# Design and Comparison of Power system stabilizer and Thyristor controlled series compensator , for Enhancement of Dynamic stability with SMIB system

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## Abstract:

A systematic procedure for designing, simulation and optimal tuning the parameters of a PSS and 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 PSS and TCSC controller is developed in MATLAB/SIMULINK. The design problem of PSS and TCSC controller is formulated as an optimization problem and genetic algorithm (GA) is employed to search for the optimal PSS and 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 modeling 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. With constraints on data availability and for study of power system stability it is adequate to model the synchronous generator with field circuit and one equivalent damper on q-axis known as the model 1.1. This paper presents a systematic procedure for modeling and simulation of a single-machine infinite-bus power system , so that impact of PSS and TCSC on power system stability can be more reasonably evaluated. The model of the example power system is developed using MATLAB/SIMULINK which can be can be used for teaching the power system stability phenomena, and also for research works especially to develop generator controllers using advanced technologies. Further, the parameters of the PSS and TCSC controller are optimized using genetic algorithm. The non-linear simulation results are presented to validate the effectiveness of the proposed approach. It has been observed that the dynamic stability of the power system gets significantly improved with the help of TCSC as compared to PSS and the power system dynamic response also gets improved under various power system conditions.

*Keywords*- Power system stabilizer (PSS), Single machine infinite bus system (SMIB), Synchronous generator model, Dynamic stability, Thyristor controlled series compensator (TCSC).

## 1.INTRODUCTION:

Electric energy is an essential ingredient for the industrial and all round development of any country. It is a coveted form of energy, because it can be generated centrally in bulk and transmitted economically over long distances. Further, for domestic and industrial applications it can be adapted easily and efficiently. The per capita consumption of electrical energy is a reliable indicator of a country's state of development. The basic structure , the main components of electric power system are Generating stations, transmission lines and the distribution systems. Generating stations and a distribution systems are connected through transmission lines, which is also connect one power system (grid, area) to another. A distribution system connects all the loads in a particular area to the transmission lines.
Modern power systems are designed to operate efficiently to supply power on demand to various load centers with high reliability [1]. The generating stations are often located at distant locations for economic,

environmental and safety reasons. In addition to transmission lines that carry power from the sources to loads, modern power systems are also highly interconnected for economic reasons.

The benefits of interconnected system are:
i. Exploiting load diversity
ii. Sharing of generation reserves
iii. Economy gained from the use of large efficient units without sacrificing reliability.

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. Now, more than ever, advanced technologies are vital for the reliable and secure operation of power systems. To attain both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the existing transmission system infrastructure is required. Better utilization of the existing power system is provided through the application of advanced control technologies recent development of power electronics introduces the employ of FACTS controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be oppressed to improve the voltage stability, and steady state and transient stabilities of a complex power system . This allows increased utilization of existing network closer to its thermal loading capacity, and thus avoiding the need to construct new transmission lines. The well known FACTS devices are namely SVC, STATCOM, TCSC, SSSC and UPFC.

Electromechanical oscillations in power systems are a problem that has been challenging engineers for years. These oscillations may be very inadequately damped in some cases, resulting in mechanical weariness at the machines and undesirable power variations across the important transmission lines. For this reason, the applications of the controllers to provide better damping for these oscillations are of utmost importance. With increasing transmission line loading over long distances, the application of PSSs might in some cases, not provide adequate damping for the inter-area power swings in a multi-machine system. In these cases, other efficient solutions are needed to be studied. Flexible AC transmission systems devices are one of the recent propositions to assuage such situations by controlling the power flow along the transmission lines and improving power oscillations damping. The use of these controllers increases the flexibility of the operation by providing more options to the power system operators. Amongst the available FACTS devices for transient stability enhancement, the TCSC is the most versatile one. The TCSC is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application and potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating the sub-synchronous resonance and improving the transient stability[2].

In the steady state, FACTS controllers like TCSC, help in controlling and increasing the power flow through a line. However, the other important aspects of these controllers are their ability to be used during the large disturbances like faults to improve the transient stability of a power system. A traditional lead-lag damping 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 methods. On the other hand, it was shown that the appropriate selection of the conventional lead-lag controller parameters results in effective damping to low frequency electromechanical oscillations. Unfortunately, the problem of the conventional lead-lag POD controller design is a multimodal optimization problem (i.e., there exists more than one local optimum).Hence, the conventional optimization techniques are not suitable for such a problem. Thus, it is required that the heuristic methods, which are widely used for the global optimization problems are developed.

The interaction among stabilizers may increase or degrade the damping of the particular modes of rotor oscillation. This problem may occur especially after the clearance of a critical fault, if FACTS devices are applied in the same area. Interactions between damping controllers can adversely influence the rotor damping of generators and under weakly interconnected system conditions it can even cause dynamic instability and restrict the operating power range of the generators. To improve the overall system performance, many researches were made on the coordination between PSSs and FACTS damping controllers.

Some of these methods are based on the complex nonlinear simulation, while the others are based on the linearized power system model. However, linear methods cannot properly capture the complex dynamics of the system, especially during the critical faults. This develops difficulties for tuning the TCSC damping controller and PSS in that the controllers tuned to provide the desired performance at a small signal condition do not guarantee acceptable performances in the event of large disturbances [4 & 5].

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) is becoming popular for solving the optimization problems in different fields of application, mainly because of their robustness in finding an optimal solution and ability to provide a near-optimal solution close to a global minimum. Unlike strict mathematical methods, the GA does not require the condition that the variables in the optimization problem be continuous and different; it only requires that the problem to be solved can be computed. 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 . Therefore, in the present work GA is employed to optimize the parameters of PSS and TCSC controller.

This paper is organized as follows. In Section II, Design of Power System, is presented. The proposed controller design of PSS and TCSC in Section III. In section IV ,SMIB with TCSC and PSS .A short overview of GA is presented in Section V. Simulation results are provided and discussed in Section VI and conclusions are given in Section VII.

## 2. Design of Power system:

An SMIB power system with TCSC is shown in Fig. 1 [6]. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line. *Vt* and *Eb* are the generator terminal and infinite bus voltage respectively; *XT*, *XL* and *XTH* represent the reactance of the transformer, transmission line per circuit and the Thevenin's impedance of the receiving end system respectively.
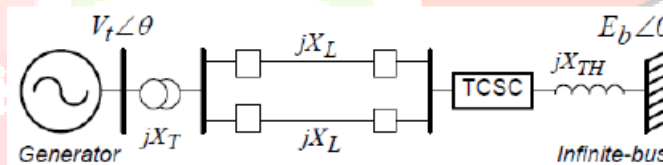


Fig. 1 Single-machine infinite-bus power system with TCSC .

The synchronous generator is represented by model 1.1 i.e. with field circuit and one equivalent damper winding on q-axis. The machine equations are :

$$\prime = \omega_B \ (S_m - S_{m0}) \tag{1}$$

$$dS_m / dt \ = \ [-D \ (S_m - S_{m0}) + T_m - T_e] \ /2H \tag{2}$$

$$dE_{q'} / \ dt = [-E_{q'} + x_d - x_{d'}.i_d + E_{fd}] / \ T_{do'} \tag{3}$$

$$dE_{d'} / = \ -[E_{d'} + (x_q - x_{qi}).i_q]/T_{qo'} \tag{4}$$

$$T_e = E_{d'}.i_d + E_{q'}.i_q + (x_{d'} - x_{q'}).i_d.i_q \tag{5}$$

For a lossless network, the stator algebraic equations and the network equations are expressed as:

$$E_{q'} + x_{d'}.i_d = v_q \tag{6}$$

$$E_{d'} + x_{q'}.i_q = v_d \tag{7}$$

$v_q = -x_e.i_d + E_b.\cos \delta$ (8)

$v_d = -x_e.i_q - E_b.\sin \delta$ (9)

Solving the above equations, the variables *id* and *iq* can be obtained as:

$i_d = (E_b.\cos\delta - E_q')/(x_e + x_d')$ (10)

$i_q = (E_b.\sin\delta - E_d')/(x_e + x_q')$ (11)

# 3. TCSC AND PSS

The basic Thyristor Controlled Series Capacitor (TCSC) scheme was proposed in 1986 by Vithyayaathil with others as a method of "rapid adjustment of network impedance" . TCSC is a later member of the first generation of FACTS devices. TCSC allows utility to transfer more power further on a particular line by reducing inductive reactance of the line. The world's first three phase TCSC was developed by ABB and installed at Kayenta substation, Arizona in 1992, that raises the capacity of a transmission line by almost 30% .

*3.1. Design of TCSC*
The basic module of a TCSC is shown in Fig. 2. It consists of three components: capacitor bank *C*, bypass inductor *L* and bidirectional thyristors T1 and T2. A metal-oxide varistor (MOV) is connected across the capacitor to prevent the occurrence of over-voltages across the capacitor. 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 .
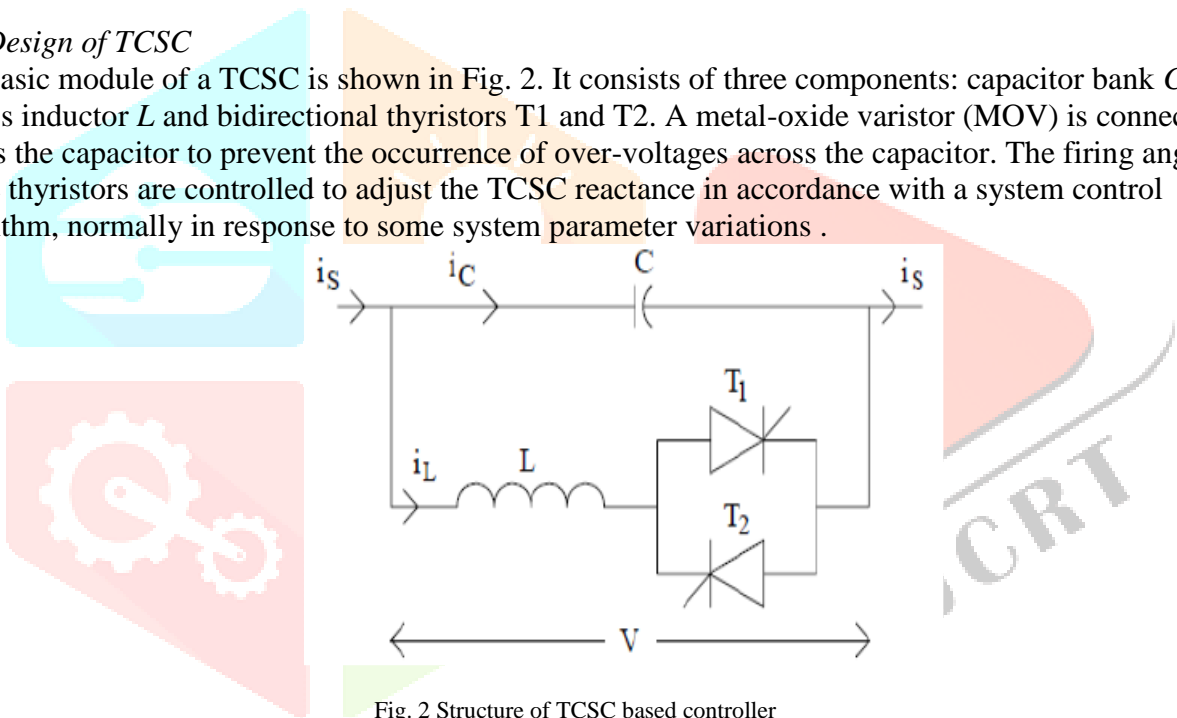


Fig. 2 Structure of TCSC based controller

The structure of TCSC-based damping controller, to modulate the reactance offered by the TCSC, *XTCSC(α)* is shown in Fig 3. The input signal of the controller is the speed deviation *Δω* and the output signal is the reactance offered by the TCSC, *XTCSC(α)*. The structure consists of a gain block with gain *KT*, a signal washout block and two-stage phase compensation blocks. The signal washout block serves as a high-pass filter, with the time constant *TWT*, high enough to allow signals associated with oscillations in input signal to pass unchanged.
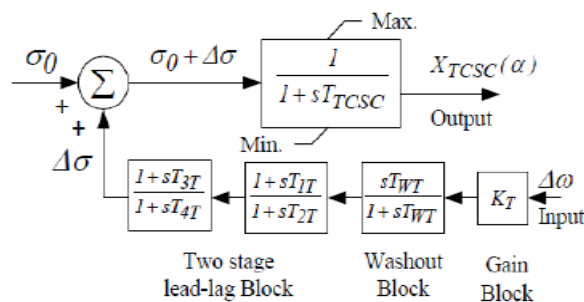


Fig. 3 Structure of TCSC-based controller

*3.2. Basic structure of TCSC controller*

According to the variation of the thyristor firing angle ($\alpha$) or conduction angle ($\sigma = 2.(\pi - \alpha)$), this process can be modeled 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 $XTCSC$. There exists a steady-state relationship between $\alpha$ and the reactance $XTCSC$. This relationship can be described by the following equation:

$XTCSC\,(\alpha)$

$= -\,{}_c^2\,/\,(X_c - Xp)\,.\,(\sigma + sin\sigma)\,/\,\pi$

$+\,4.X_c{}^2\,/\,(Xc - Xp)\,.cos^2(\sigma\,/\,2)\,/\,(k2 - 1)\,.\,[k.\tan(k\sigma\,/\,2) - \tan(\sigma\,/2)\,]\,/\,\pi$ (12)

Since the relationship between $\alpha$ and the equivalent fundamental frequency reactance offered by TCSC, *XTCSC ($\alpha$)* 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 $\alpha$.
Thus XTCSC (min) $\leq XTCSC \leq XTCSC$ (max), *with XTCSC* (max) = *XTCSC* ($\alpha$min) *and XTCSC* (min) = *XTCSC* (180°) = *XC*. In this paper, the controller is assumed to operate only in the capacitive region,
 i.e., *$\alpha$min > $\alpha$r* where *$\alpha$r* corresponds to the resonant point, as the inductive region associated with 90° < $\alpha$ < *$\alpha$r* induces high harmonics that cannot be properly modeled in stability studies .

*3.3. Design of the PSS*

A widely used conventional lead-lag PSS structure is shown in Fig 4. It consists of a gain block with gain *KP*, a signal washout block, and two-stage phase compensation block with time constants *T1P, T2P* and *T3P, T4P*. In this structure, *TWP* is the washout time constant; *$\Delta\omega$* is the speed deviation and *VS* is the stabilizing signal output of PSS.

The phase compensation block provide the appropriate phase-lead characteristics to compensate for the phase lag between the exciter input and the generator electrical (air-gap) torque. The signal washout block  serves as a high pass filter, with the time constants *TW* high enough to allow signals associated with oscillations in *$\Delta\omega$* to pass unchanged. Without it steady change in speed would modify the terminal voltage. From the viewpoint of washout function, the value of *TW* is not allow signals associated with oscillations in *$\Delta\omega$* to pass unchanged. Without it steady change in speed would modify the terminal voltage. From the viewpoint of washout function, the value of *TW* is not critical and may be in the range of 1 to 20 seconds. The stabilizing gain block determines the amount of damping introduced by the PSS .
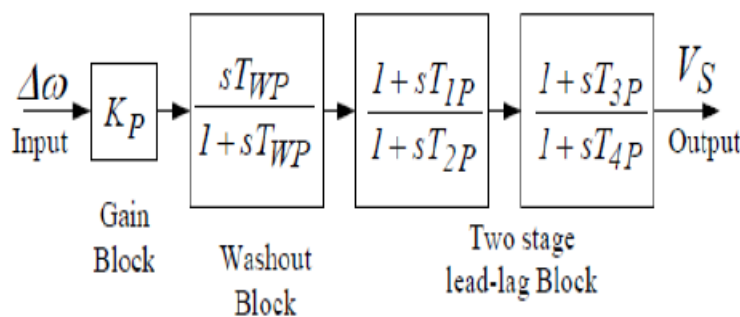


Fig. 4 Structure of PSS controller

## 4.SMIB with PSS and TCSC:

In this, we focus our attention on single machine infinite bus (SMIB) power systems. Since a SMIB system qualitatively exhibits important aspects of the behavior of a multi machine system and is relatively simple to study, it is extremely useful in describing the general concepts of power systems stability, the influence of

various factors upon stability, and alternative controller concepts. An infinite bus is a source of constant frequency and voltage either in magnitude and angle.

Consider the particular SMIB power system arrangement shown in Fig.5. The actual dynamic response of a synchronous generator in a practical power system when a fault occurs is very complicated including much nonlinearity such as the magnetic saturation. However, the classical third order dynamic generator model has been commonly used for designing the excitation controller[7 & 9].
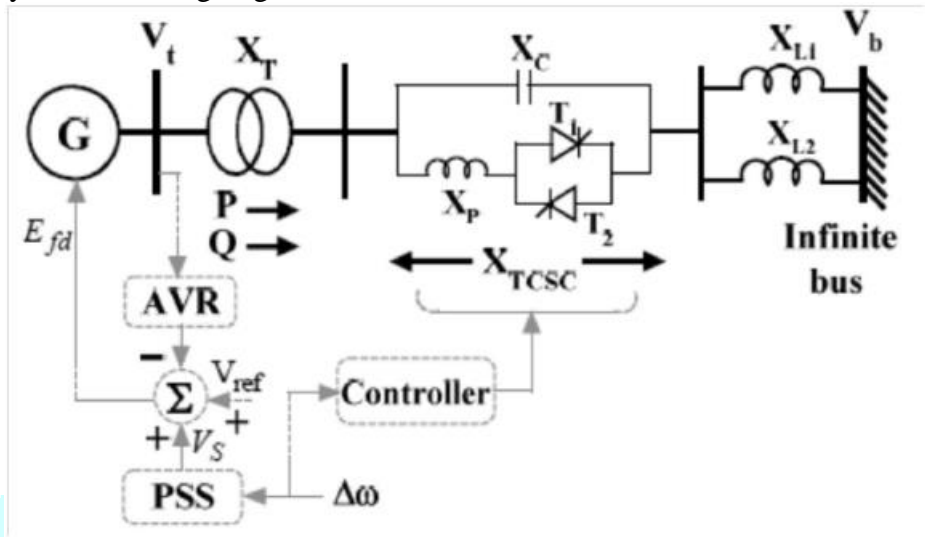


Fig. 5.Single-machine infinite-bus power system with PSS and TCSC controller.

### 4.1.OPTIMIZING PARAMETERS OF PSS AND TCSC  SIMULATNEOUS CONTROLLERS

Objective function J is defined as follows:

$$J = \sum \int_0^{t_1} t \left| \Delta\omega(t, X) \right| dt,$$

(13)

where $\Delta\omega(t, X)$ is the speed deviation of the generator for simultaneous TCSC and PSS parameters control lers. X is the optimization parameters of this controller (KT, T1T, T2T, T3T, T4T, KP, T1P, T2P, T3P, T4P) and t1 is the timeframe of the simulation. Here, the goal is to minimize the objective function.

There are the following inequalities for TCSC controller  in Fig.3.

$$K_T^{\min} \langle K_T \langle K_T^{\max}$$

$$T_{1T}^{\min} \langle T_{1T} \langle T_{1T}^{\max}$$

$$T_{2T}^{\min} \langle T_{2T} \langle T_{2T}^{\max}$$

$$T_{3T}^{\min} \langle T_{3T} \langle T_{3T}^{\max}$$

$$T_{4T}^{\min} \langle T_{4T} \langle T_{4T}^{\max}.$$

Similarly the following inequalities are held for PSS controller in Fig. 4:

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

$$T_{1P}^{\min} \langle T_{1P} \langle T_{1P}^{\max}$$

$$T_{2P}^{\min} \langle T_{2P} \langle T_{2P}^{\max}$$

$$T_{3P}^{\min} \langle T_{3P} \langle T_{3P}^{\max}$$

$$T_{4P}^{\min} \langle T_{4P} \langle T_{4P}^{\max}.$$

Here  GA  is  used separately for optimization and optimal point of TCSC and PSS parameters  controllers are  searched.

5.OVERVIEW OF GENETIC ALGORITHM (GA)

GA has been used for optimizing the parameters of the control system that are complex and difficult to solve by conventional optimization 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. Candidate solutions are usually represented as strings of fixed length, called chromosomes. A fitness or objective function is used to  reflect the goodness of each member of the population. Given a random initial population, GA operates  in cycles called generations, as follows:[9].

• 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.

The computational flow chart of the GA optimization approach followed in the present paper
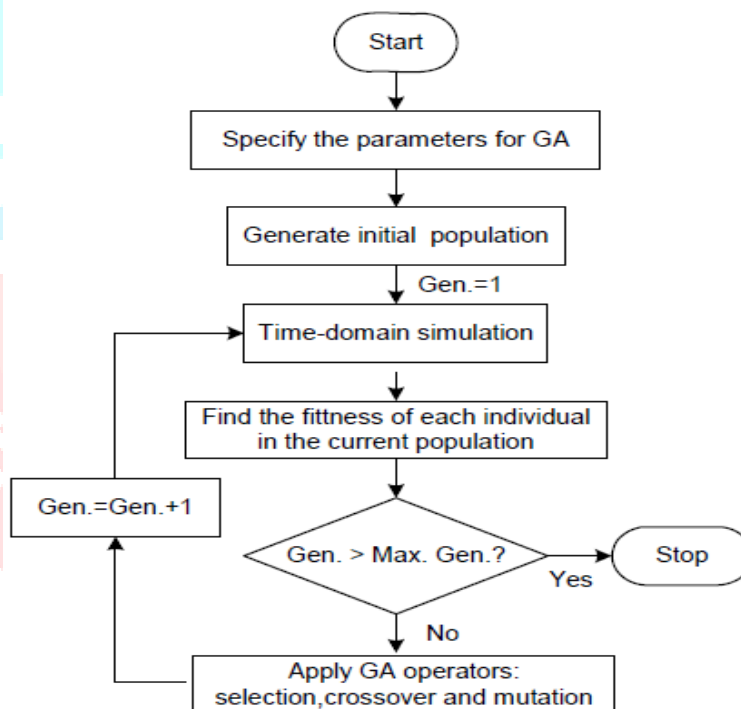is shown in Fig. 6.



Fig. 6. Flowchart of the genetic algorithm

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 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.

The designer has the freedom to explicitly specify the required performance objectives in terms of time domain bounds on the closed loop responses. Hence the GA methods yield optimal parameters
 and the method is free from the curse of local optimality. In view of the above, the proposed approach employs GA to solve this optimization problem and search for optimal set of TCSC-based damping controller parameters[10].

# 6.RESULTS

## 6.1. Application of GA Optimization Technique

In order to optimally tune the parameters of the TCSC based controller, as well as to assess its performance and robustness under wide range of operating conditions with various fault disturbances and fault clearing sequences, the MATLAB/SIMULINK model of the example power system shown [7] .

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 (1-13) . The SIMULINK model for calculation of id and iq is shown in Fig. 7. The relevant parameters are given in Appendix.

The operating point considered is:

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

For the purpose of optimization of equation (13), 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. 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. Optimization is terminated by the pre specified number of generations. The best individual of the final generation is the solution [8 &12]. 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 2.

Table 1.: 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 |

## 6.2.Dynamic Performance of SMIB System with PSS and TCSC:

The power system stabilizer (PSS) and thyristor controlled series compensator (TCSC) are employed in single machine infinite bus system to damp out low frequency oscillations occurred in the system when severe disturbance taken place at any one of the transmission lines. The employment of these controllers will improve the transient stability of in single machine infinite bus system. In this section , go through the results of single machine infinite bus system equipped with PSS and TCSC damping controllers without coordination and with coordination using GA optimization.
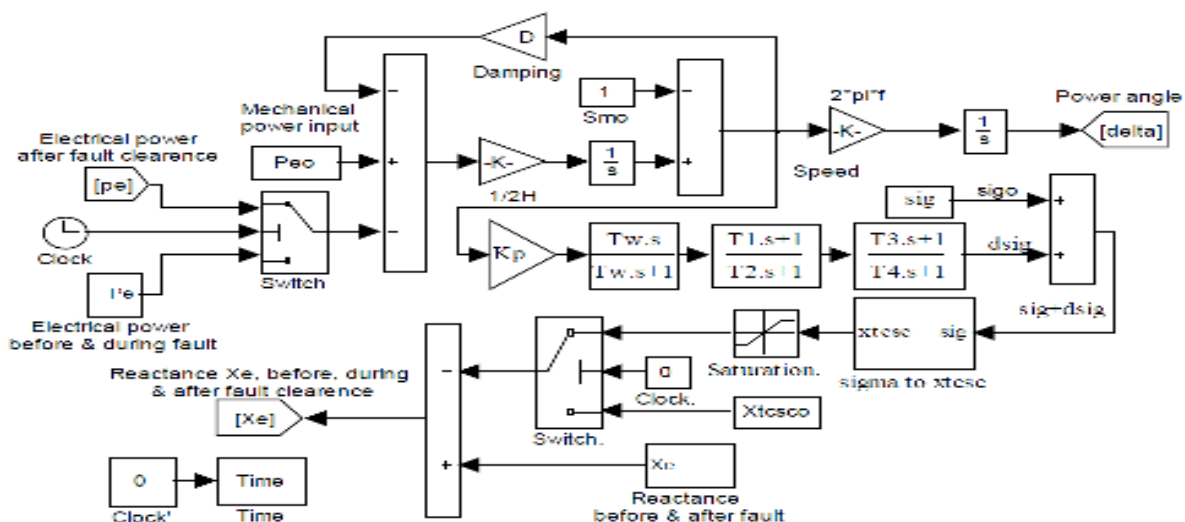


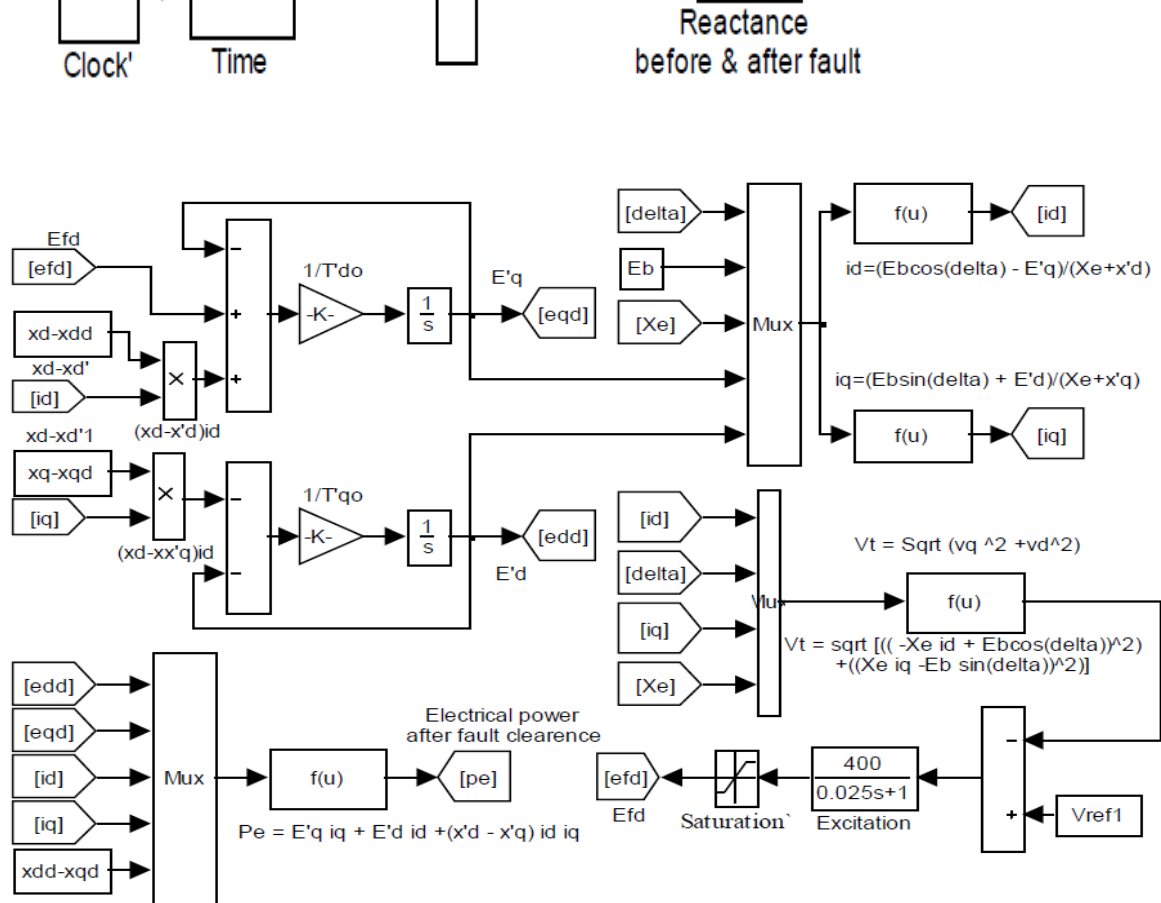Fig. 7. SIMULINK model of SMIB with TCSC controller

Fig. 8. SIMULINK model for calculation of *id* , *iq*.

The objective function is evaluated for each individual by simulating the system dynamic model considering a three phase fault at the generator terminal bus bar at $t = 1.0$ sec. For the purpose of optimization of equation (13), routines from GA toolbox were used. The fitness function comes from time domain simulation of power system model shown in Fig. 6. Using each set of controllers' parameters, the time-domain simulation is performed and the fitness value is determined. Good solutions are selected, and by means of the GA operators, new and better solutions are achieved. This procedure continues until a desired termination criterion is achieved. Although the chances of GA giving a local optimal solution are very few, sometimes getting a suboptimal solution is also possible. While applying GA, a number of parameters are required to be specified. An appropriate choice of these parameters affects the speed of convergence of the algorithm. 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.

The close-loop behaviour of the system with different control schemes is simulated using MATLAB programming. A three phase fault is applied at one of the transmission line is considered for analysis of SMIB system with TCSC. The performance of the system is analyzed under following different loading conditions:

a) Nominal loading: $P_e=1.0$p.u. and $Q_e=0.25$p.u.

b) Heavy loading: $P_e=1.2$p.u. and $Q_e=0.35$p.u.

c) Lightly loading: $P_e= 0.8$p.u. and $Q_e=0.15$p.u.

The fault that we consider here is a symmetrical three-phase short circuit fault on one of the parallel lines at a point which is very nearer to the generator bus bar, occurs at a time t=1sec, and it is cleared at t=1.1sec (i.e. the fault is applied for 6 cycles).Here frequency considered is 60 Hz. The results of time responses computed with the alternative controllers for nominal loading, heavy loading and lightly loading respectively are shown in Fig. 8 to 10. The responses of rotor angle variation, rotor speed variation are shown in figures 8 to 10 respectively.
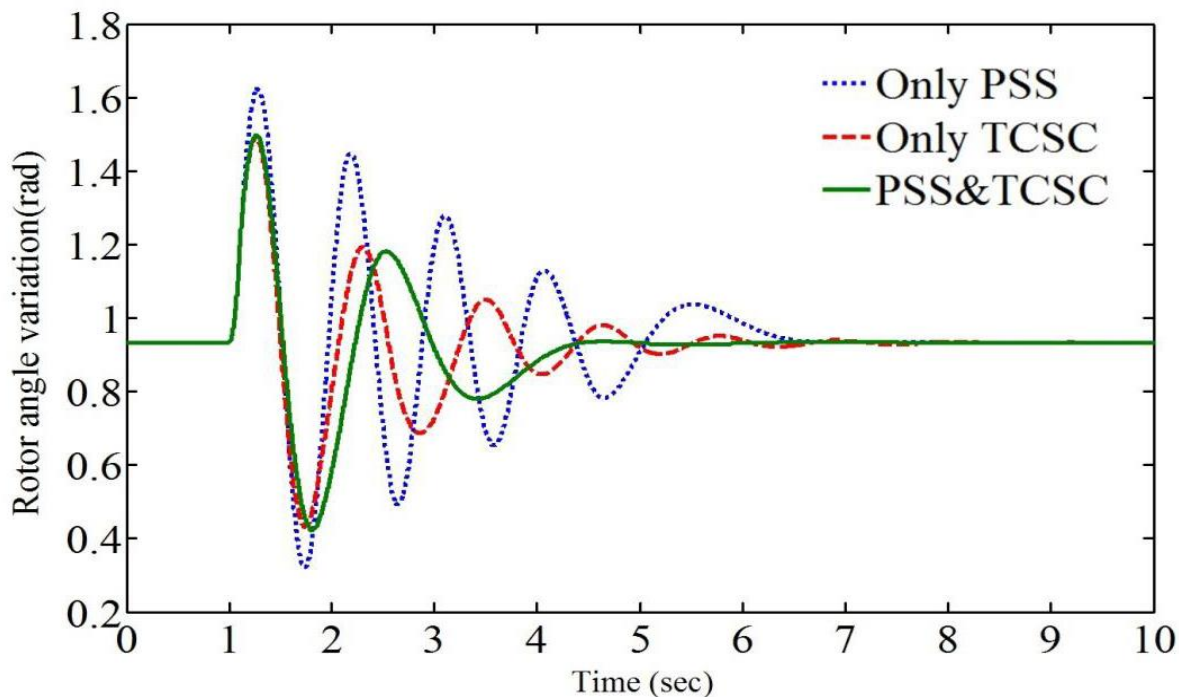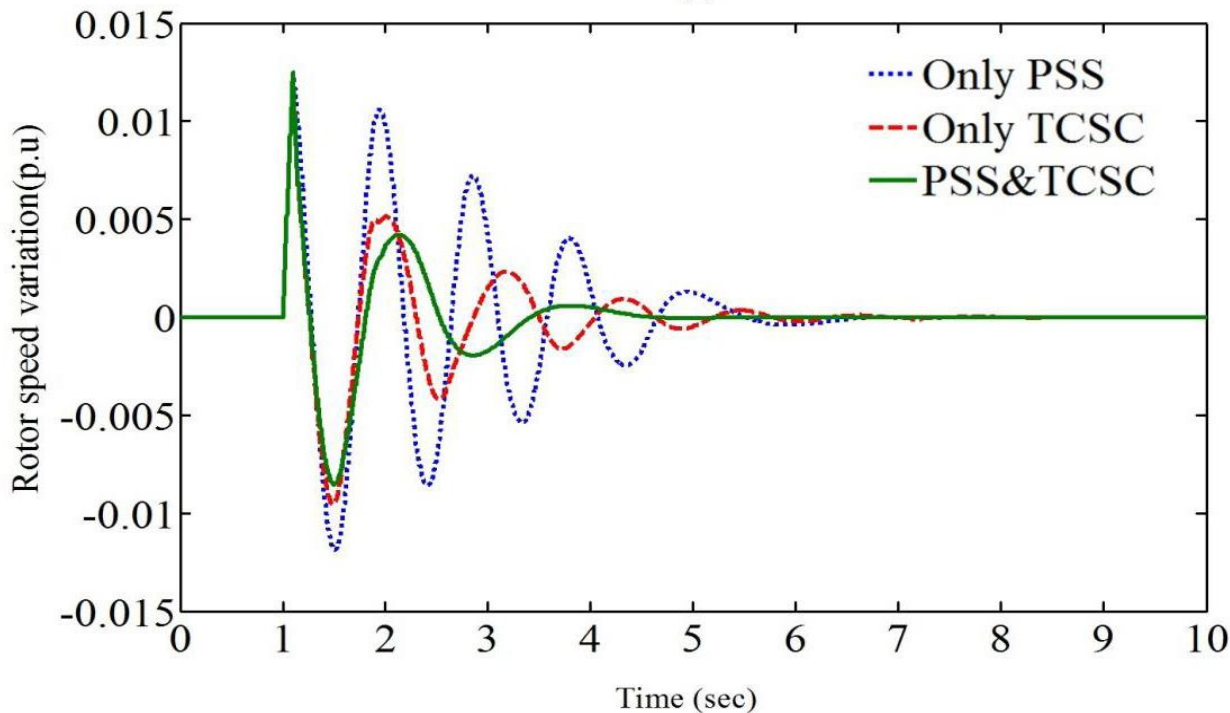
Fig.9.(a) & (b) **Nominal Loading ( Pe=1.0p.u. and Qe=0.25p.u.)** System dynamic response for a six cycle fault disturbance with Nominal Loading condition. (a) Rotor angle variation (b) Rotor speed variation.
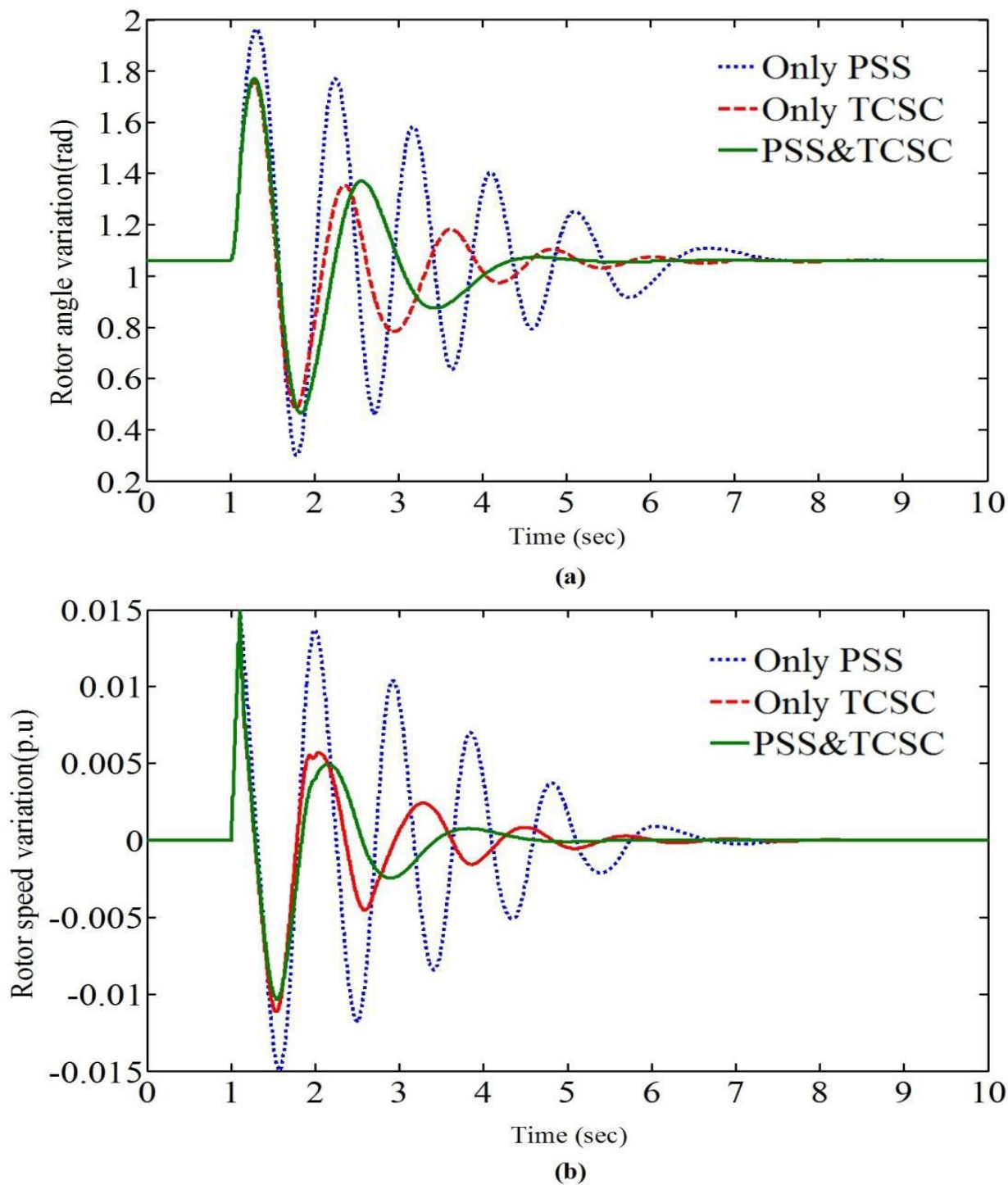
Fig.10.(a) & (b).**Heavy Loading ( Pe=1.2p.u. and Qe=0.35p.u)** , System dynamic response for a six cycle fault disturbance with Heavy Loading condition. (a) Rotor angle variation (b) Rotor speed variation.
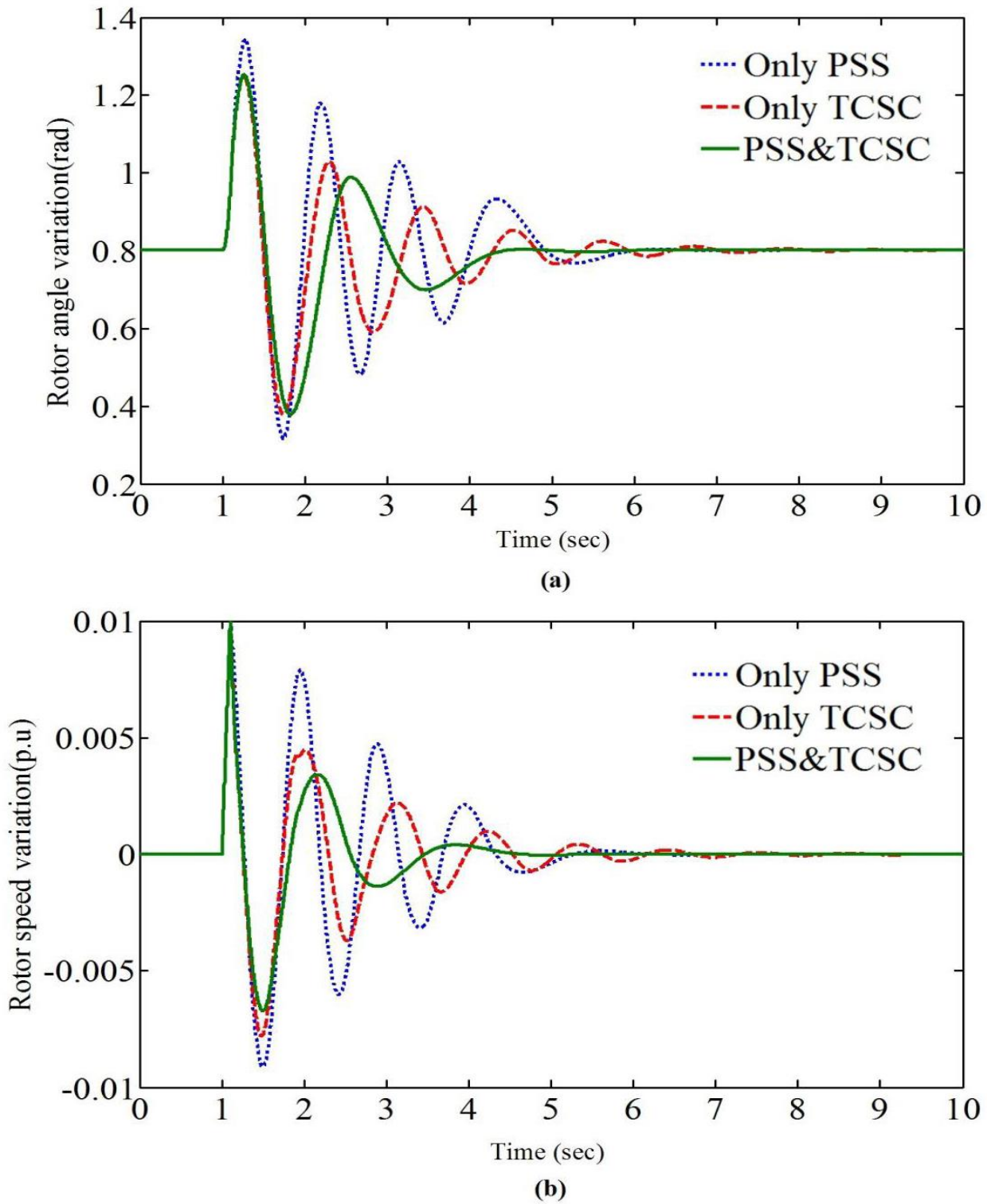
Fig.11. (a) & (b),**Lightly Loading ( Pe= 0.8p.u. and Qe=0.15p.u.)** System dynamic response for a six cycle fault disturbance with Light Loading condition. (a) Rotor angle variation (b) Rotor speed variation

TCSC and PSS controller parameters:

| Controller | Gain | Time Constants | | | |
|---|---|---|---|---|---|
| | $K$ | T1 | T2 | T3 | T4 |
| TCSC | 30.0311 | 0.0364 | 0.0283 | 0.0243 | 0.1578 |
| PSS | 7.3495 | 0.1929 | 0.0145 | 0.0767 | 0.0137 |

TABLE 2.Comparison with GA

# 7.CONCLUSION

A MATLAB/SIMULINK model is developed for a single-machine infinite bus power system with PSS and 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. The effect of PSS and TCSC on rotor angle and electrical power oscillations has been studied for a SMIB system using SIMULINK. It is concluded from the results that TCSC is more effective than PSS and the settling time of the power system gets reduced when PSS and TCSC are used in the power system to achieve stability and with TCSC Power transfer capability of the transmission line is also improved. An objective function is minimized using GA for finding the optimal control parameters of coordinated controller. Different control schemes are employed on the test system to investigate the performance of the proposed controller. The time domain simulation of a non-linear system is carried out in MATLAB software package. The robustness of the proposed coordinated controller is investigated by testing its performance under different loading conditions. The simulation results show that the test system dynamic performance and overall damping effect are
enhanced by simultaneous tuning of PSS and TCSC damping controllers. Therefore,
coordinated control of PSS and TCSC based damping controller provides better damping of
power oscillations.Comparison of PSS and TCSC performance on a multi-machine system will be taken up as a part of future research work.

## NOMENCLATURE

| | |
|---|---|
| δ | **Rotor angle of synchronous generator in radians** |
| ωB | **Rotor speed deviation in rad/sec** |
| Sm | **Generator slip in p.u.** |
| Smo | **Initial operating slip in p.u.** |
| H | **Inertia constant** |
| D | **Damping coefficient** |
| Tm | **Mechanical power input in p.u.** |
| Te | **Electrical power output in p.u.** |
| E fd | **Excitation system voltage in p.u.** |
| T' do | **Open circuit d-axis time constant in sec** |
| T' qo | **Open circuit q-axis time constant in sec** |
| xd | **d-axis synchronous reactance in p.u.** |
| x' d | **d-axis transient reactance in p.u.** |
| xq | **q-axis synchronous reactance in p.u.** |
| x' q | **q-axis transient reactance in p.u.** |
| XC | **Nominal reactance of the fixed capacitor C** |
| X P | **Inductive reactance of inductor L connected in parallel with C.** |
| σ | **Conduction angle of TCSC** |
| α | **Firing angle of TCSC** |
| k | **Compensation ratio, $k^2 = X_C / X_P$** |

## APPENDIX

System data: All data are in pu unless specified otherwise .
Generator: $H$=3.542, D = 0, $Xd$ = 1.7572, $Xq$ = 1.5845,
$Xd' = 0.4245$, $Xq' =1.04$,
$T'do = 6.66$, $T'qo$=0.44, $Ra$=0, $Pe$=0.6,
$Qe = 0.02224$, $\delta 0 = 44.37°$.
Exciter: $KA = 400$, $TA = 0.025$ s, $Efd$ limits = -7.0 to 7.0
Transmission line: $R$=0, $XL = 0.8125$, $XT = 0.1364$, $XTH = 0.13636$, $G$=0, $B$=0;

TCSC controller: $TTCSC$ = 15 ms, $\alpha0$ = 142°,
$XTCSC0$ = 0.62629, $k$=2, $Tw$ = 10s, $Xmax$ = 0.8 $XL$, $Xmin$ = 0.

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