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MODELLING, SIMULATION AND OPTIMAL TUNING OF TCSC CONTROLLER

Panda, S.[*]; Padhy, N. P.[*] & Patel, R. N.[**]
[*]Department of Electrical Engineering, IIT, Roorkee, Uttaranchal-247667, India
[**]Department of Electrical Engineering, SSCET, Bhilai, India
E-Mail: speeddee@iitr.ernet.in

Abstract

A systematic procedure for modeling, simulation and optimal tuning the parameters of a Thyristor Controlled Series Compensator (TCSC) controller, for the power system stability enhancement is presented in this paper. For the simulation purpose, the model of single-machine infinite bus (SMIB) power system with TCSC controller is developed in MATLAB/SIMULINK. The design problem of TCSC controller is formulated as an optimisation problem and genetic algorithm (GA) is employed to search for the optimal TCSC controller parameters. By minimizing a time-domain based objective function, in which the oscillatory rotor speed deviation of the generator is involved; stability performance of the power system is improved. The results obtained from simulations validate the effectiveness of proposed modelling and tuning approach for power system stability improvement. The simulation results also show that the proposed TCSC controller is effective in damping a range of small disturbance conditions in the power system.

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Key Words: Thyristor Controlled Series Compensator, Modelling, Optimal Tuning, Genetic Algorithm, Power System Stability

1. INTRODUCTION

Recent development of power electronics introduces the use of Flexible AC transmission Systems (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this unique feature of FACTS can be exploited to improve the stability of a power system. TCSC is one of the important members of FACTS family that is increasingly applied by the utilities in modern power systems with long transmission lines. 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 SSR; POD; and enhancing transient stability [1]. The detailed explanations about the FACTS controllers are well documented in the literature and can be found in [2, 3].

Mattavelli *et al.* [4] developed a continuous-time, large-signal dynamic model for a TCSC. The model was based on the representation of voltages and currents as time-varying Fourier series, and focused on the dynamics of the short-term Fourier coefficients. Han *et al.* [5] presented the detailed dynamics of the TCSC with the analysis of the periodic state equations, using the state variable approach. Transient characteristics as well as steady state characteristics of the TCSC were also presented using the analytical equations for three operating modes of the TCSC. A fundamental frequency model for TCSC for analyzing the factors that influence the transient stability of TCSC with the change in operating conditions was developed by Xiaolu *et al.* [6]. The proposed model inherently incorporated the thyristor triggering logic and the TCSC was thought as variable impedance. Li *et al.* [7] proposed a

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method to simulate the nonlinear performance of TCSC and evaluated the impact of TCSC on power system stability. Jiang, D. and Lei, X. [8] presented a nonlinear control scheme for the TCSC to damp power oscillations and improve transient stability of power system. The paper developed by Lei *et al.* [9], presented a coordinated control scheme for excitation systems and TCSC controls for improving the stability of a power system. The control scheme was developed with nonlinear optimal variable aim strategies. Geng *et al.* [10] described the TCSC as a first order lag element. The factors affecting the transient response of TCSC were also discussed by the authors. Del Rosso *et al.* [11] examined the use of TCSC for stability improvement of power systems. An appropriate TCSC model for angle stability studies was used to design a simple controller based primarily on the dynamic response of the system. An analysis of different locally measurable controller input signals was also conducted by the authors. Panda *et al.* [12] presented a small signal, Phillips-Heffron model of single-machine infinite bus power system installed with a TCSC where the parameters of the TCSC damping controller are optimized by a multi-objective genetic algorithms.

Most of these proposals 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 FACTS controllers in that, the controllers tuned to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances.

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. 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 namely: the eigenvalue 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 [13].

Recently, GA is becoming popular to solve the optimisation problems in different fields of applications. GA employs search procedures based on the mechanics of natural selection and survival of the fittest. The GAs, which use a multiple point instead of a single point search and work with the coded structure of variables instead of the actual variables, require only the objective function thereby making searching for a global optimum simpler [14]. As the GA has an apparent benefit to adapt to irregular search space of an optimisation problem, many researchers have employed GA for optimisation problems in the power system [15-17]. Therefore, in the present work GA is employed to tune the parameters of the TCSC controller.

It is well known that the reactance adjusting of TCSC is a complex dynamic process. Effective design and accurate evaluation of the TCSC control strategy depend on the simulation accuracy of this process. This paper presents a simple transfer function model of the TCSC in the MATLAB/SIMULINK environment. The GA based optimal tuning algorithm is used to optimise the parameters of the TCSC controller. Simulation results show the advantages of using the modelling and tuning method when performing control and stability analysis in a power system involving a TCSC controller.

The remainder of this paper is organized in five major sections. A brief review of TCSC is presented in Section 2. Power system modeling with the proposed TCSC controller structure is presented in Section 3. In Section 4, application of GA is presented. The results are presented and discussed in Section 5. Finally, in Section 6 conclusions are given.

2. THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)

TCSC is one of the most important and best known series FACTS controllers. It has been in use for many years to increase line power transfer as well as to enhance system stability. Basically a TCSC consists of three components: capacitor banks *C*, bypass inductor *L* and bidirectional thyristors. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations [3]. According to the variation of the thyristor firing angle (α) or conduction angle (σ), this process can be modelled as a fast switch between corresponding reactance offered to the power system.

Assuming that the total current passing through the TCSC is sinusoidal; the equivalent reactance at the fundamental frequency can be represented as a variable reactance X_{TCSC}. There exists a steady-state relationship between α and the reactance X_{TCSC}. This relationship can be described by the following equation [7]:

$$X_{TCSC}(\alpha) = X_C - \frac{X_C^2}{(X_C - X_P)}\frac{\sigma + \sin\sigma}{\pi} + \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2(\sigma/2)}{(k^2-1)}\frac{(k\tan(k\sigma/2) - \tan(\sigma/2))}{\pi} \quad (1)$$

where,

X_C = Nominal reactance of the fixed capacitor *C*.

X_P = Inductive reactance of inductor *L* connected in parallel with *C*.

$\sigma = 2(\pi - \alpha)$, the conduction angle of TCSC controller.

$k = \sqrt{X_C / X_P}$, the compensation ratio.

Since the relationship between α and the equivalent fundamental frequency reactance offered by TCSC, $X_{TCSC}(\alpha)$ is a unique-valued function, the TCSC is modeled here as a variable capacitive reactance within the operating region defined by the limits imposed by α. Thus $X_{\text{TCSC}min} \le X_{\text{TCSC}} \le X_{\text{TCSC}max}$, with $X_{\text{TCSC}max} = X_{\text{TCSC}}(\alpha_{min})$ and $X_{\text{TCSC}min} = X_{\text{TCSC}}(180^0) = X_C$. In this paper, the controller is assumed to operate only in the capacitive region, i.e., $\alpha_{min} > \alpha_r$ where α_r corresponds to the resonant point, as the inductive region associated with $90^0 < \alpha < \alpha_r$ induces high harmonics that cannot be properly modeled in stability studies.

3. POWER SYSTEM MODELLING

3.1 Modelling of SMIB with TCSC

The SMIB power system with TCSC (shown in Fig. 1), is considered in this study. The generator has a local load of admittance $Y = G + jB$ and the transmission line has impedance of $Z = R + jX$. In the figure V_T and V_B are the generator terminal and infinite bus voltage respectively. The generator is represented by the third-order model comprising of the electromechanical swing equation and the generator internal voltage equation. The state equations may be written as [18]:

$$\dot{\omega} = [P_m - P_e - D(\omega - 1)]/M \quad (2)$$

$$\dot{\delta} = \omega_b(\omega - 1) \quad (3)$$

$$V_T = v_d + jv_q \tag{4}$$

$$I = i_d + ji_q \tag{5}$$

where, P_m and P_e are the input and output powers of the generator respectively; M and D are the inertia constant and damping coefficient respectively; ω_b is the synchronous speed; V_T is the terminal voltage; I is the current, δ and ω are the rotor angle and speed respectively.

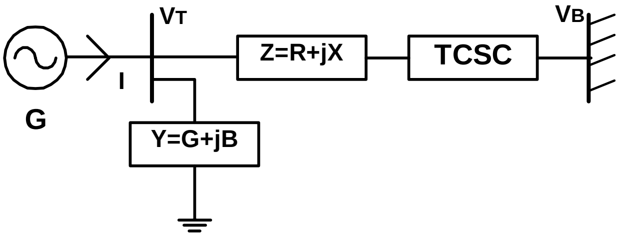


Figure 1: Single-machine infinite-bus power system with TCSC.

The *d*- and *q*-axis components of armature current, *I* can be calculated as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} Y_d \\ Y_q \end{bmatrix} E_q' - \frac{V_B}{Z_e^2} \begin{bmatrix} R_2 & X_1 \\ -X_2 & R_1 \end{bmatrix} \begin{bmatrix} \sin\delta \\ \cos\delta \end{bmatrix} \tag{6}$$

where,

$$Y_d = (C_1 X_1 - C_2 R_2)\big/ Z_e^2\,;\; Y_q = (C_1 R_1 + C_2 X_2)\big/ Z_e^2\,;\; C_1 = 1 + RG - XB\,;\; C_2 = RB + XG\,;$$

$$Z_e^2 = R_1 R_2 + X_1 X_2\,;\; R_1 = R - C_2 X_d'\,;\; R_2 = R - C_2 X_q\,;\; X_1 = X_{Eff} + C_1 X_q\,;$$

$$X_2 = X_{Eff} + C_1 X_d' \text{ and } X_{Eff} = X - X_{TCSC}(\alpha)$$

The generator power P_e, the internal voltage $\dot{E}_q'$ and the terminal voltage V_T can be expressed as:

$$Pe = E_q' i_q + (X_q - X_d')\cdot i_d . i_q \tag{7}$$

$$\dot{E}_q' = \left[E_{fd} - E_q' - (X_d - X_d')\right]\cdot i_d \big/ T_{d0}' \tag{8}$$

$$V_T = \sqrt{(X_q i_q)^2 + (E_q' - X_d i_d)^2} \tag{9}$$

Here, E_{fd} is the field voltage; T_{d0}' is the open circuit field time constant; X_d and X_d' are the *d*-axis reactance and the *d*-axis transient reactance of the generator respectively.

The *IEEE Type-ST1* excitation system is considered in this work. It can be described as:

$$\dot{E}_{fd} = \left[K_A(V_{ref} - V_T) - E_{fd}\right]\big/ T_A \tag{10}$$

where, K_A and T_A are the gain and time constant of the excitation system; V_{ref} is the reference voltage.

3.2 Modelling the TCSC controller structure

The commonly used lead–lag structure is chosen in this study as a TCSC controller. The structure of the TCSC controller is shown in Fig. 2. It consists of: a gain block with gain K_P, 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, with the time constant T_W, high enough to allow signals associated with oscillations in input signal to pass unchanged. Without it steady changes in input would modify the output. From the viewpoint of the washout function the value of T_W is not critical and may be in the range 1 to 20 seconds [19]. σ_0 is the initial conduction angle as desired by the power flow control loop. The power low control loop acts quit slowly in practice and hence σ_0 is assumed to remain constant during large-disturbance transient period.

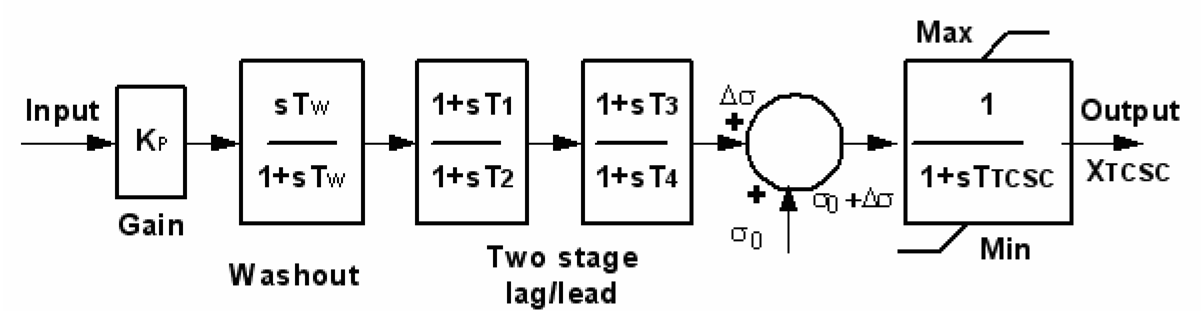


Figure 2: Structure of TCSC controller.

The transfer function of the TCSC controller is:

$$u = K_P \left(\frac{sT_w}{1+sT_w} \right) \left(\frac{1+sT_1}{1+sT_2} \right) \left(\frac{1+sT_3}{1+sT_4} \right) y \tag{11}$$

where, u and y are the TCSC controller output and input signals respectively; K_P is the stabilizer gain and T_W is the washout time constant.

In this structure, T_W , T_2 and T_4 are usually prespecified. In this study T_W =10 sec and $T_2 = T_4 = 0.1$ sec are used. The controller gain K_P and time constants T_1 and T_3 are to be determined. In this study, the input signal of the proposed TCSC controller is the speed deviation $\Delta\omega$, and the output is change in conduction angle $\Delta\sigma$. The desired value of line reactance is obtained according to the change in the conduction angle. This signal is put through a first order lag representing the natural response of the controller and the delay introduced by the internal control which yields the reactance offered by the TCSC, $X_{\text{TCSC}}(\alpha)$ [3]. The effective reactance is given by:

$$X_{Eff} = X - X_{TCSC}(\alpha) \tag{12}$$

where, $X_{\text{TCSC}}(\alpha)$ is the reactance of TCSC at firing angle α.

The value of α is changed according to the change in out put of TCSC controller $\Delta\sigma$, as $\sigma = \pi - \sigma / 2$ and $\sigma = \sigma_0 + \Delta\sigma$, σ_0 being initial value of conduction angle.

4. APPLICATION OF GENETIC ALGORITHM

4.1 Genetic algorithm (GA)

GA has been used as optimising the parameters of control system that are complex and difficult to solve by conventional optimisation methods. GA maintains a set of candidate solutions called population and repeatedly modifies them. At each step, the GA selects individuals from the current population to be parents and uses them to produce the children for the next generation. A fitness or objective function is used to reflect the goodness of each member of population. Given a random initial population, GA operates in cycles called generations, as follows [14]:

- Each member of the population is evaluated using a 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.

4.2 Objective function

It is worth mentioning that the TCSC controller is designed to minimize the power the power angle deviation after a large disturbance and to quickly damp the power system oscillations. These oscillations are reflected in the deviations in the generator rotor angle $(\Delta\delta)$, speed $(\Delta\omega)$ and accelerating power (ΔP_a).

Therefore the objective can be formulated as the minimization of:

$$J = \int_{t=0}^{t=t_{sim}} t \cdot \left[\Delta\omega(t) \right] \cdot dt \tag{13}$$

where, $\Delta\omega\ (t)$ denotes the rotor speed deviation and t_{sim} is the time range of the simulation.

For objective function calculation, the time-domain simulation of the non-linear power system model is carried out for the simulation period. It is aimed to minimise this objective function in order to improve the system response in terms of the settling time and overshoots.

4.3 Optimization problem

Tuning a controller parameter can be viewed as an optimisation problem in multi-modal space as many settings of the controller could be yielding good performance. Traditional method of tuning doesn’t guarantee optimal parameters and in most cases the tuned parameters needs improvement through trial and error. In GA based method, the tuning process is associated with an optimality concept through the defined objective function and the time domain simulation. Hence this method yields optimal parameters and the method is free from the curse of local optimality. In GA optimisation technique, the designer has the freedom to explicitly specify the required performance objectives in terms of time domain bounds on the closed loop responses. In view of the above, the proposed approach employs GA to solve this optimisation problem and search for optimal TCSC controller parameters.

In this study, it is aimed to minimise the proposed objective functions J. The problem constraints are the TCSC controller parameter bounds. Therefore, the design problem can be formulated as the following optimization problem:

$$\text{Minimize } J \tag{14}$$

Subject to

$$K_P^{\min} \le K_P \le K_P^{\max}$$

$$T_1^{\min} \le T_1 \le T_1^{\max}$$

$$T_3^{\min} \le T_3 \le T_3^{\max} \tag{15}$$

5. RESULTS AND DISCUSSION

In order to show the advantages of modeling the TCSC controller dynamics and tuning its parameters in the way presented in this paper, simulation studies of a SMIB power system with TCSC are carried out. The MATLAB/SIMULINK model of the example power system is developed using equations (1-10) as shown in Fig. 3. The SIMULINK model for calculation of id and iq is shown in Fig. 4. The relevant parameters are given in Appendix.

The operating point considered is:

$P_M = 0.95$ pu, $V_B = 1.0$ pu, $\alpha_0 = 158^0$, $\delta_0 = 56.4^0$

For the purpose of optimisation of equation (14), routines from GA toolbox were used. For different problems, it is possible that the same parameters for GA do not give the best solution and so these can be changed according to the situation. In Table I the parameters for GA optimization routines are given. The description of these operators and their properties can be found in reference [20]. One more important point that affects the optimal solution more or less is the range for unknowns. For the very first execution of the program, more wide solution space can be given and after getting the solution one can shorten the solution space nearer to the values obtained in the previous iteration. Optimisation is terminated by the prespecified number of generations. The best individual of the final generation is the solution. The flowchart of the GA algorithm and the convergence rate of the objective function are shown in Figs. 5 (a) & (b). Bounds for unknown parameters of gain and time constants used in the present study and the obtained parameters of TCSC controller by the GA run are given in are shown in Table II.

Table I: Typical parameters used in genetic algorithms.

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

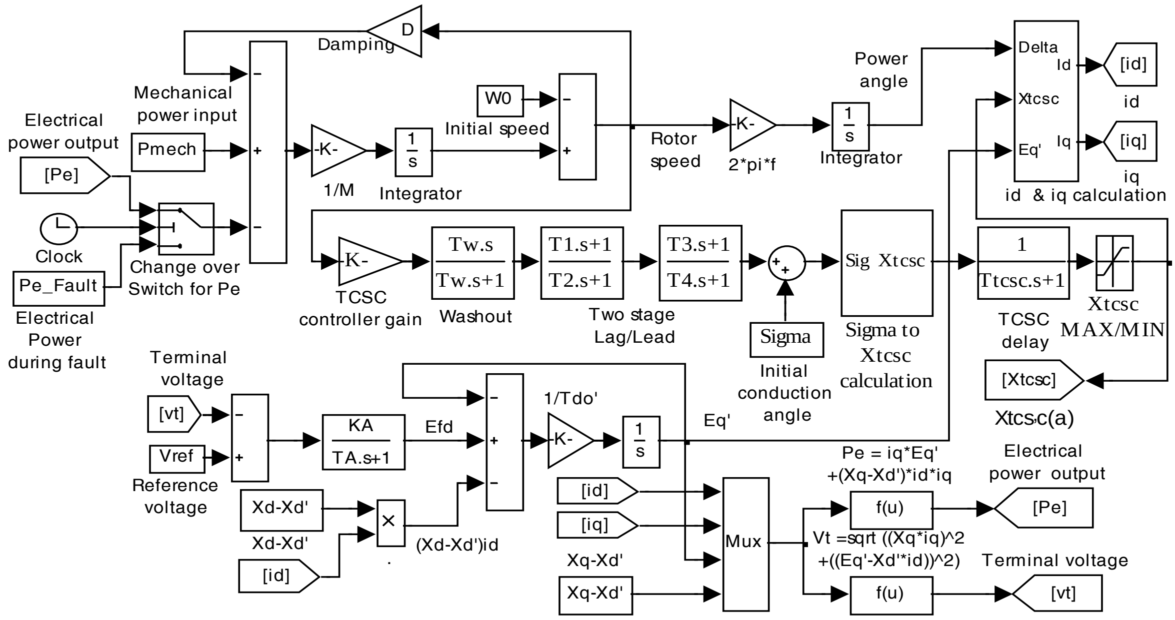


Figure 3: SIMULINK model of SMIB with TCSC controller.

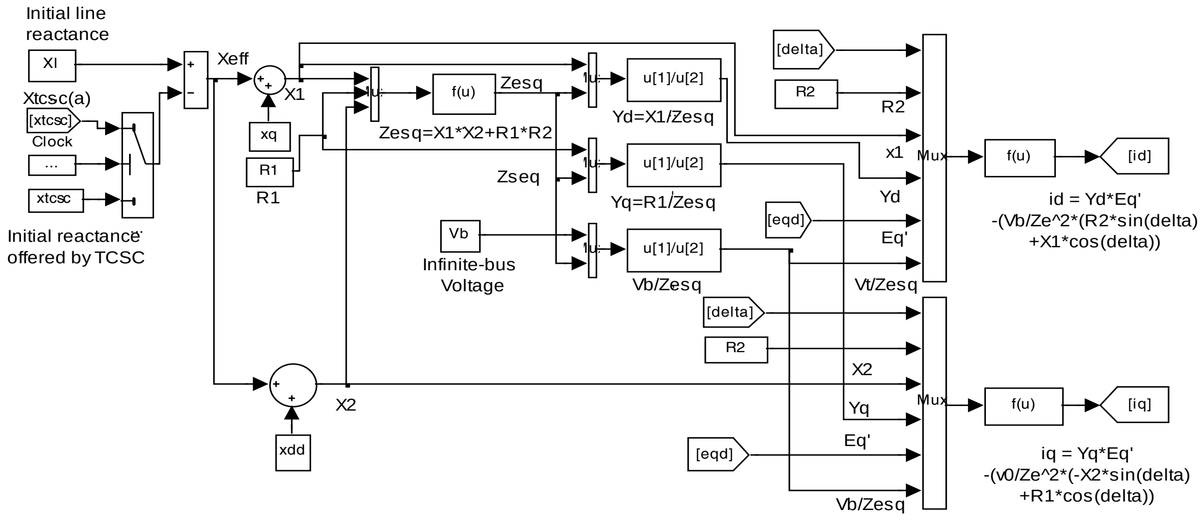


Figure 4: SIMULINK model for calculation of i_d & i_q.

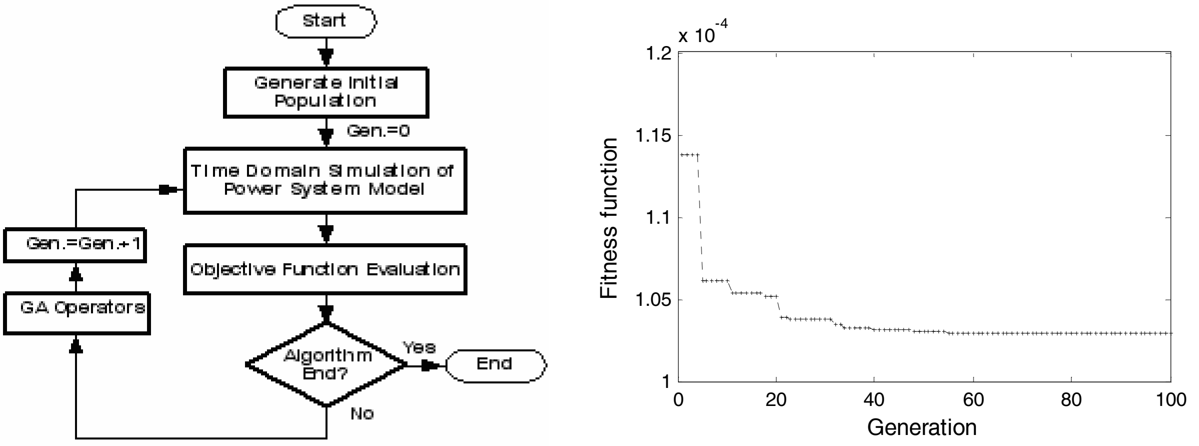
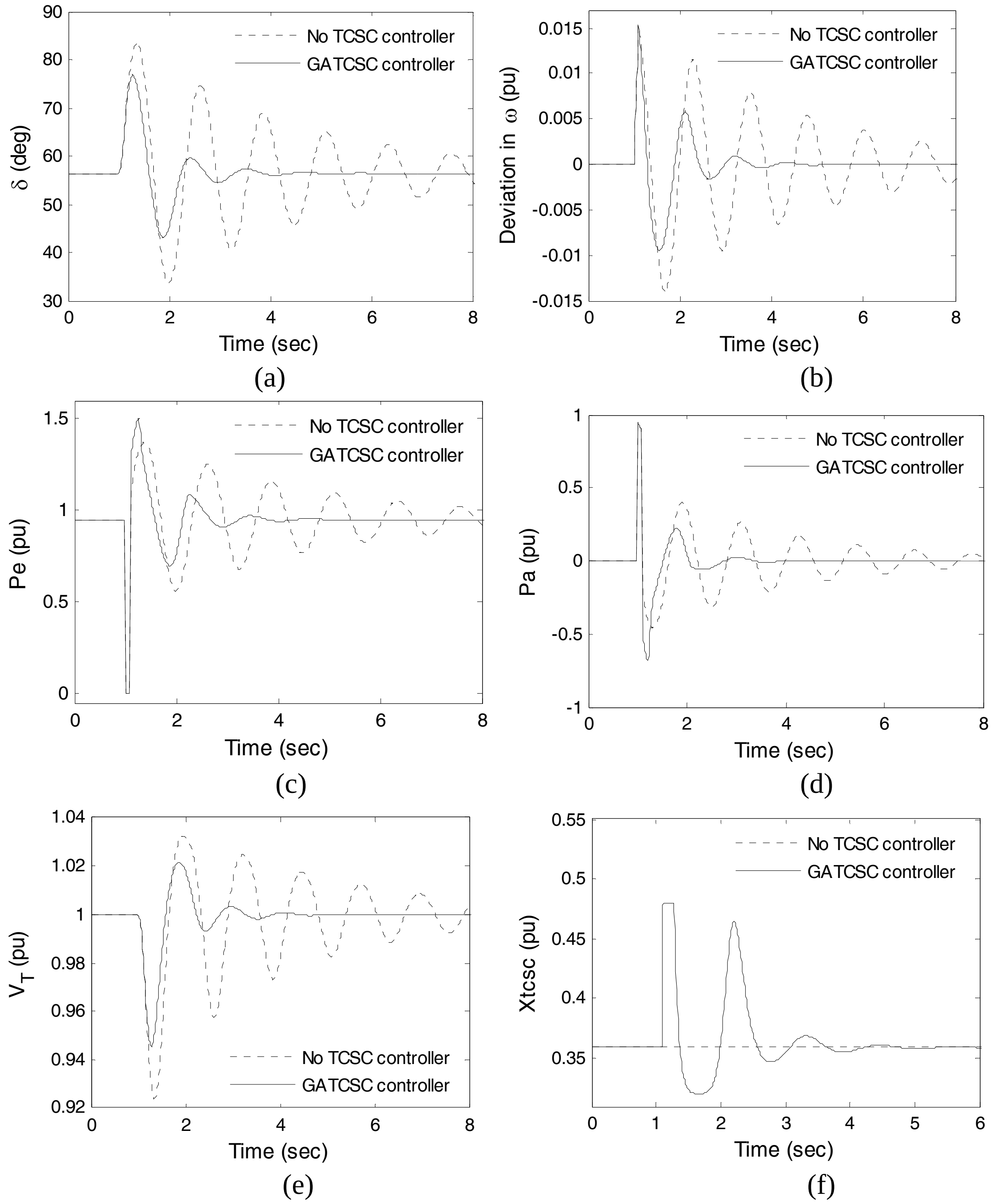


Figure 5: (a) Flowchart of the GA optimisation algorithm, (b) Convergence of objective function.

Table II: Bounds of unknown variables and optimised parameters by GA.

Parameters	**Gain**	**Time constants**	
	K_P	T_1	T_3
Minimum range	40	0.01	0.01
Maximum range	120	0.5	0.5
Optimised parameters obtained by GA	55.6605	0.1692	0.0447



(a) (b)

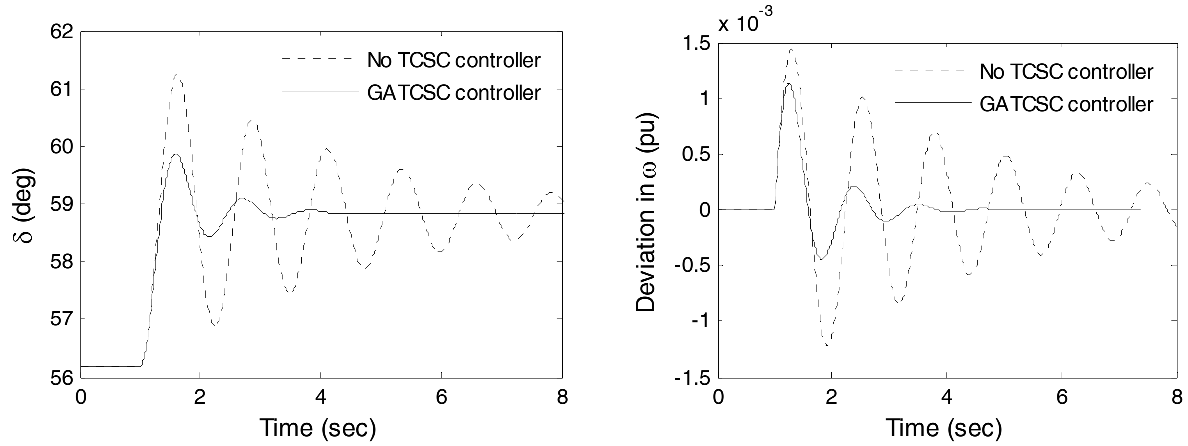
(c) (d)

(e) (f)

Figure 6: System response for a 100ms three-phase fault. (a) power angle, δ
(b) speed deviation, $\Delta\omega$ (c) electrical power output, P_e (d) accelerating power, P_a
(e) terminal voltage, V_T (f) reactance offered by TCSC, X_{TCSC}.

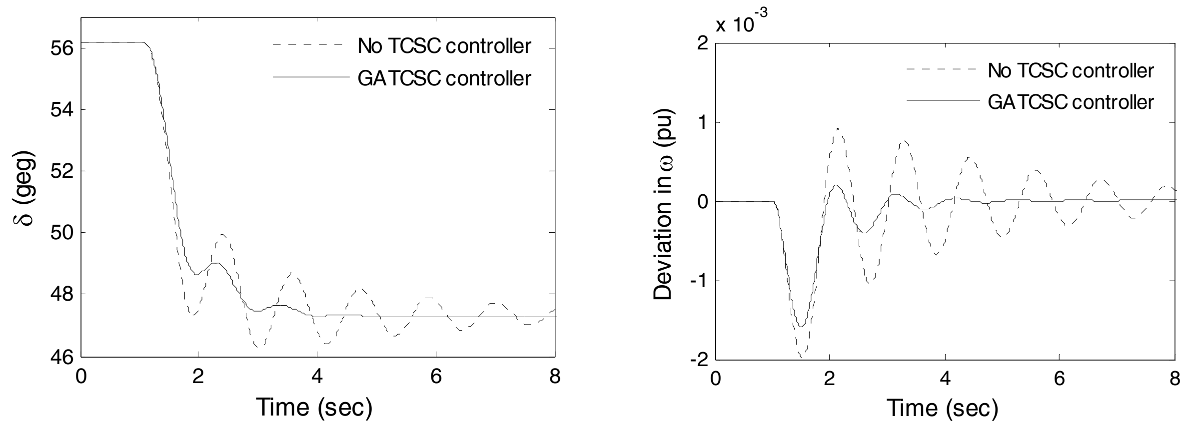
The performance of the optimised controller is tested by nonlinear simulations of the power system subjected to a severe disturbance. A three phase fault is applied at the generator terminals at t = 1 sec and cleared after 100 ms. The original system is restored upon the fault clearance. To study the performance of TCSC controller, two cases are considered; with and without genetically tuned TCSC controller. Fig. 6 (a)-(f) show the system response with respect to time for the two cases. Here the legend No TCSC controller indicates the absence of TCSC stability improvement controller, even though the TCSC is in the system and the legend GATCSC indicates the response with genetically tuned TCSC controller. It is clear from the Figs.6 (a)-(f) that, the genetically tuned TCSC controller improves the stability performance of the example power system and power system oscillations are well damped out.

To assess the damping characteristics of genetically tuned TCSC controller, a small disturbance in mechanical power input is considered. The input mechanical power is increased by a step of 5% at t =1 s. Figs. 7 (a) & (b) show the response of power angle and speed deviation for the above two cases. It is clear from the figures that the proposed GATCSC controller is also effective in damping low frequency oscillations.



(a) (b)

Figure 7: System response for a 5 % step increase in mechanical power.
(a) power angle, δ (b) speed deviation, $\Delta\omega$.



(a) (b)

Figure 8: System response for a 10 % step increase in reference voltage.
(a) power angle, δ (b) speed deviation, $\Delta\omega$.

For completeness, the performance of the proposed GATCSC controller for a disturbance in reference voltage is also considered. The reference voltage is increased by a step of 10 % at *t* =1 s, and the responses of power angle and speed deviation are shown in Figs. 8 (a) & (b). It is clear from the figures that genetically tuned TCSC controller damps low frequency oscillations effectively when the power system is subjected to small disturbances.

6. CONCLUSION

This paper presents a systematic procedure for modeling, simulation and optimal tuning of TCSC controller for enhancing power system stability. A MATLAB/SIMULINK model is developed for a single-machine infinite bus power system with TCSC. For the TCSC controller design problem, a parameter-constrained, time-domain based, objective function, is developed to improve the performance of power system subjected to a disturbance. Then, GA is employed to search for the optimal TCSC controller parameters. The controller is tested on example power system subjected to large and small disturbances. The simulation results show that, the genetically tuned TCSC controller improves the stability performance of the power system and power system oscillations are effectively damped out. Further it is observed that the proposed TCSC controller is effective in damping low frequency oscillations resulting from small disturbances conditions like increase in mechanical power input and reference voltage settings.

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APPENDIX

System data: All data are in pu unless specified otherwise.
Generator: $H = 3.0$ *s.,* $D = 4$, $X_d=1.0$, $X_q=0.6$, $X_d{}'=0.3$,
$T_{do}' = 5.044$, $Ra=0$, $P_e=0.95$, $Q_e=0.2084$, $\delta_0=56.4^0$.
Exciter: $K_A=10$, $T_A=0.01$ *s*
Transmission line: $R=0$, $X = 0.7$, $G=0$, $B=0$;
TCSC Controller: $T_{TCSC} = 15$ *ms*, $\alpha_0 = 158^0$, $X_{TCSC0} = 0.\,3591$, $k=2$, $T_2 = T_4$,=0.1 *s*, $T_W = 10$ *s*, $X_{MAX} = 0.7\,X$, $X_{MIN} = 0$.