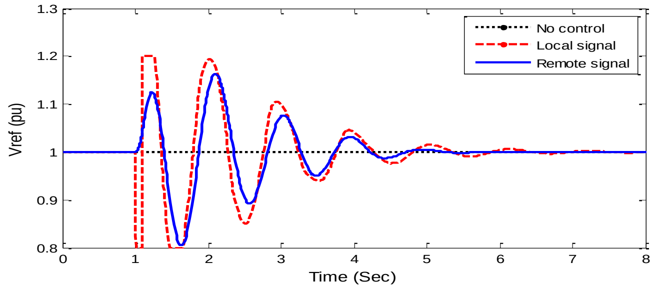

Fig.11 Vref voltage with Light loading

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 II. 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.9-11 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.

Case III: Heavy loading:

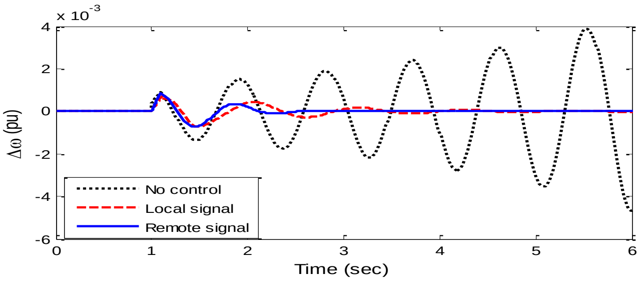

Fig. 12 Speed deviation response for 5 cycle 3-ph fault in transmission line with Heavy loading

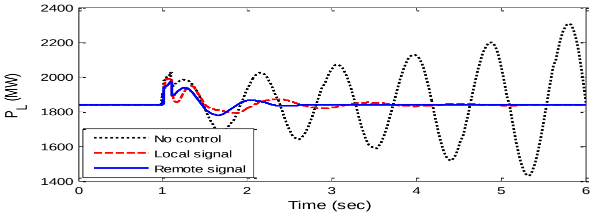

Fig. 13 Tie-line power flow response for 5 cycle 3-ph fault in transmission line with Heavy loading.

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 12-13 from which it is clear that the system is unstable without control under this severe disturbance and the stability of the system is maintained with the proposed DE optimized STATCOM-based damping controller

Case IV: Effect of signal transmission delay:

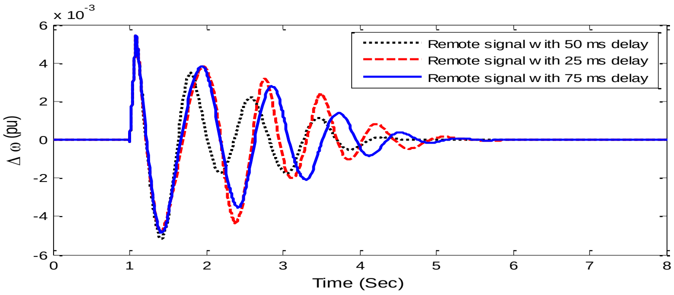

Fig. 14 Speed deviation response showing for case-IV

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. 14 that the performances of the proposed controllers are hardly affected by the signal transmission delays.

VI.CONCLUSION

This paper has thoroughly investigated power system stability improvement by a static synchronous compensator (STATCOM)-based damping controller. The design problem is formulated as an optimization problem, Differential Evolution (DE) algorithm is employed to search for the optimal controller parameters. The performance of the proposed controller is evaluated under different disturbances for single-machine infinite bus power system using both local and remote signals. It is observed that from power system stability improvement point of view 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 [18].

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, $R_1 = 0.02546\ \Omega/\text{km}$,

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, $E_{fmin} = 0$, $E_{fmax} = 7$, $K_p = 0$
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

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