Power System with PSS and FACTS Controller: Modelling, Simulation and Simultaneous Tuning Employing Genetic Algorithm

Sidhartha Panda and Narayana Prasad Padhy

***Abstract*—**This paper presents a systematic procedure for modelling and simulation of a power system installed with a power system stabilizer (PSS) and a flexible ac transmission system (FACTS)-based controller. For the design purpose, the model of example power system which is a single-machine infinite-bus power system installed with the proposed controllers is developed in MATLAB/SIMULINK. In the developed model synchronous generator is represented by model 1.1. which includes both the generator main field winding and the damper winding in q-axis so as to evaluate the impact of PSS and FACTS-based controller on power system stability. The model 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, to avoid adverse interactions, PSS and FACTS-based controller are simultaneously designed employing genetic algorithm (GA). The non-linear simulation results are presented for the example power system under various disturbance conditions to validate the effectiveness of the proposed modelling and simultaneous design approach.

***Keywords*—**Genetic algorithm, modelling and simulation, MATLAB/SIMULINK, power system stabilizer, thyristor controlled series compensator, simultaneous design, power system stability.

NOMENCLATURE

δ	Rotor angle of synchronous generator in radians
ω_B	Rotor speed deviation in rad/sec
S_m	Generator slip in p.u.
S_{mo}	Initial operating slip in p.u.
H	Inertia constant
D	Damping coefficient
T_m	Mechanical power input in p.u.
T_e	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
x_d	d-axis synchronous reactance in p.u.
x'_d	d-axis transient reactance in p.u.
x_q	q-axis synchronous reactance in p.u.
x'_q	q-axis transient reactance in p.u.
X_C	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, $k = \sqrt{X_C / X_P}$
V_t	Generator terminal voltage
E_b	Infinite-bus voltage
V_S	Stabilizing signal from power system stabilizer
T_W	Washout time constant

Sidhartha Panda is a research scholar in the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, Uttaranchal, 247667, India. (e-mail: speeddee@iitr.ernet.in, panda_sidhartha@rediffmail.com).
Narayana Prasad Padhy is Associate professor in the Department of Electrical Engineering, IIT, Roorkee India.(e-mail:, nppeefee@iitr.ernet.in)

I. INTRODUCTION

WITH the advent of flexible ac transmission system (FACTS) devices [1], such as thyristor controlled series compensator (TCSC), static synchronous compensator (STATCOM) and unified power flow controller (UPFC), the unified model of single-machine infinite-bus (SMIB) power system installed with a TCSC, STATCOM and a UPFC have been developed [2]-[4]. These models are the popular tools amongst power engineers for studying the dynamic behaviour of synchronous generators, with a view to design control equipment. However, the model only takes into account the generator main field winding and the generator damping windings are not accounted for. Further, these liner methods cannot properly capture complex dynamics of the system, especially during major disturbances. This presents difficulties for designing the FACTS controllers in that, the controllers designed to provide desired performance at small signal condition do not guarantee acceptable performance in the event of major disturbances.

In [5], a systematic procedure for modeling, simulation and optimal tuning of TCSC controller in a SMIB power system was presented where the MATLAB/SIMULINK based model was developed and genetic algorithm (GA) was employed to design the TCSC controller. However, the model only takes into account the generator main field winding and the synchronous machine was represented by model 1.0. For more reasonable evaluation of a SMIB power system with FACTS controller, a higher-order synchronous machine model (model 1.1), which includes one damper winding along the q-axis, is reported in the literature [6]. As power system stabilizers (PSS) are now routinely used in the industry, this paper considers a SMIB power system installed with a PSS and a FACTS controller, where the synchronous machine is represented by a higher order model (model 1.1).

The problem of PSS parameter tuning in the presence of FACTS-based controller is a complex exercise, as uncoordinated local control of these controllers may cause destabilizing interactions. To improve overall system performance, many researches were done on the coordination between PSS and FACTS power oscillation damping (POD) controllers [7]-[9]. 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 [10].

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 [11]. Therefore, in the present work GA is employed to simultaneously tune the parameters of PSS and FACTS controller.

This paper is organized as follows. In Section II, the modeling of power system under study, which is a SMIB power system with a PSS and a thyristor controlled series compensator (TCSC), is presented. The proposed controller structures and problem formulation are described in Section III. A short overview of GA is presented in Section IV. Simulation results are provided and discussed in Section V and conclusions are given in Section VI.

II. Power System Under Study

The SMIB power system with TCSC shown in Fig. 1 is considered in this study. The synchronous generator is delivering power to the infinite-bus through a double circuit transmission line and a TCSC. In Fig. 1, V_t and E_b are the generator terminal and infinite bus voltage respectively; X_T, X_L and X_{TH} represent the reactance of the transformer, transmission line per circuit and the Thevenin's impedance of the receiving end system respectively.

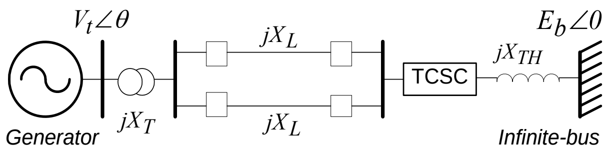

Fig. 1 Single-machine infinite-bus power system with TCSC

A. Modelling the Synchronous Generator Infinite-bus Power System

The synchronous generator is represented by model 1.1, i.e. with field circuit and one equivalent damper on q-axis. The machine equations are [12]:

$$\frac{d\delta}{dt} = \omega_B \left(S_m - S_{mo}\right) \tag{1}$$

$$\frac{dS_m}{dt} = \frac{1}{2H}\left[-D\left(S_m - S_{mo}\right) + T_m - T_e\right] \tag{2}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left[-E'_q + \left(x_d - x'_d\right) i_d + E_{fd}\right] \tag{3}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}\left[-E'_d + \left(x_q - x'_q\right) i_q\right] \tag{4}$$

The electrical torque T_e is expressed in terms of variables E'_d, E'_q, i_d and i_q as:

$$Te = E'_d\, i_d + E'_q\, i_q + \left(x'_d - x'_q\right) i_d\, i_q \tag{5}$$

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

$$E'_q + x'_d\, i_d = v_q \tag{6}$$

$$E'_d - x'_q\, i_q = v_d \tag{7}$$

$$v_q = -x_e i_d + E_b \cos\delta \tag{8}$$

$$v_d = x_e i_q - E_b \sin\delta \tag{9}$$

Solving the above equations, the variables i_d and i_q can be obtained as:

$$i_d = \frac{E_b \cos\delta - E'_q}{x_e + x'_d} \tag{10}$$

$$i_q = \frac{E_b \sin\delta + E'_q}{x_e + x'_q} \tag{11}$$

The above notation for the variables and parameters described are standard and defined in the nomenclature. For more details, the readers are suggested to refer [12]-[13].

B. Modelling the 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. It consists of three components: capacitor banks, bypass inductor 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.

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 [14]:

$$X_{TCSC}(\alpha) = X_C - \frac{X_C^2}{(X_C - X_P)}\frac{(\sigma + \sin\sigma)}{\pi} + \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2(\sigma/2)}{(k^2-1)}\frac{[k\tan(k\sigma/2) - \tan(\sigma/2)]}{\pi} \tag{12}$$

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 $X_{TCSCmin} \le X_{TCSC} \le X_{TCSCmax}$, with $X_{TCSCmax} = X_{TCSC}(\alpha_{min})$ and $X_{TCSCmin} = X_{TCSC}(180^0) = X_C$. 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.

III. Problem Formulation

A. Structure of the TCSC Controller

The structure of TCSC-based damping controller, to modulate the reactance offered by the TCSC, $X_{TCSC}(\alpha)$ is shown in Fig. 2. The input signal of the proposed controllers is the speed deviation (Δω), and the output signal is the reactance offered by the TCSC, $X_{TCSC}(\alpha)$. The structure consists of a gain block with gain K_T, a signal washout block and two-stage phase compensation blocks. The signal washout block serves as a high-pass filter, with the time constant T_{WT}, high enough to allow signals associated with oscillations in input signal to pass unchanged.

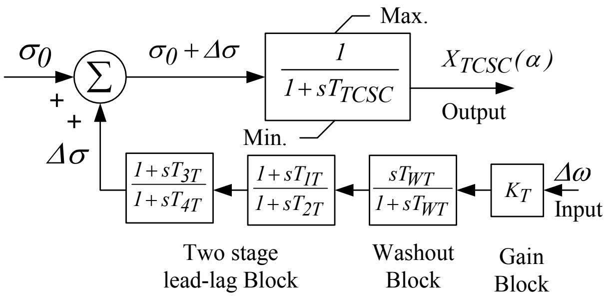

Fig. 2 Structure of TCSC-based controller

From the viewpoint of the washout function, the value of T_{WT} is not critical and may be in the range of 1 to 20 seconds [13]. The phase compensation block (time constants T_{1T}, T_{2T} and T_{3T}, T_{4T}) provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. In the Fig. 2, σ_0 represents the initial conduction angle as desired by the power flow control loop. The steady state power flow loop acts quite slowly in practice and hence, in the present study, σ_0 is assumed to be constant during large disturbance transient period.

B. Structure of the PSS

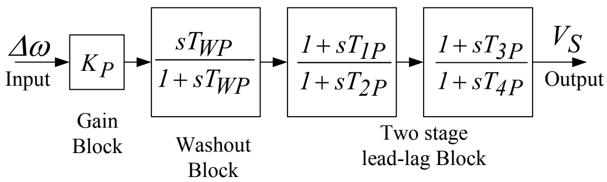

Fig. 3 Structure of the power system stabilizer

A widely used conventional lead-lag PSS is considered in this study. Its structure is shown in Fig. 3. It consists of a gain block with gain K_P, a signal washout block, and two-stage phase compensation block with time constants T_{1P}, T_{2P} and T_{3P}, T_{4P}. In this structure, T_{WP} is the washout time constant; $\Delta\omega$ is the speed deviation and V_S is the stabilizing signal out put of PSS.

C. Problem Formulation

In the present study, a washout time constant of $T_{WT} = T_{WP}$ =1.0s is used. The controller gains K_T & K_P and the time constants T_{1T}, T_{2T}, T_{3T}, T_{4T} & T_{1P}, T_{2P}, T_{3P} and T_{4P} are to be determined. In case of PSS, the stabilizing signal output V_S is zero during steady state conditions. Following a disturbance, the signal V_S is modified according to the change in the $\Delta\omega$ during dynamic conditions. In case of TCSC-based controller, $\Delta\sigma$ and σ_0 are constant during steady state conditions. During dynamic conditions, conduction angle (σ) and hence $X_{TCSC}(\alpha)$ is modulated to improve power system stability. The desired value of compensation is obtained through the change in the conduction angle ($\Delta\sigma$), according to the variation in $\Delta\omega$. The effective conduction angle σ during dynamic conditions is given by:

$$\sigma = \sigma_0 + \Delta\sigma \tag{13}$$

D. Objective Function

It has been shown that that for the TCSC-based controller design problem, the best system response is obtained when the controller parameters are optimized using integral of time multiplied absolute value of the error (ITAE) as objective function [15]. In view of the above, in this paper, the objective function is defined as follows:

$$J = \int_0^{t_{sim}} t\,|\Delta\omega(t)|\,dt \tag{14}$$

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

IV. 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 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. 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:

- 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.

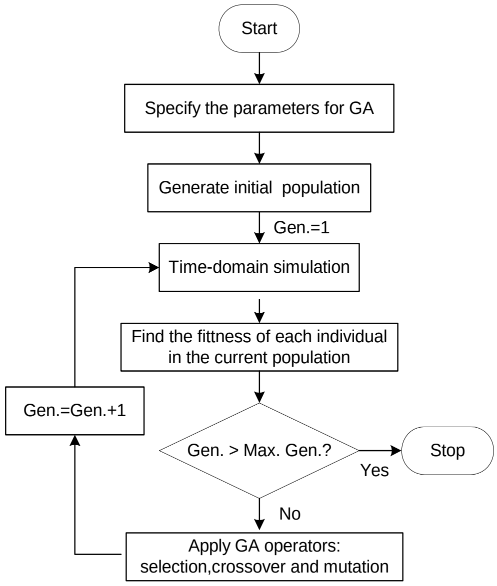

Fig. 4 Flowchart of the genetic algorithm

The computational flow chart of the GA optimization approach followed in the present paper is shown in Fig. 4.

V. Results and Discussions

A. Application of GA Optimization Technique

In order to simultaneously tune the parameters of the PSS and the TCSC-based controller, as well as to assess their performance and robustness under wide range of various fault disturbances, the MATLAB/SIMULINK model of the example power system shown in Fig. 1 is developed using equations (1)–(11). The developed MATLAB/SIMULINK model of synchronous generator with PSS and TCSC controller is shown in Fig. 5. The SIMULINK model for calculation of i_d, i_q, E'_d, E'_q and P_e is shown in Fig. 6. The relevant parameters are given in appendix.

The objective function is evaluated for each individual by simulating the system dynamic model considering a three-phase fault at the generator terminal busbar at t = 1.0 sec. For the purpose of optimisation of equation (16), routines from GA toolbox were used. The fitness function comes from time-domain simulation of power system model shown in Fig. 5. 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

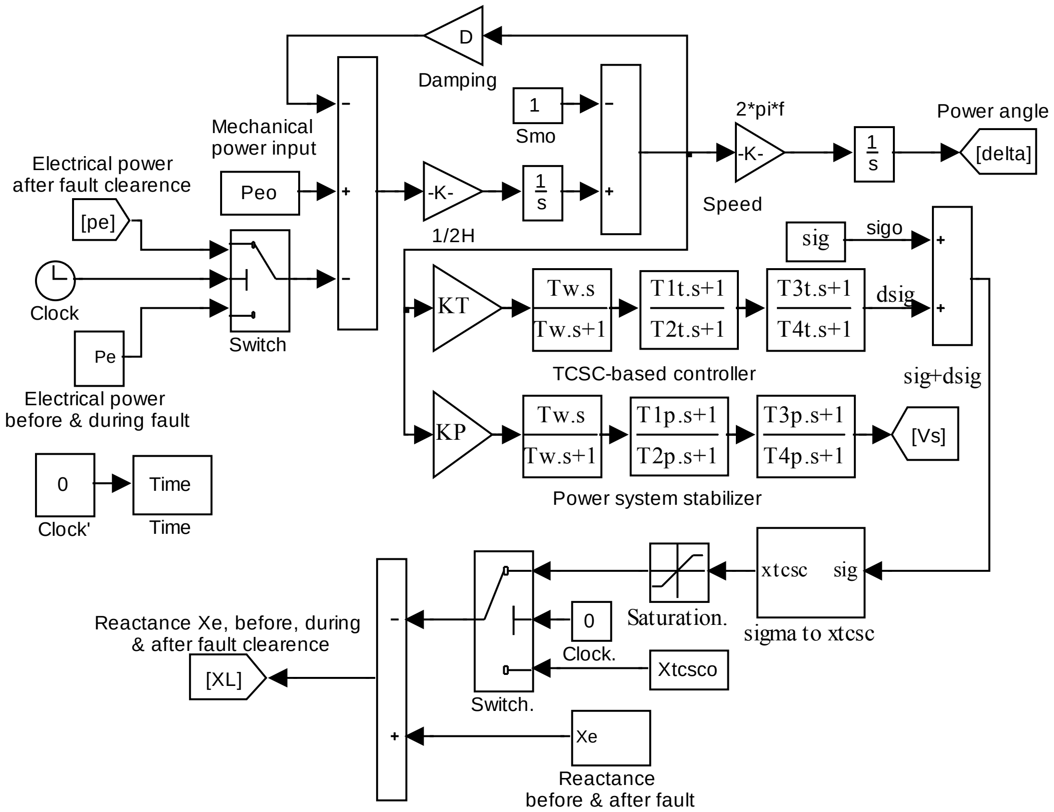

Fig. 5 SIMULINK model of SMIB with PSS and TCSC controller

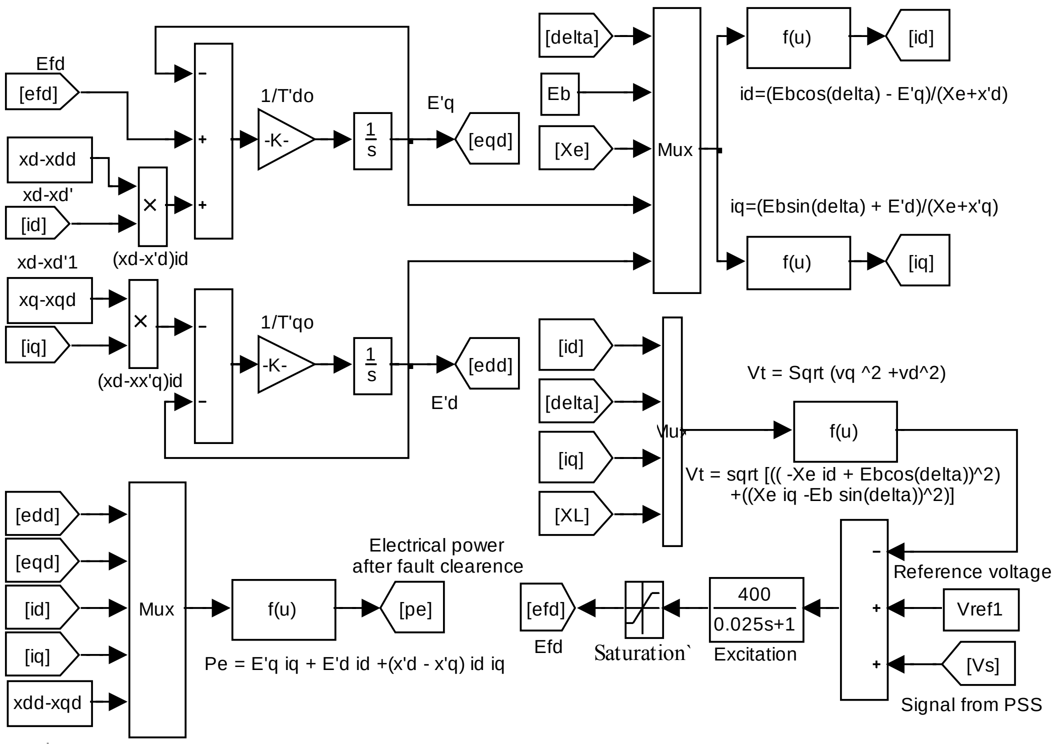

Fig. 6 SIMULINK model for calculation of i_d, i_q, E'_d, E'_q, E_{fd} and P_e

TABLE I
PARAMETERS USED IN GENETIC ALGORITHM

Parameter	Value/Type
Maximum generations	200
Population size	50
Type of selection	Normal geometric [0 0.08]
Type of crossover	Arithmetic [2]
Type of mutation	Nonuniform [2 200 3]
Termination method	Maximum generation

TABLE II
OPTIMIZED TCSC CONTROLLER PARAMETERS USING GENETIC ALGORITHM

Parameters/ Controller	Gain	Time constants			
	K	T_1	T_2	T_3	T_4
TCSC	30.0311	0.0364	0.0283	0.0243	0.1578
PSS	7.3495	0.1929	0.0145	0.0767	0.0137

for GA do not give the best solution, and so these can be changed according to the situation. The parameters for GA optimization routines used in the present paper are given in Table I. The description of these operators and their properties can be found in reference [16]. One more important point that affects the optimal solution more or less is the range for unknowns. For the very first execution of the programme, a wider 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 optimized parameters are shown in Table II. Fig. 7 shows the convergence rate objective function J with the number of generations.

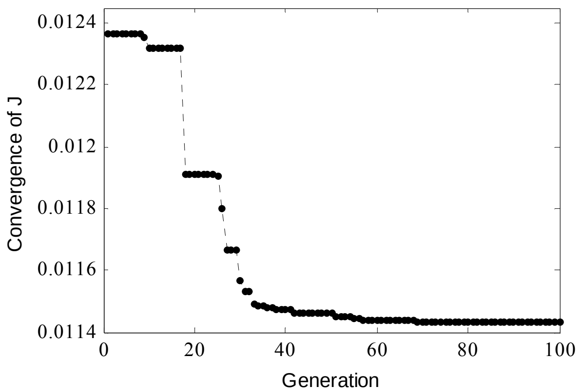

Fig. 7 Convergence rate of objective function J.

B. *Simulation Results*

In order to show the effectiveness of the proposed model of power system with PSS and TCSC-based controller and simultaneous tuning the controller parameters in the way presented in this paper, simulation studies are carried out for the example power system subjected to various severe disturbances as well as small disturbance. To evaluate the performance of the proposed simultaneous design approach the response with the proposed controllers are compared with the response with TCSC controller only given in reference [6]. The response without the controller (no control) is shown with dotted line with legend NC; the responses with TCSC controller only is shown with legend TCSC with thin solid line and the response with the simultaneously designed TCSC & PSS controller is shown with thick solid line with legend TCSC & PSS. The following disturbances are considered:

Case-1: Three-phase Fault Disturbance

A three phase fault is applied at the generator terminal busbar at t = 1 sec and cleared after 5 cycles. The original system is restored upon the fault clearance. The system power angle response for the above contingency is shown in Fig. 8. It is clear from the Fig. 8 that, without controller even though the system is stable, power system oscillations are poorly damped. The TCSC controller significantly suppresses the oscillations in the power angle and provides good damping characteristics to low frequency oscillations by stabilizing the system quickly. It is also clear from the Fig. 8 that, application both PSS and TCSC-based controller where the controllers are tuned by the proposed simultaneous design approach gives the best response in terms of overshoot and settling time. The first swing in the power angle δ, is also slightly suppressed and the settling time is greatly reduced with the simultaneous design approach.

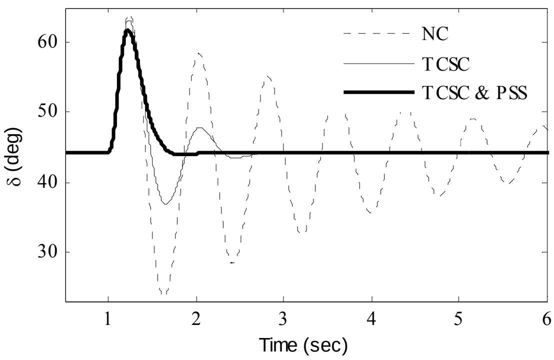

Fig. 8 Response of power angle δ for a 5-cycle three-phase fault disturbance (*Case-1*)

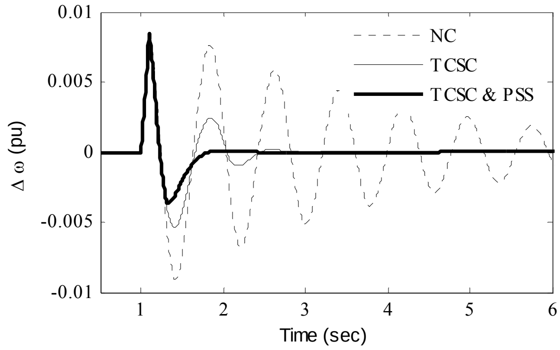

Fig. 9 Variation of speed deviation $\Delta\omega$: *Case-1*

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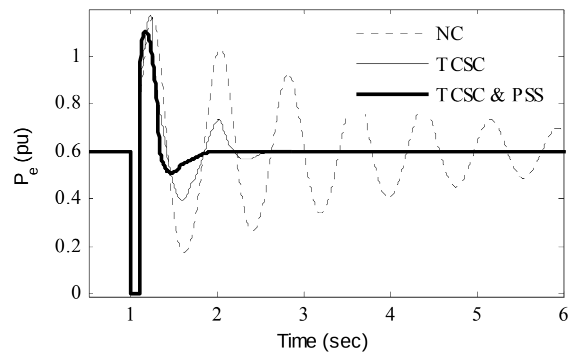

Fig. 10 Variation of electrical power P_e : *Case-1*

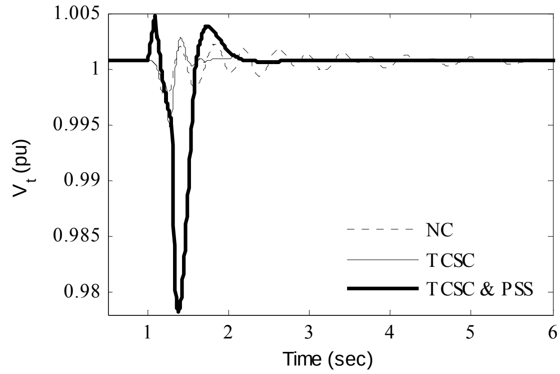

Fig. 14 Variation of terminal voltage V_t : *Case-1*

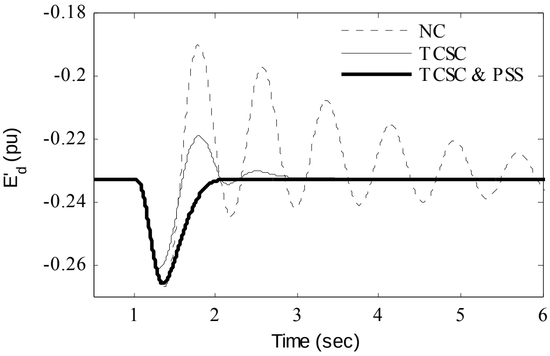

Fig. 11 Variation of voltage E'_d : *Case-1*

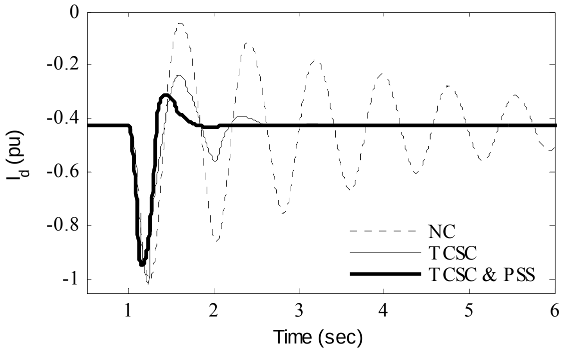

Fig. 15 Variation of current I_d : *Case-1*

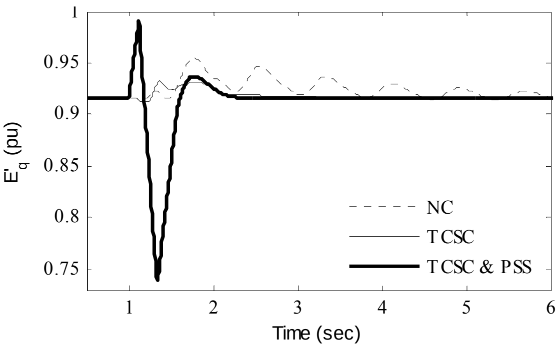

Fig. 12 Variation of voltage E'_q : *Case-1*

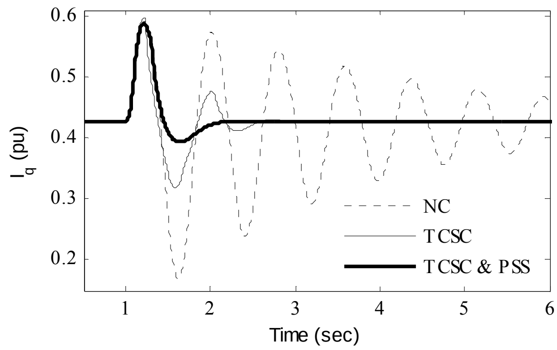

Fig. 16 Variation of current I_q : *Case-1*

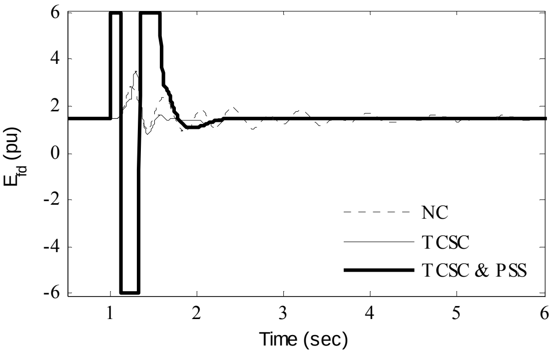

Fig. 13 Variation of voltage E_{fd} : *Case-1*

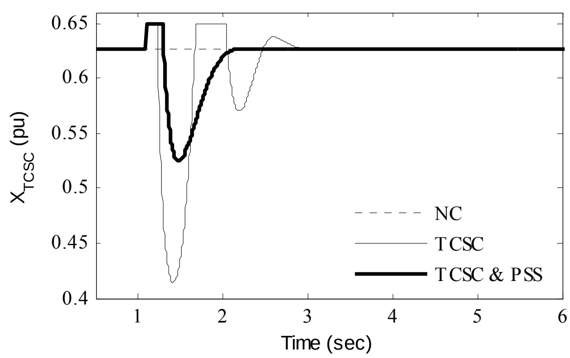

Fig. 17 Variation of X_{TCSC} : *Case-1*

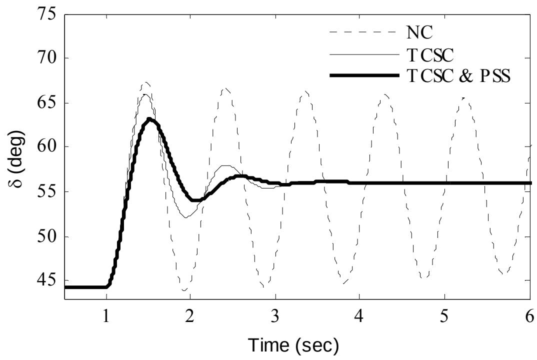

Fig. 18 Variation of power angle δ : *Case-2*

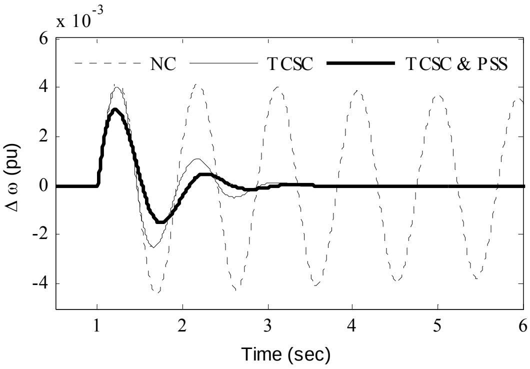

Fig. 19 Variation of speed deviation $\Delta\omega$: *Case-2*

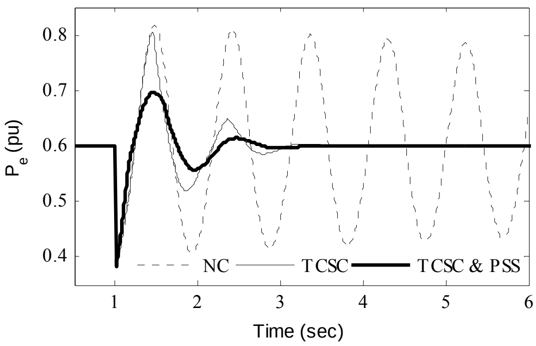

Fig. 20 Variation of electrical power P_e : *Case-2*

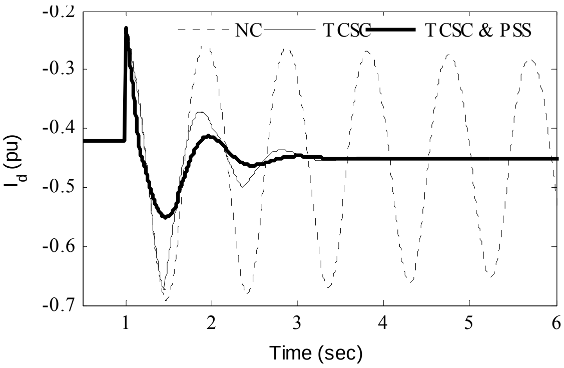

Fig. 21 Variation of current I_d : *Case-2*

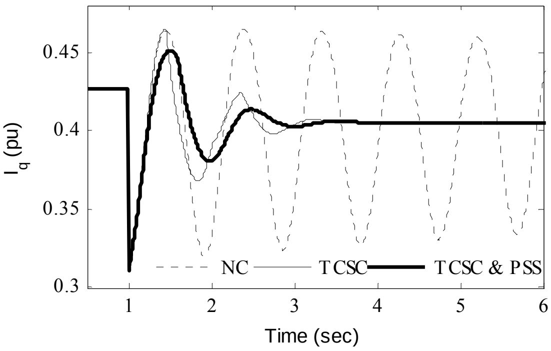

Fig. 22 Variation of current I_q : *Case-2*

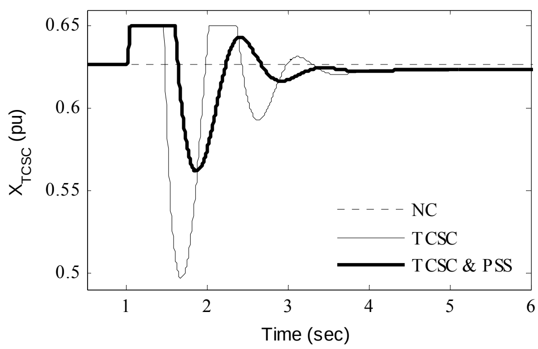

Fig. 23 Variation of X_{TCSC} : *Case-2*

Figs. 9 - 17 shows the variation of speed deviation, electrical power P_e, voltages E'_d , E'_q , E_{fd} , V_t , currents i_d , i_q and reactance offered by TCSC: X_{TCSC} , respectively all with respect to time for the above mentioned contingency in *Case-1*. It is clear from these Figs. that, the simultaneous design of PSS and TCSC-based controller by the proposed approach significantly improves the stability performance of the example power system and power system oscillations are well damped out.

Case-2: Line-outage Disturbance

In this case another severe disturbance is considered. One of the transmission line is permanently tripped out at t = 1 sec. The system response for the above contingency is shown in Figs. 18-26. The simulation results show the effectiveness of the proposed modelling and simultaneous tuning approach. It is also clear from the Figs. that PSS and TCSC-based controller operate in a coordinated manner and improves the stability performance of the power system compared to the case where only TCS-based controller is acting.

Case-3: Small Disturbance

In order to verify the effectiveness of the proposed simultaneous design approach under small disturbance, the mechanical power input to the generator is increased by 1 pu at t = 1 sec. The system response under this small disturbance contingency is shown in Figs. 24-27. It is clear form the Figs. 24-27 that, the proposed GA optimized PSS and TCSC-based controller act in a coordinated has good damping characteristics to low frequency oscillations and quickly stabilizes the system under this small disturbance.

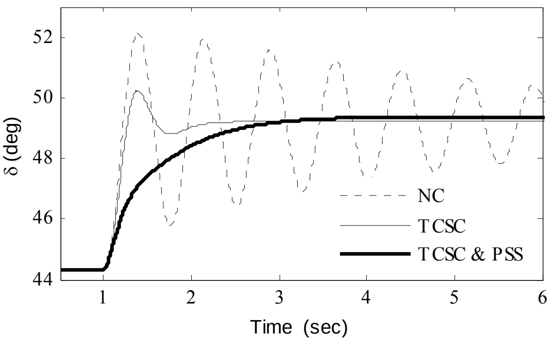

Fig. 27 Variation of power angle δ : *Case-3*

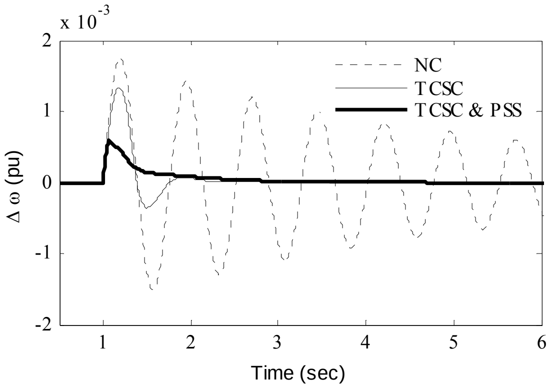

Fig. 28 Variation of speed deviation $\Delta\omega$: *Case-3*

VI. Conclusion

A systematic procedure for modelling and simulation of a power system installed with a PSS and a FACTS-based controller is presented in this paper. The model is developed in the MATLAB/SIMULINK environment which provides a means for carrying out power system stability analysis and for explaining the generator dynamic behaviour as effected by a PSS and FACTS. In this model, the synchronous generator with field circuit and one equivalent damper on q-axis is considered which is far more realistic compared to the model available in open literature. Further, to avoid adverse interactions, the proposed controllers are simultaneously designed. For the 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 coordinately tune the parameters of the PSS and TCSC controller. The performance of the proposed controllers is tested on example power system subjected to various large and small disturbances. Simulation results show that, application both PSS and TCSC where the controllers are tuned by the proposed simultaneous design approach gives the best response in terms of overshoot and settling time. The first swings in the power angle, speed deviation and the electrical power are also greatly suppressed and the settling time is greatly reduced with the simultaneous design approach.

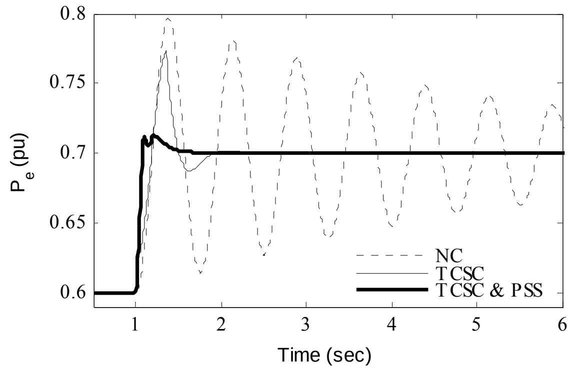

Fig. 29 Variation of electrical power P_e : *Case-3*

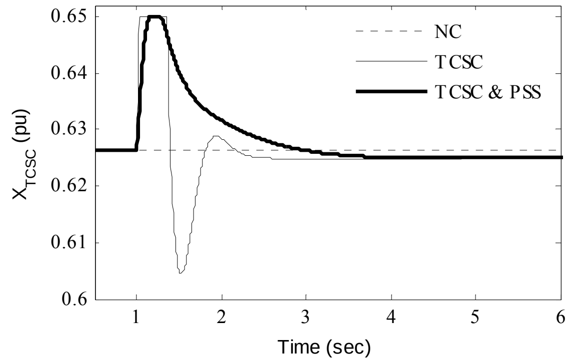

Fig. 31 Variation of X_{TCSC} : *Case-3*

Appendix

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

Generator: H = 3.542, D = 0, X_d=1.7572, X_q=1.5845, X'_d=0.4245, X'_q=1.04, T'_{do} = 6.66, T'_{qo}=0.44, Ra=0, P_e=0.6, Q_e=0.02224, δ_0=44.37^0.

Exciter: K_A=400, T_A=0.025 s

Transmission line: R=0, X_L = 0.8125, X_T=0.1364, X_{TH}=0.13636, G=0, B=0;

TCSC Controller: T_{TCSC} = 15 ms, α_0 = 142^0, X_{TCSC0} = 0.62629, k=2, T_W = 10 s, X_{MAX} = 0.8 X_L, X_{MIN} = 0.

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Sidhartha Panda received the M.E. degree in Power Systems Engineering from University College of Engineering, Burla, Sambalpur University, India in 2001. Currently, he is a Research Scholar in Electrical Engineering Department of Indian Institute of Technology Roorkee, India. He was an Associate Professor in the Department of Electrical and Electronics Engineering, VITAM College of Engineering, Andhra Pradesh, India and Lecturer in the Department of Electrical Engineering, SMIT, Orissa, India. His areas of research include power system transient stability, power system dynamic stability, FACTS, optimization techniques, distributed generation and wind energy.

Narayana Prasad Padhy was born in India and received his Degree (Electrical Engineering), Masters Degree (Power Systems Engineering) with Distinction and Ph.D., Degree (Power Systems Engineering) in the year 1990, 1993 and 1997 respectively in India. Then he has joined the Department of Electrical Engineering, Indian Institute of Technology (IIT) India, as a Lecturer, Assistant Professor and Associate Professor during 1998, 2001 and 2006 respectively. Presently he is working as a Associate Professor in the Department of Electrical Engineering, Indian Institute of Technology (IIT) India. He has visited the Department of Electronics and Electrical Engineering, University of Bath, UK under Boyscast Fellowship during 2005-06 . His area of research interest is mainly Power System Privatization, Restructuring and Deregulation, Transmission and Distribution network charging, Artificial Intelligence Applications to Power System and FACTS.