IMPROVING POWER SYSTEM STABILITY USING REAL-CODED GENETIC ALGORITHM BASED PI CONTROLLER FOR STATCOM

Sangram Keshore Mohapatra
C V Raman College of Engineering, Bhubaneswar, Odisha, India, sangram_muna@rediffmail.com

Kumaresh Rout
Gandhi Institute for Technological Advancement, Bhubaneswar, Odisha, India, kumar.brave@gmail.com

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SANGRAM KESHORI MOHAPATRA[1] & KUMARESH ROUT[2]

[1]Dept. of Electrical Engineering, C V Raman College of Engineering, Bhubaneswar, Odisha, India
[2]Dept. of Electrical & Electronics, Gandhi Institute for Technological Advancement, Bhubaneswar, Odisha, India
E-mail : sangram_muna@rediffmail.com[1], kumar.brave@ gmail.com[2]

Abstract – In this paper investigates the power-system stability improvement by a static synchronous compensator (STATCOM) based damping controller. The present study is considered both local and remote signals. The design problem of the proposed controller is formulated as an optimization problem, and Real-Coded Genetic (RCGA) algorithm is employed to search for the optimal controller parameters. The performances of the proposed controllers are evaluated under different disturbances and loading conditions for single-machine infinite bus power system. The performance of the proposed controllers has been investigated. Simulation results are presented under various operating conditions and disturbances to show the effectiveness and robustness of the proposed approach

Keywords – *Static synchronous compensator, PI controller design, power system stability, Real-coded genetic algorithm, single-machine infinite-bus power system.*

I. INTRODUCTION

The recent advances in power electronics have led to the development of the flexible alternating current transmission system (FACTS) [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]. Power systems are complex, nonlinear and often exhibit low-frequency power oscillations due to inadequate system damping. Satisfactory damping of power system oscillations is an important issue addressed when dealing with rotor angle stability of power systems [3]. With the advent of Flexible AC Transmission System (FACTS) technology, STATCOM is a shunt FACTS devices and it has been employed to control the reactive power flow in the power. In addition to voltage control, which is the main tasks of the STATCOM, it may also be employed for additional tasks such as stability of power system [1, 4,5-6]. Static Synchronous Compensator (STATCOM) is member of FACTS family that is connected in shunt with the system [7]. Even though the primary purpose of STATCOM is to support bus voltage by supplying (or absorbing) reactive power, it is also capable of improving the power system stability [8, 9]. 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 etc. In the design of an efficient and effective damping controller, selection of the appropriate input signal is a primary issue. Most of the literatures on STATCOM are based on small disturbance analysis that requires linearization of the system involved. However, liner methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for tuning the STATCOM controller in that, the controllers tuned to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances. Despite significant strides in the development of advanced control schemes over the past two decades, the classical proportional-integral (PI) controller and its variants, remain the controllers of choice in many industrial applications. This controller structure remains an engineer's preferred choice because of their structural simplicity, reliability, and the favorable ratio between performance and cost. Beyond these benefits, these controllers also offer simplified dynamic modeling, lower user-skill requirements, and minimal development effort, which are issues of substantial importance to engineering practice [10].

The problem of FACTS controller parameter tuning is a complex exercise. A number of conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers .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

Genetic Algorithm (GA) appeared as a promising evolutionary technique for handling the optimization problems [11]. GA has been popular in academia and the industry mainly because of its intuitiveness, ease of implementation, and the ability to effectively solve highly nonlinear, mixed integer optimization problems that are typical of complex engineering systems. In view of the above, this paper proposes to use Real coded genetic algorithm (RCGA) optimization technique for the STATCOM-based controller.

In this paper, a comprehensive assessment of the effects of STATCOM-based damping controller has been carried out. Here STATCOM-based controller structure i.e. proportional-integral (PI) structure is considered. The design problem of the proposed controller is transformed into an optimization problem. The design objective is to improve the stability of a single-machine infinite-bus (SMIB) power system, subjected to severe disturbances. GA-based optimal tuning algorithm is used to optimally tune the parameters of this controller. The proposed controller shave been applied, tested and compared on a weakly connected power system. The dynamic performances of the PI structured STATCOM-controller is analyzed at different loading conditions and under various disturbance condition.

II. SYSTEM MODEL

A. Single-Machine infinite-bus power system with STATCOM

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 [12]. In Fig. 1, Trf 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
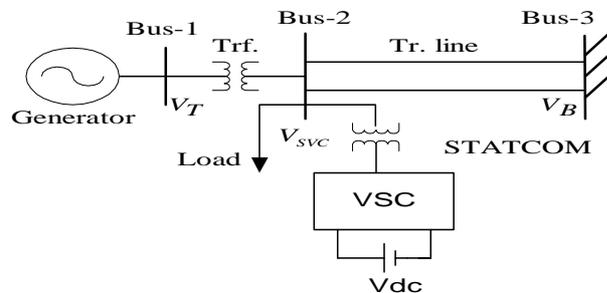
Fig. 1 : Single-machine infinite-bus power system with STATCOM

III. THE PROPOSED APPROACH

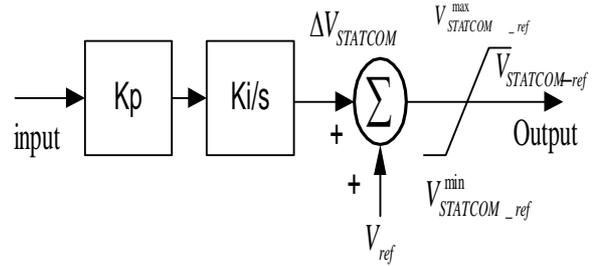### A. Structure of STATCOM based damping controller.

Fig. 2 : Structure of STATCOM based controller.

In Fig.2 the proportional, integral parameters of the PI controller are Kp, Ki respectively and 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 present study, an integral time absolute error of the speed deviations is taken as the objective function J expressed as:

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

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.

Minimize J $\qquad$ (2)

Subject to

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

$$Ki^{min} \leq Ki \leq K_i^{max} \qquad (3)$$

IV. OVERVIEW OF GENETIC ALGORITHM (GA)

The Genetic algorithm (GA) has been used to solve difficult engineering problems that are complex and difficult to solve by conventional optimization methods. GA maintains and manipulates a population of solutions and implements a survival of the fittest strategy in their search for better solutions. The fittest individuals of any population tend to reproduce and

survive to the next generation thus improving successive generations. The inferior individuals can also survive and reproduce. Implementation of GA requires the determination of six fundamental issues: chromosome representation, selection function, the genetic operators, initialization, termination and evaluation function. Brief descriptions about these issues are provided in the following sections.

A. Chromosome representation

Chromosome representation scheme determines how the problem is structured in the GA and also determines the genetic operators that are used. Each individual or chromosome is made up of a sequence of genes. Various types of representations of an individual or chromosome are: binary digits, floating point numbers, integers, real values, matrices tc. Generally natural representations are more efficient and produce better solutions. Real-coded representation is more efficient in terms of CPU time and offers higher precision with more consistent results [12]

B. Selection function

To produce successive generations, selection of individuals plays a very significant role in a genetic algorithm. The selection function determines which of the individuals will survive and move on to the next generation. A probabilistic selection is performed based upon the individual's fitness such that the superior

individuals have more chance of being selected. There are several schemes for the selection process: roulette wheel selection and its extensions, scaling techniques, tournament, normal geometric, elitist models and ranking methods. The selection approach assigns a probability of selection P_j to each individuals based on its fitness value. In the present study, normalized geometric selection function has been used.In normalized geometric ranking, the probability of selecting an individual Pi is defined as:

$$P_i = q'(1-q)^{r-1} \qquad (4)$$

$$q' = \frac{q}{1-(1-q)^P} \qquad (5)$$

Where

q = probability of selecting the best individual

r = rank of the individual (with best equals 1)

P = population size

C. Genetic operators

The basic search mechanism of the GA is provided by the genetic operators. There are two basic types of operators: crossover and mutation. These operators are used to produce new solutions based on existing solutions in the population. Crossover takes two individuals to be parents and produces two new individuals while mutation alters one individual to produce a single new solution. The following genetic operators are usually employed: simple crossover, arithmetic crossover and heuristic crossover as crossover operator and uniform mutation, non-uniform mutation, multi-non-uniform mutation, boundary mutation as mutation operator. Arithmetic cross over and non-uniform mutation are employed in the present study as genetic operators. Crossover generates a random number r from a uniform distribution from 1 to m and creates two new individuals by using equations:

$$x'_i = \begin{cases} x_i, & if\ i < r \\ y_i, & otherwise \end{cases} \qquad (6)$$

$$y'_i = \begin{cases} y_i, & if\ i < r \\ x_i, & otherwise \end{cases} \qquad (7)$$

Arithmetic crossover produces two complimentary linear combinations of the parents, where $r = U(0, 1)$:

$$\bar{X}' = r\bar{X} + (1 - r)\bar{Y} \qquad (8)$$

$$\bar{Y}' = r\bar{Y} + (1 - r)\bar{X} \qquad (9)$$

Non-uniform mutation randomly selects one variable j and sets it equal to an non-uniform random number

$$x'_i = \begin{cases} x_i + (b_i - x_i)\ f(G) & if\ r_1 < 0.5, \\ x_i + (x_i + a_i)\ f(G) & if\ r_1 \geq 0.5, \\ x_i, & otherwise \end{cases}$$

Where,

$$f(G) = \left(r_2 \left(1 - \frac{G}{G_{max}} \right) \right)^b$$

r_1, r_2 = uniform random nos. between 0 to 1.

G = current generation.

G_{max} = maximum no. of generations.

b = shape parameter.

D. Initialization, termination and evaluation function

An initial population is needed to start the genetic algorithm procedure. The initial population can be randomly generated or can be taken from other methods. The GA moves from generation to generation until a stopping criterion is met. The stopping criterion could be maximum number of generations, population convergence criteria, lack of improvement in the best solution over a specified number of generations or target value for the objective function. Evaluation functions or objective functions of many form scan be used in a GA so that the function can map the population into a partially ordered set.

V. RESULTS AND DISCUSSIONS

The optimization of the proposed STATCOM-based damping controller parameters is carried out by minimizing the fitness given in Eq. (1) employing RCGA. 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. SVC-based controller parameters for SMIB power system

Signal/parameters	Kp	Ki
Remote	15.3449	174.9005
Local	184.3194	56.5611

Table II. Loading conditions considered

Loading conditions	P_e in per unit (pu)	δ_0 in Degree
Nominal	0.85	51.5^0
Light	0.5	29.32^0
Heavy	1.0	60.74^0

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:

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. 3-6 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 Remote signal are considered with solid line respectively. For comparison, It can be seen from Figs. 3-6 that the proposed approach Remote signal is better than Local signal.
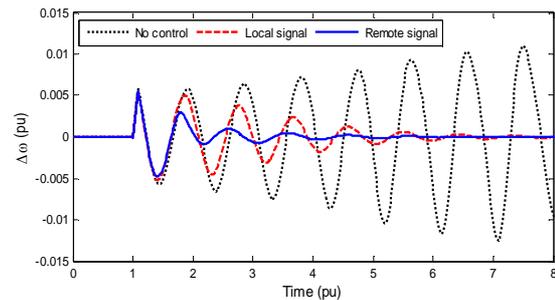

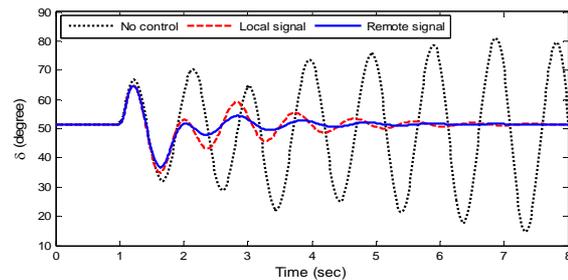**Fig. 3 : Speed deviation response for 5 cycle 3-ph fault in transmission line with nominal loading**

Fig. 4 : Rotor angle response for 5cycle 3-ph fault in transmission line with nominal loading
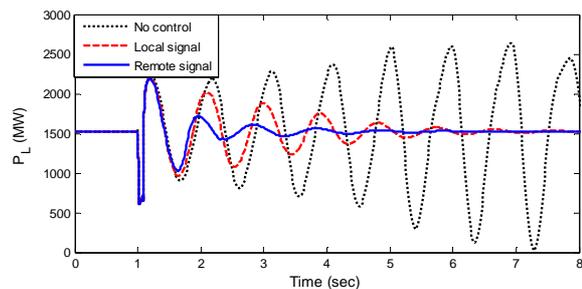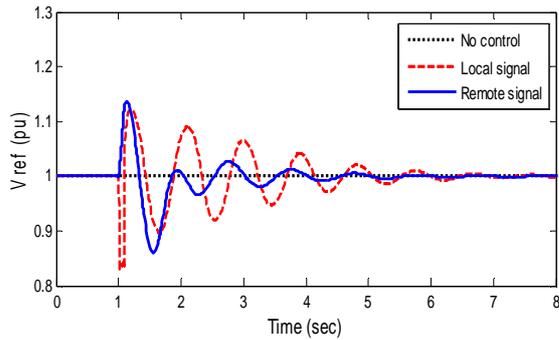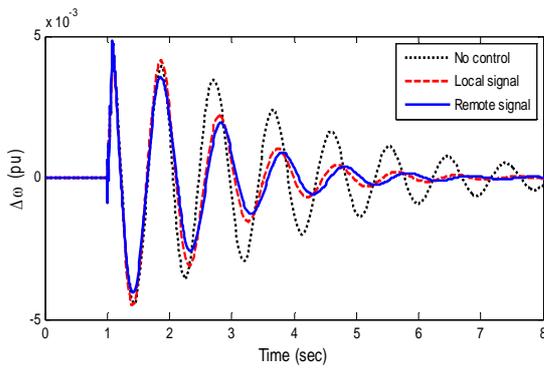

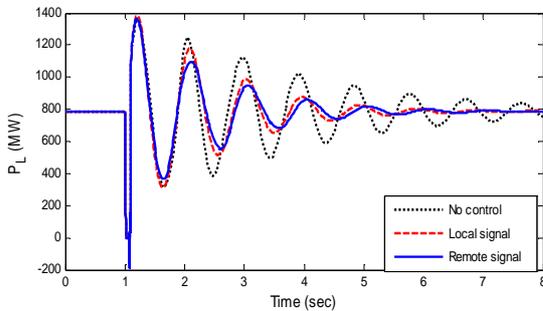**Fig. 5 : Tie-line power flow response for 5 cycle 3-ph fault in transmission line with nominal loading.**

Fig. 6 : V_ref voltage with nominal loading.

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

Fig. 7 : Speed deviation response for 5 cycle 3-ph fault in transmission line with Light loading
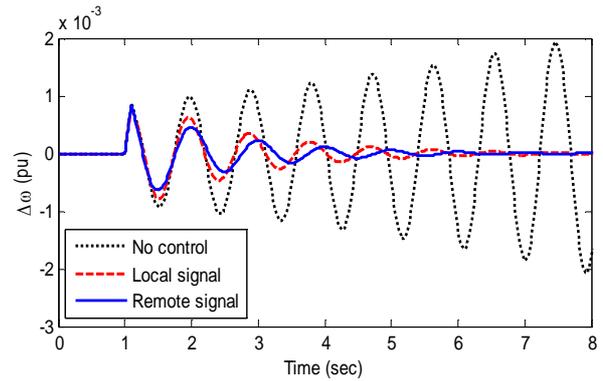

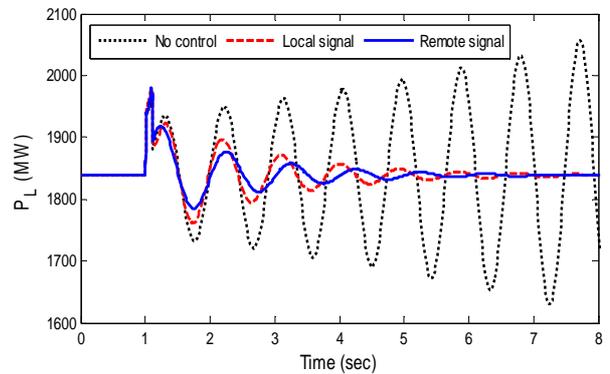**Fig. 8 : Tie-line power flow response for 5 cycle 3-ph fault in transmission line with Light loading**

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.7-8 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.

3) Heavy loading, small disturbance:

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

Fig. 10 : 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 9-10 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 GA optimized STATCOM-based damping controller.

VI. CONCLUSION

In this study, power system stability improvement by a static synchronous compensator (STATCOM)-based damping controller is thoroughly investigated. The design problem is formulated as an optimization problem, Real-coded Genetic algorithm (RCGA) 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 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 [12].

(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-3 H/km, L_0 = 4.1264e-3 H/ km, C_1 = 12.74e-9 F/ km, C_0 = 7.751e-9 F/ km

*Hydraulic turbine and governo*r: K_a = 3.33, T_a = 0.07, G_{min} = 0.01, G_{max} = 0.97518, V_{gmin} = - 0.1 pu/s, V_{gmax} = 0.1 pu/s, R_p = 0.05, K_p = 1.163, K_i = 0.105, K_d = 0, T_d = 0.01 s,β = 0, T_w = 2.67 s

Excitation system: T_{LP} = 0.02 s, K_a = 200, Ta = 0.001 s, K_e = 1, T_e = 0, T_b = 0, Tc = 0, K_f = 0.001, Tf = 0.1 s, E_{fmin} = 0, E_{fmax} = 7, K_p = 0

STATCOM parameters: 500 KV, ±200 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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