

# Optimal Supplementary Damping Controller Design for TCSC Employing RCGA

S. Panda, S. C. Swain, A. K. Baliarsingh, C. Ardil

**Abstract**—Optimal supplementary damping controller design for Thyristor Controlled Series Compensator (TCSC) is presented in this paper. For the proposed controller design, a multi-objective fitness function consisting of both damping factors and real part of system electromechanical eigenvalue is used and Real- Coded Genetic Algorithm (RCGA) is employed for the optimal supplementary controller parameters. The performance of the designed supplementary TCSC-based damping controller is tested on a weakly connected power system with different disturbances and loading conditions with parameter variations. Simulation results are presented and compared with a conventional power system stabilizer and also with the TCSC-based supplementary controller when the controller parameters are not optimized to show the effectiveness and robustness of the proposed approach over a wide range of loading conditions and disturbances.

**Keywords**—Power System Oscillations, Real-Coded Genetic Algorithm (RCGA), Thyristor Controlled Series Compensator (TCSC), Damping Controller, Power System Stabilizer.

## I. INTRODUCTION

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 [1]. 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 [2-4].

Series capacitive compensation was introduced decades ago to cancel a portion of the reactance line impedance and thereby increase the transmittable power. Subsequently, with the FACTS technology initiative, variable series compensation is highly effective in both controlling power flow in the transmission line and in improving stability. Thyristor

Controlled Series Compensator (TCSC) is one of the important members of FACTS family that is increasingly applied with long transmission lines by the utilities in modern power systems. It can have various roles in the operation and control of power systems, such as scheduling power flow; decreasing unsymmetrical components; reducing net loss; providing voltage support; limiting short-circuit currents; mitigating subsynchronous resonance; damping the power oscillation; and enhancing transient stability [5-7]. Even though the primary purpose of TCSC is to control the power flow and increase the loading capacity of transmission lines, it is also capable of improving the power system stability. When a TCSC is present in a power system to control the power flow, a supplementary damping controller could be designed to modulate the TCSC reactance during small disturbances in order to improve damping of system oscillations [8, 9].

A conventional lead-lag controller 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. Traditionally, for the small signal stability studies of a power system, the linear model of Phillips-Heffron has been used for years, providing reliable results. Although the model is a linear model, it is quite accurate for studying low frequency oscillations and stability of power systems. The problem of TCSC supplementary damping 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 namely the pole placement technique [10], phase compensation/root locus technique [11], residue compensation [12], 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. Also, the designed controller should provide some degree of robustness to the variations loading conditions, and configurations as the machine parameters change with operating conditions. A set of controller parameters which stabilise the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations [8, 9].

In recent years, one of the most promising research fields has been “Evolutionary Techniques”, an area utilizing

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analogies with nature or social systems. These techniques constitute an approach to search for the optimum solutions via some form of directed random search process. Evolutionary techniques are finding popularity within research community as design tools and problem solvers because of their versatility and ability to optimize in complex multimodal search spaces applied to non-differentiable objective functions.

Recently, Genetic Algorithm (GA) appeared as a promising evolutionary technique for handling the optimization problems [13]. 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 optimisation problems that are typical of complex engineering systems. It has been reported in the literature that Real-Coded Genetic Algorithm (RCGA) is more efficient in terms of CPU time and offers higher precision with more consistent results. In view of the above, this paper proposes to use RCGA optimization technique for the optimal supplementary damping controller design. For the proposed controller design, a multi-objective objective function where both damping factors and real part of system electromechanical eigenvalue are considered. The optimal supplementary TCSC controller parameters are obtained employing RCGA. The proposed supplementary damping controller is tested on a weakly connected power system with different disturbances and loading conditions with parameter variations. Simulation results are presented to show the effectiveness and robustness of the proposed approach over a wide range of loading conditions and disturbances.

The remainder of the paper is organized in five major sections. A brief review of TCSC is presented in Section II. Power system modeling with the proposed TCSC-based supplementary damping controller is presented in Section III. The design problem and the objective function are presented in section IV. In Section V, an overview of RCGA is presented. The results are presented and discussed in Section VI. Finally, in Section VII conclusions are given.

## II. OVERVIEW OF TCSC

The basic circuit module of Thyristor Controlled Series Compensator (TCSC) scheme is shown in Fig. 1. It consists of the series compensating capacitor shunted by a Thyristor Controlled Reactor (TCR). In practical TCSC implementation several such basic modules may be connected in series to obtain the desired voltage rating and operating characteristics.

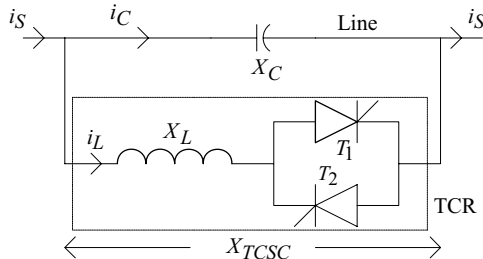


Fig. 1. Basic circuit module of TCSC

Fig. 2 shows typical variation of  $X_{TCSC}(\alpha)$  vs. firing angle  $\alpha$ . The degree of series compensation is controlled by increasing or decreasing the thyristor conduction period and thereby the current through the TCR. The firing angle  $\alpha$  of the TCR is defined as the angle in electrical degrees between the positive going zero crossing of the voltage across the inductor and the positive going zero crossing of the current through it. Firing angles below  $90^\circ$  have no control over the inductor current, while the firing angles above  $180^\circ$  are not allowed because the thyristor valves must be fired symmetrically. With the usual TCSC arrangement in which the impedance of the TCR reactor  $X_L$ , is smaller than that of capacitor,  $X_C$  the TCSC has two operating ranges around its internal resonance: one is the  $\alpha_{Clim} \leq \alpha \leq \pi/2$  range, where  $X_{TCSC}(\alpha)$  is the capacitive, and the other is the  $0 \leq \alpha \leq \alpha_{Lim}$  range, where  $X_{TCSC}(\alpha)$  is inductive, as illustrated in Fig. 2.

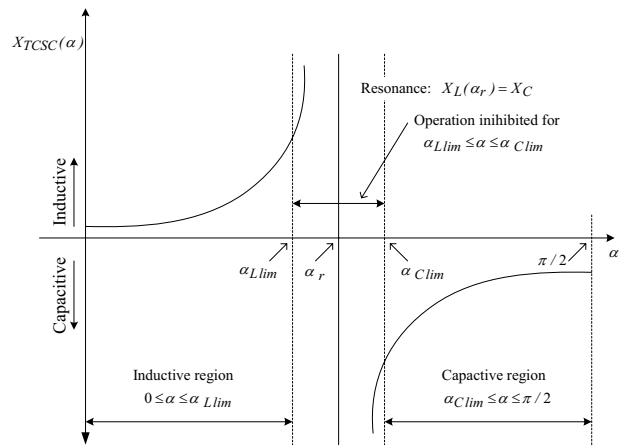


Fig. 2 Variation of  $X_{TCSC}(\alpha)$  with firing angle  $\alpha$  of TCSC

## III. MODELING THE POWER SYSTEM WITH TCSC SUPPLEMENTARY DAMPING CONTROLLER

The single-machine infinite-bus (SMIB) power system installed with a TCSC as shown in Fig. 3 is considered in this study. In the figure  $X_T$  and  $X_{TL}$  represent the reactance of the transformer and the transmission line respectively,  $V_T$  and  $V_B$  are the generator terminal and infinite bus voltage respectively.

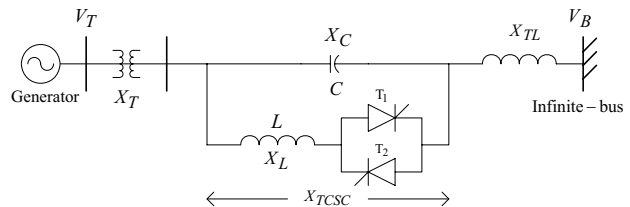


Fig. 3 Single-machine infinite-bus power system with TCSC

### A. Non-Linear Equations

The non-linear differential equations of the SMIB system with TCSC are derived by neglecting the resistances of all components of the system (generator, transformer and transmission lines) and the transients of the transmission lines and transformer. The non-linear differential equations are [9]:

$$\begin{aligned}\dot{\delta} &= \omega_b \Delta \omega \\ \dot{\omega} &= \frac{1}{M} [P_m - P_e] \\ \dot{E}'_q &= \frac{1}{T'_{do}} [-E_q + E_{fd}] \\ \dot{E}'_{fd} &= \frac{K_A}{1 + sT_A} [V_R - V_T]\end{aligned}\quad (1)$$

where,

$$P_e = \frac{E'_q V_B}{X_{d\Sigma'}} \sin \delta - \frac{V_B^2 (X_q - X'_d)}{2X_{d\Sigma'} X_{q\Sigma'}} \sin 2\delta$$

$$E_q = \frac{X_{d\Sigma'} E'_q}{X_{d\Sigma'}} - \frac{(X_q - X'_d)}{X_{d\Sigma'}} V_B \cos \delta$$

$$V_{Td} = \frac{X_q V_B}{X_{q\Sigma'}} \sin \delta$$

$$V_{Tq} = \frac{X_{Eff} E'_q}{X_{d\Sigma'}} + \frac{V_B X'_d}{X_{d\Sigma'}} \cos \delta$$

$$V_T = \sqrt{(V_{Td}^2 + V_{Tq}^2)}$$

$$X_{Eff} = X_T + X_{TL} - X_{TCSC}(\alpha)$$

$$X'_{d\Sigma'} = X'_d + X_{Eff}, \quad X'_{q\Sigma'} = X_q + X_{Eff}$$

$$X_{d\Sigma} = X_d + X_{Eff}$$

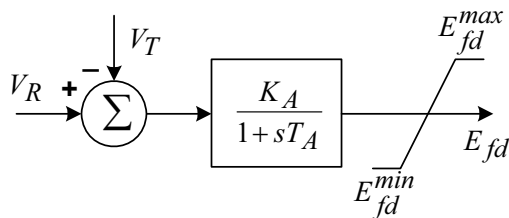


Fig. 4 Simplified IEEE type ST 1A excitation system

The simplified IEEE Type-ST1A excitation system is considered in this work. The diagram of the IEEE Type-ST1A excitation system is shown in Fig. 4. The inputs to the excitation system are the terminal voltage  $V_T$  and reference voltage  $V_R$ . The gain and time constants of the excitation system are represented by  $K_A$  and  $T_A$  respectively.

### B. Linearized Equations

In the design of electromechanical mode damping stabilizer, a linearized incremental model around an operating point is usually employed. The Phillips-Heffron model of the power system with FACTS devices is obtained by linearizing the set of equations (1) around an operating condition of the power system. The linearized expressions are as follows:

$$\begin{aligned}\dot{\Delta \delta} &= \omega_b \Delta \omega \\ \dot{\Delta \omega} &= [-K_1 \Delta \delta - K_2 \Delta E'_q - K_P \Delta \sigma - D \Delta \omega] / M \\ \dot{\Delta E'_q} &= [-K_3 \Delta E'_q - K_4 \Delta \delta - K_Q \Delta \sigma + \Delta E_{fd}] / T'_{do} \\ \dot{\Delta E_{fd}} &= [-K_A (K_5 \Delta \delta + K_6 \Delta E'_q + K_V \Delta \sigma) - \Delta E_{fd}] / T_A\end{aligned}\quad (2)$$

where,

$$K_1 = \partial P_e / \partial \delta, \quad K_2 = \partial P_e / \partial E'_q, \quad K_P = \partial P_e / \partial \sigma$$

$$K_3 = \partial E_q / \partial E'_q, \quad K_4 = \partial E_q / \partial \delta, \quad K_Q = \partial E_q / \partial \sigma$$

$$K_5 = \partial V_T / \partial \delta, \quad K_6 = \partial V_T / \partial E'_q, \quad K_V = \partial V_T / \partial \sigma$$

The modified Phillips-Heffron model of the single-machine infinite-bus (SMIB) power system with TCSC-based damping controller is obtained using linearized equation set (2). The corresponding block diagram model is shown in Fig. 5.

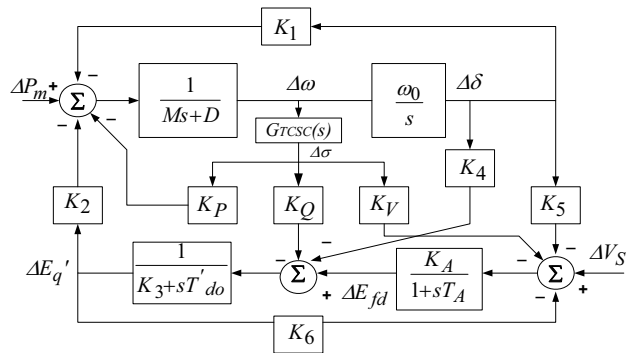


Fig. 5 Modified Phillips-Heffron model of SMIB with TCSC-based supplementary damping controller

## IV. THE PROPOSED APPROACH

## A. Structure of Proposed TCSC-based Supplementary Damping Controller

The commonly used lead-lag structure is chosen in this study as TCSC-based supplementary damping controller as shown in Fig. 6. The structure consists of a gain block; a signal washout block and two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter which allows signals associated with oscillations in input signal to pass unchanged. Without it steady changes in input would modify the output.

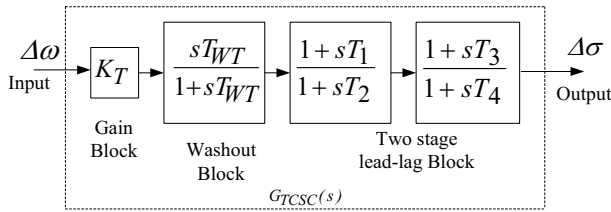


Fig. 6. Structure of the proposed TCSC-based supplementary damping controller

The input signal of the proposed TCSC-based controller is the speed deviation  $\Delta\omega$  and the output is the change in conduction angle  $\Delta\sigma$ . During steady state conditions  $\Delta\sigma = 0$  and so the effective reactance  $X_{Eff}$  is given by:

$X_{Eff} = X_T + X_{TL} - X_{TCSC}(\alpha_0)$ . During dynamic conditions the series compensation is modulated for damping system oscillations. The effective reactance in dynamic conditions is given by:  $X_{Eff} = X_T + X_{TL} - X_{TCSC}(\alpha)$ , where  $\sigma = \sigma_0 + \Delta\sigma$  and  $\sigma = 2(\pi - \alpha)$ ,  $\alpha_0$  and  $\sigma_0$  being initial value of firing and conduction angle respectively.

From the viewpoint of the washout function the value of washout time constant is not critical in lead-lag structured controllers and may be in the range 1 to 20 seconds [1]. In the present study, washout time constant of  $T_{WT}$  10 s is used. The controller gains  $K_T$ ; and the time constants  $T_{1T}$ ,  $T_{2T}$ ,  $T_{3T}$  and  $T_{4T}$  are to be determined.

## B. Objective Function

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 need improvement through trial and error. The aim of any evolutionary optimization technique is basically to optimize (minimize/maximize) an objective function or fitness function satisfying the constraints of either state or control variable or both depending upon the requirement. In the present paper, an eigenvalue based fitness function reflecting damping factor of each of the electromechanical eigenvalues at numbers of

different operating conditions is employed. The objective function 'f' is expressed as:

$$f = f_1 + \beta f_2 \quad (3)$$

Where,

$$f_1 = \sum_{j=1}^{OP} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_o - \sigma_{i,j}] \text{ and}$$

$$f_2 = \sum_{j=1}^{OP} \sum_{\xi_{i,j} \geq \xi_0} [\xi_o - \xi_{i,j}]$$

In equation (3), the value of ' $\beta$ ' is a weighting factor and is chosen as 10 [1], OP is the total number of operating points for which the optimization process is performed;  $\sigma_{i,j}$  is the real part of the  $i^{\text{th}}$  eigenvalue of the  $j^{\text{th}}$  operating point;  $\xi_{i,j}$  is the damping factor of the  $i^{\text{th}}$  eigenvalue of the  $j^{\text{th}}$  operating point;  $\sigma_o$  and  $\xi_o$  are the desired stability and damping required.

If only ' $f_1$ ' is taken as the objective function, the closed loop eigenvalues are placed in the region to the left of dashed line as shown in Fig. 7 (a). Similarly if only ' $f_2$ ' is taken as the objective function then it limits the maximum overshoot of the eigenvalues as shown in Fig. 7 (b). When both damping factors and real part of system electromechanical eigenvalue are considered in the objective function as given in equation (3), the eigenvalues are restricted within a D-shaped area as shown in the Fig. 7 (c).

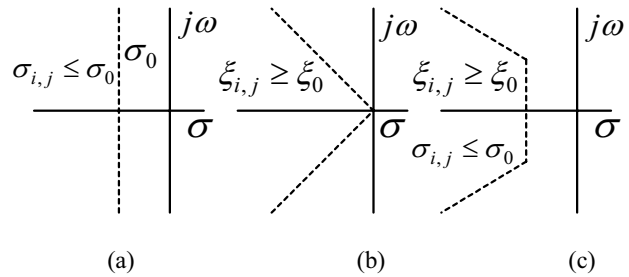


Fig. 7. Eigenvalue location for different objective functions

## V. OVERVIEW OF REAL-CODED GENETIC ALGORITHM

Genetic Algorithm (GA) can be viewed as a general-purpose search method, an optimization method, or a learning mechanism, based loosely on Darwinian principles of biological evolution, reproduction and "the survival of the fittest." GA maintains a set of candidate solutions called population and repeatedly modifies them. At each step, the GA selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Candidate solutions are usually represented as strings of fixed length, called chromosomes.

Given a random initial population GA operates in cycles called generations, as follows [13]:

- Each member of the population is evaluated using a

objective function or fitness function.

- The population undergoes reproduction in a number of iterations. One or more parents are chosen stochastically, but strings with higher fitness values have higher probability of contributing an offspring.
- Genetic operators, such as crossover and mutation, are applied to parents to produce offspring.
- The offspring are inserted into the population and the process is repeated.

Over successive generations, the population “evolves” toward an optimal solution. GA can be applied to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear. GA has been used to solve difficult engineering problems that are complex and difficult to solve by conventional optimization methods.

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, etc. 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.

#### 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  $P_i$  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  $P_i$  is defined as:

$$P_i = q^i (1 - q)^{r-1} \quad (4)$$

$$q^i = \frac{q}{1 - (1 - q)^P} \quad (5)$$

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 crossover 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:

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

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

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

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

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

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

$$x_i' = \begin{cases} x_i + (b_i - x_i) f(G) & \text{if } r_1 < 0.5, \\ x_i + (x_i - a_i) f(G) & \text{if } r_1 \geq 0.5, \\ x_i, & \text{otherwise} \end{cases} \quad (10)$$

where,

$$f(G) = \left( r_2 \left( 1 - \frac{G}{G_{\max}} \right) \right)^b \quad (11)$$

$r_1, r_2$  = 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.

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 forms can be used in a GA so that the function can map the population into a partially ordered set.

## VI. RESULTS AND DISCUSSIONS

### A. Application of RCGA

The optimization of the proposed TCSC-based supplementary damping controller parameters is carried out by evaluating the fitness given in equation (3), considering various operating conditions. The operating conditions considered for the design are shown in Table I. The system electromechanical eigenvalues without proposed TCSC-based supplementary damping controller are shown in Table I. It is clear from Table I that the open loop system is unstable

TABLE I OPERATING CONDITIONS CONSIDERED DURING DESIGN

Sl. No.	P (pu)	Q (pu)	$\delta_0$ (deg)	System eigenvalues without control
1	1.1	0.777	87.8	$0.4864 \pm 3.9793i$
2	1.05	0.6766	82.2667	$0.4196 \pm 4.3530i$
3	1.0	0.5949	77.3516	$0.3618 \pm 4.6208i$
4	0.95	0.5255	72.8112	$0.3108 \pm 4.8245i$
5	0.9	0.4652	68.5179	$0.2655 \pm 4.9846i$
6	0.85	0.4121	64.3957	$0.2251 \pm 5.1124i$
7	0.8	0.3649	60.3951	$0.1891 \pm 5.2152i$
8	0.75	0.3227	56.4818	$0.1573 \pm 5.2979i$
9	0.7	0.2849	52.6310	$0.1292 \pm 5.3643i$
10	0.65	0.2510	48.8243	$0.1048 \pm 5.4170i$
11	0.6	0.2205	45.0479	$0.0836 \pm 5.4585i$
12	0.55	0.1933	41.2911	$0.0656 \pm 5.4904i$
13	0.5	0.1690	37.5457	$0.0505 \pm 5.5145i$
14	0.45	0.1475	33.8057	$0.0380 \pm 5.5321i$
15	0.4	0.1286	30.0665	$0.0278 \pm 5.5445i$

at all the loading conditions because of negative damping of electromechanical mode (i.e. the real part of eigenvalues lie in right-half of s-plane in all cases).

For the implementation of RCGA normal geometric selection is employed which is a ranking selection function based on the normalized geometric distribution. Arithmetic crossover takes two parents and performs an interpolation along the line formed by the two parents. Non uniform mutation changes one of the parameters of the parent based on a non-uniform probability distribution. This Gaussian distribution starts wide, and narrows to a point distribution as the current generation approaches the maximum generation. The parameters employed for the implementations of RCGA in the present study are given in Table II. The desired values of real part of eigen value ( $\sigma_0$ ) and damping factor ( $\xi_0$ ) are taken as -1.0 and 0.2 respectively.

The convergence of fitness function with the generations is shown in Fig. 8. The optimal TCSC-based supplementary damping controller parameters are:

$$K_T = 62.9885, T_{1T} = 0.1210, T_{2T} = 0.1531,$$

$$T_{3T} = 0.2931, T_{4T} = 0.2728$$

TABLE II PARAMETERS USED IN RCGA

Parameter	Value/Type
Maximum generations	100
Population size	50
Type of selection	Normal geometric [0 0.08]
Type of crossover	Arithmetic [2]
Type of mutation	Nonuniform [2 100 3]
Termination method	Maximum generation

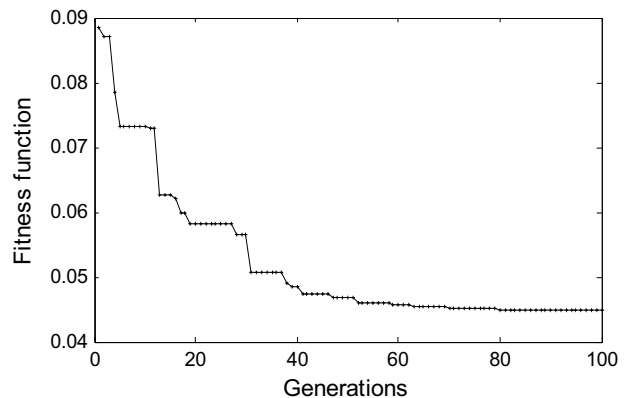


Fig. 8. Convergence of fitness function with the generations

Table III shows the system electromechanical eigenvalues with proposed TCSC-based supplementary damping controller. In Table III the system eigenvalues with a conventionally designed [14] power system stabilizer (CPSS) are also shown for all the loading conditions. It is clear from table III that with CPSS the system stability is maintained as the electromechanical mode eigenvalue shift to the left of the

line in  $s$ -plane for all loading conditions. It is also clear from Table III that the shift in electromechanical mode eigenvalue to the left of the line in the  $s$ -plane is maximum with proposed supplementary TCSC-based damping controller. Hence the system stability and damping characteristics greatly improve with proposed controller.

TABLE III EIGENVALUES WITH PROPOSED CONTROLLER

Sl. No.	P (pu)	System eigenvalues With control	
		CPSS	TCSC-based
1	1.1	$-0.4069 \pm 3.6597i$	$-4.2716 \pm 6.5001i$
2	1.05	$-0.5853 \pm 4.0303i$	$-4.2358 \pm 6.4096i$
3	1.0	$-0.7279 \pm 4.3109i$	$-4.2214 \pm 6.3006i$
4	0.95	$-0.8409 \pm 4.5390i$	$-4.2188 \pm 6.1753i$
5	0.9	$-0.9262 \pm 4.7318i$	$-4.2221 \pm 6.0350i$
6	0.85	$-0.9846 \pm 4.8981i$	$-4.2265 \pm 5.8814i$
7	0.8	$-1.0170 \pm 5.0418i$	$-4.2279 \pm 5.7163i$
8	0.75	$-1.0249 \pm 5.1649i$	$-4.2220 \pm 5.5425i$
9	0.7	$-1.0110 \pm 5.2682i$	$-4.2050 \pm 5.3645i$
10	0.65	$-0.9787 \pm 5.3530i$	$-4.1742 \pm 5.1887i$
11	0.6	$-0.9316 \pm 5.4207i$	$-4.1290 \pm 5.0236i$
12	0.55	$-0.8730 \pm 5.4732i$	$-4.0725 \pm 4.8784i$
13	0.5	$-0.8056 \pm 5.5129i$	$-4.0120 \pm 4.7610i$
14	0.45	$-0.7319 \pm 5.5417i$	$-3.9568 \pm 4.6748i$
15	0.4	$-0.6537 \pm 5.5616i$	$-3.9151 \pm 4.6195i$

### B. Simulation Results

To assess the effectiveness and robustness of the proposed controller, different loading conditions and parameters variations as given in Table IV are considered.

TABLE IV LOADING CONDITIONS CONSIDERED

Loading Conditions	P (pu)	Q (pu)	Parameter variation	$\delta_0$ (deg.)
Nominal	0.8	0.3694	No parameter variation	60.39
Light	0.5	0.169	50% increase in line reactance	37.54
Heavy	1.1	0.6479	10% decrease in line reactance and 5% increase in terminal voltage	73.57

The performance of the proposed controller is compared with a CPSS. The response with CPSS is shown in dotted lines (with legend CP). The responses with proposed TCSC-based supplementary damping controller are shown in solid lines (with legend 'TCSC'). For comparison in all these figures the response with TCSC-based supplementary damping controller when the parameters are not optimized but randomly chosen

are also shown in dashed lines (with legend WO).

#### Case I: Nominal loading no parameter variation

A 10% step increase in mechanical power input at  $t = 1.0$  s is assumed. The system speed, power angle and terminal voltage deviation response for the above contingency are shown in Figs. 9-11. It is clear from the Figs. that with a CPSS stability of the system is maintained and power system oscillations are effectively damped out. It can also be seen from the Figs. that when the controller parameters are optimized the damping characteristics greatly improve compared to the case when the parameters are not optimized.

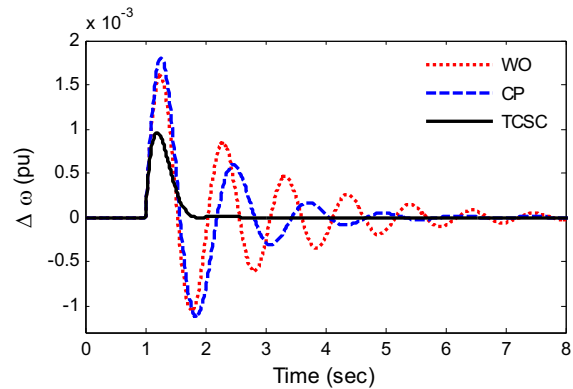


Fig. 9. Speed deviation response for Case-I

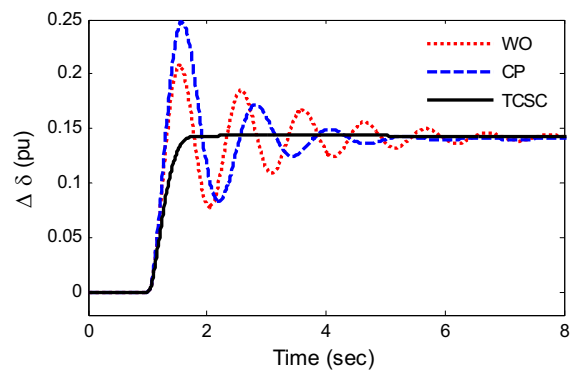


Fig. 10. Power angle deviation response for Case-I

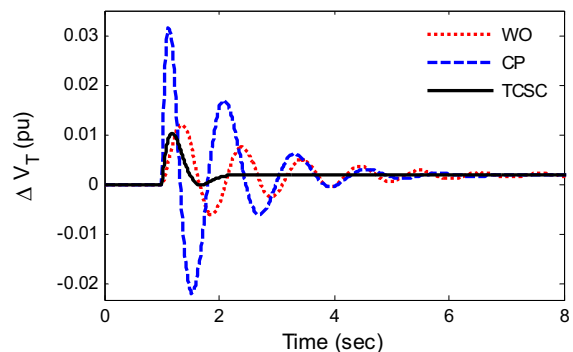


Fig. 11. Terminal voltage deviation response for Case-I

*Case II: Light loading with parameter variation*

To test the robustness of the proposed controller, the second operating condition corresponding to light loading condition with parameter variation given in Table IV is considered. The same disturbance i. e. a 10% step increase in mechanical power input at  $t = 1.0$  s is considered. The system responses for the above contingency are shown in Figs. 12-14. It is clear from the Figs. that proposed TCSC-based supplementary damping controller is robust to operating condition and parameter variation and outperform both controllers (CPSS and TCSC with random parameters).

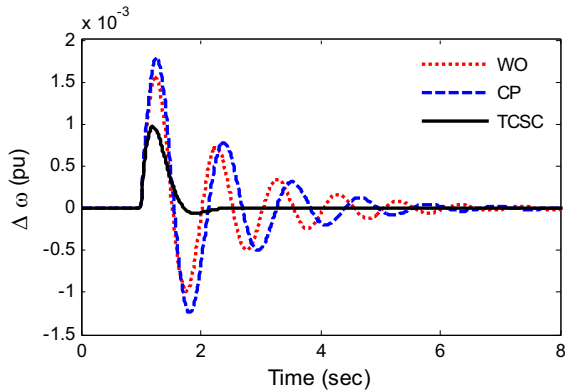


Fig. 12. Speed deviation response for Case-II

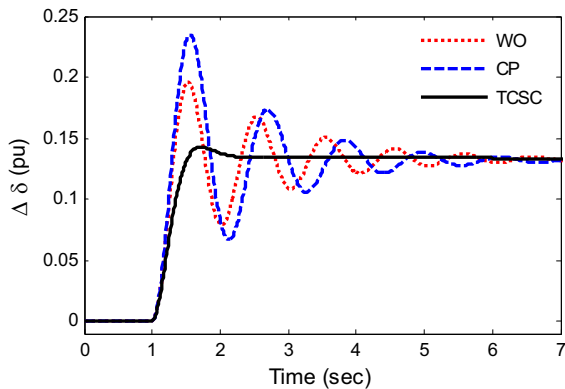


Fig. 13. Power angle deviation response for Case-II

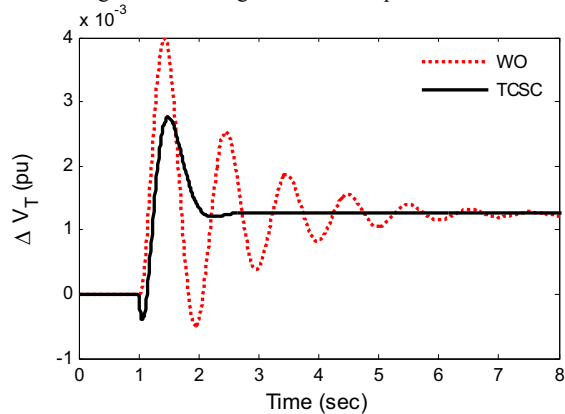


Fig. 14. Terminal voltage deviation response for Case-II

*Case III: Heavy loading with parameter variation*

The effectiveness of the proposed controllers is also tested under light loading condition with parameter variation (given in Table IV). The mechanical power input to the generator is increased by 10% at  $t=1.0$  s and the system responses are shown in Figs. 14-16. It can be seen from Figs. 15-17 that the proposed controller is robust and works effectively under various operating conditions.

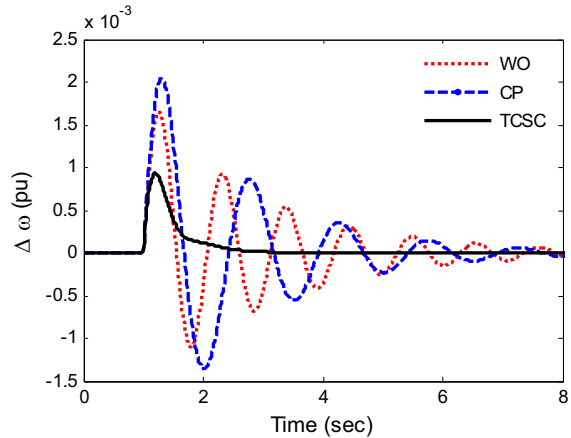


Fig. 15. Speed deviation response for Case-III

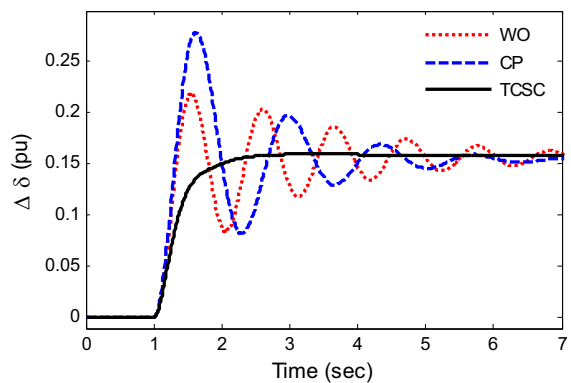


Fig. 16. Power angle deviation response for Case-III

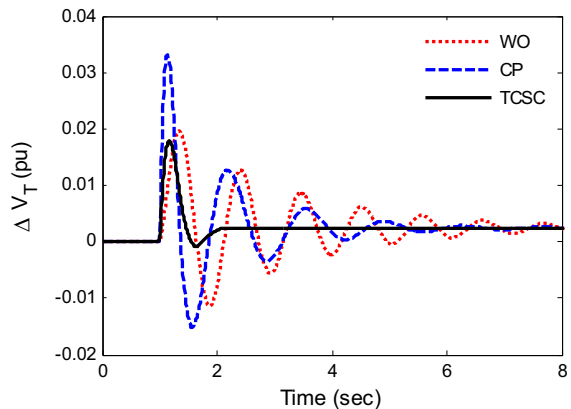


Fig. 17. Terminal voltage deviation response for Case-III

*Case IV: Disturbance in reference voltage setting:*

For completeness and verification, the effectiveness of the proposed controller is also tested for a disturbance in reference voltage setting. The reference voltage is increased by a step of 10% at  $t=1$  s at nominal loading condition. Figs. 18-20 show the system responses for the above contingency.

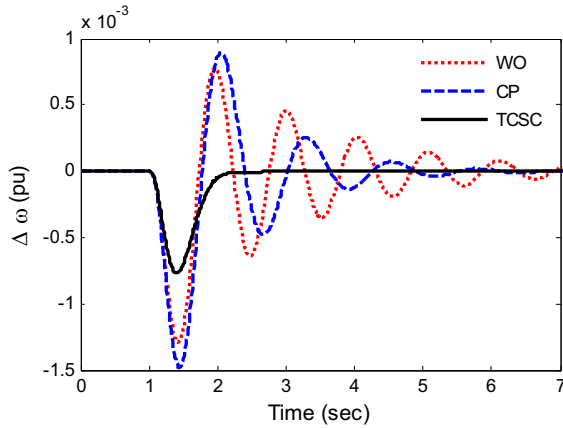


Fig. 18. Speed deviation response for Case-IV

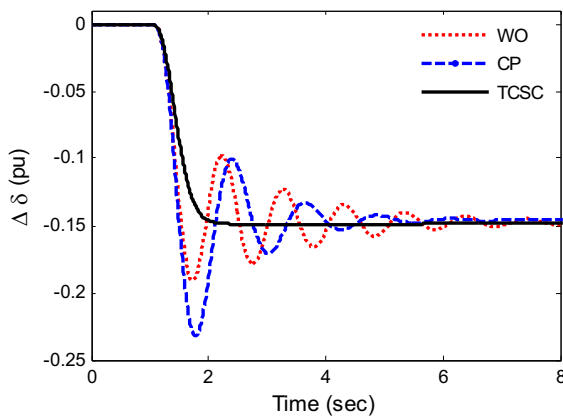


Fig. 19. Power angle deviation response for Case-IV

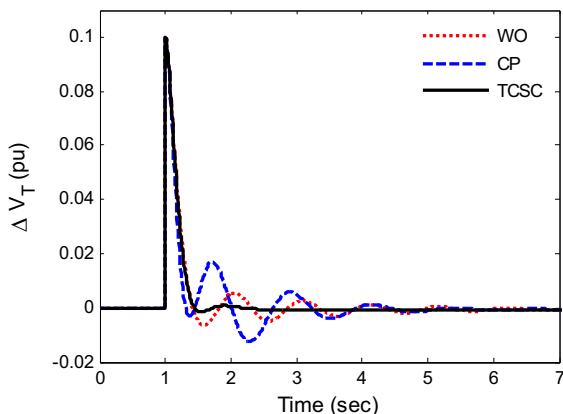


Fig. 20. Terminal voltage deviation response for Case-IV

It is clear from the Figs. that proposed TCSC-based supplementary damping controller is robust to type of disturbance and outperform both controllers (CPSS and TCSC with random parameters) for all types of disturbances.

## VI. CONCLUSION

In this study, real-coded genetic algorithm optimization technique is employed for the design of a supplementary TCSC-based damping controller. For the design problem, an eigenvalue based objective function in which both damping factors and real part of system electromechanical eigenvalue are included. The proposed supplementary TCSC-based damping controller is tested on a weakly connected power system with different disturbances and loading conditions, with parameter variations. Simulation results are presented and compared with a conventionally designed power system stabilizer and with the same TCSC-based supplementary damping controller when the controller parameters are not optimized. The effectiveness and robustness of the proposed controller is shown over a wide range of loading conditions and disturbances and with parameter variations.

## APPENDIX

Static System data: All data are in pu unless specified otherwise.

Generator:

$$M = 9.26 \text{ s}, D = 0, X_d = 0.973, X_q = 0.55,$$

$$X'_d = 0.19, T'_{do} = 7.76,$$

$$f = 60, V_T = 1.05, X_{TL} + X_T = 0.997$$

Excitor:

$$K_A = 50, T_A = 0.05 \text{ s}$$

TCSC Controller:

$$X_{TCSC0} = 0.2169, X_C = 0.2 X, X_P = 0.25 X_C$$

## ACKNOWLEDGEMENT

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