Electrical Power and Energy Systems 68 (2015) 123–131

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Reduced order H_∞ TCSC controller & PSO optimized fuzzy PSS design in mitigating small signal oscillations in a wide range

V.K. Tayal [a,*], J.S. Lather [b]

[a] Department of Electrical Engineering, Amity University, Noida, Uttar Pradesh, India
[b] Department of Electrical Engineering, National Institute of Technology, Kurukshetra, India

ARTICLE INFO

Article history:
Received 16 April 2014
Received in revised form 25 September 2014
Accepted 7 December 2014

Keywords:
PSO–Particle Swarm Optimization
FACTS–Flexible AC Transmission System
TCSC–Thyristor controlled series capacitor
PSS–Power system stabliser
FPSS–Fuzzy power system stabiliser
T–S–Takagi–Sugeno

ABSTRACT

This paper proposes hybrid control schemes for compensation of parametric and non-parametric uncertainties arising in modern power systems. The robust loop shaping design procedure considering non-parametric uncertainty term is used to design H_∞ TCSC. To further enhance steady state stability, and consider the effect of parametric uncertainties occurring due to variation in loading conditions, robust TCSC is supplemented with three types of PSS i.e. PSO-PID PSS, PSO Mamdani FPSS and PSO TS FPSS. PSO is used to optimize the parameters of PID based and Fuzzy type PSS. The proposed hybrid control schemes are found to compensate uncertainty well by stabilizing the power system over whole parametric uncertainty range. However, the proposed hybrid controller involving robust TCSC and PSO-Takagi–Sugeno FPSS shows best performance with enhanced steady state stability among all schemes. Also the T–S FPSS performs better as compared to Mamdani FPSS.

Introduction

Low frequency (0.1–1.0 Hz) power oscillations [9] are inherent in electric power systems. Traditionally, the supplementary damping in power system is provided by power system stabiliser (PSS) [4,10,12]. However, with growing transmission line loading, the power system stabiliser (PSS) may not provide enough damping for the inter-area power oscillations in a complex power system. In addition, it may result in large variations in the voltage profile, leading power factor operation and even loss of power system stability under large uncertain loading conditions [32,21,15]. In these days, Power electronic based Flexible AC Transmission Systems (FACTS) controllers are widely recognized [7,6] by power system practitioners for controlling the power flow along the transmission lines and improving power oscillation damping. One of the well known Series FACTS device, thyristor controlled series compensator (TCSC) is competent [8,3] to provide damping to the local mode and inter-area oscillations, control the power flow and improve dynamic stability.

It is a well-known fact that the conventional damping controller design synthesis is simple but tends to lack of robustness in a wide range even after a lot of tuning. Several research studies have been reported in the literature for tuning damping controller parameters. To design the power system stabilisers [2] a variety of design methods such as frequency response [16], pole placement [20], eigenvalue sensitivity [22], residue method [24] and other different robust control techniques have been proposed. To design the TCSC and PSS the most common techniques are based on simulated annealing [1], phase compensation method [33] and genetic algorithm [14]. All of the above methods do not consider the occurrence of system parameters and loading uncertainties in the power system modelling; thus the robustness of TCSC and PSS against system uncertainties cannot be guaranteed. Therefore, TCSC and PSS may not be able to make the system stable under varying conditions in force.

In order to achieve a Robust TCSC and Fuzzy PSS at all operating conditions the concepts of control theory are contextualize into power system stability. In the proposed hybrid control scheme a Robust H_∞ loop shaping TCSC damping controller and PSO optimized Fuzzy PSS in a Single Machine infinite Bus (SMIB) power system is demonstrated. The time domain simulations clearly show that the proposed hybrid controllers are highly robust to different power system uncertainties. This paper is organized as follows. Section 'Power system modelling' details system modelling, the design of the proposed TCSC and FPSS structures are detailed in Section 'Robust TCSC and PSO – fuzzy PSS control design'. Next section 'Simulation studies' presents the simulation studies and the effectiveness of TCSC and PSS has been validated on Single Machine

---

* Corresponding author.

E-mail addresses: vikysm09@gmail.com (V.K. Tayal), jslather@gmail.com (J.S. Lather).

http://dx.doi.org/10.1016/j.ijepes.2014.12.033
0142-0615/

infinite Bus (SMIB) power system in different conditions, the conclusion is given in Section 'Conclusions'. Appendix includes various parameters of the system and controllers.

Power system modelling

The study system consists of a synchronous machine connected to an infinite bus through a transmission line. A TCSC and a fuzzy power system stabiliser are installed with the system (Fig. 1). Fig. 2 shows the block diagram of Single Machine infinite bus (SMIB) power system. This diagram was developed by Heffron and Phillips [1952] to represent the dynamics of a single synchronous generator connected to the grid through a line. This model is a well-known model for synchronous generators. This model is a linear model; still it is quite accurate for studying low frequency oscillations and stability of power systems. It has also been successfully used for designing classical power system controllers, which are still active in most power utilities.

The state space representation for the model in Fig. 2 is expressed as:

$$\Delta\dot{X} = A\cdot\Delta X + B\cdot\Delta U$$

$$\Delta Y = C\cdot\Delta Y + D\cdot\Delta U$$

where the output vector $\Delta Y = [\Delta\omega]$ and the state vector is $\Delta X = [\Delta\delta, \Delta\omega, \Delta E'_q, \Delta E_{fd}]^T$. $\Delta U = [\Delta U_{PSS}, \Delta U_{TCSC}]^T$ denotes the control signals from Fuzzy PSS and Robust TCSC, whereas angular speed deviation ($\Delta\omega$) is used as an input signal.

To design the PSO – Fuzzy PSS and Robust TCSC, the PSO tuned Fuzzy Logic Control and H_∞ loop shaping approaches are applied respectively. The coefficients K_1, K_2, K_3, K_4, K_5, K_6, k_V (K_7), K_p (K_8) and K_q (K_9) as shown in Fig. 2 are calculated for an example power system [3], with the real power varying from 0.1 pu to 1.0 pu, at 0.85 power factor (Table 1). The terminal voltage V_t, is maintained constant at 1.0 pu and the transmission line reactance considered 0.4 pu. The simulations were performed considering the reactance of the TCSC equal to 0.3 pu. The above variation of K constants at different operating points is considered as parametric uncertainty for H_∞ TCSC controller design.

Robust TCSC and PSO – fuzzy PSS control design

Robust TCSC loop shaping control design using Glover–McFarlane method

The Robust TCSC design is based on the H_∞ robust stabilisation combined with classical loop-shaping, where loop-shape refers to the magnitude of the loop transfer function $L = GK$ as a function of frequency. The control method for designing Robust TCSC controller uses a combination of loop shaping and robust stabilization as proposed in [17,18,29]. The first step is to select a pre- and post-compensator W_1 and W_2, so that the gain of the shaped plant $Gs = W_2GW_1$ (Fig. 3) is sufficiently high at frequencies where good disturbance attenuation is required and is sufficiently low at frequencies where good robust stability is required. The second step is to compute a Glover–McFarlane H_∞ normalized co prime factor loop-shaping controller $K = W_2 * Ks * W_1$, where $K_s = K_\infty$ is an optimal H_∞ controller.

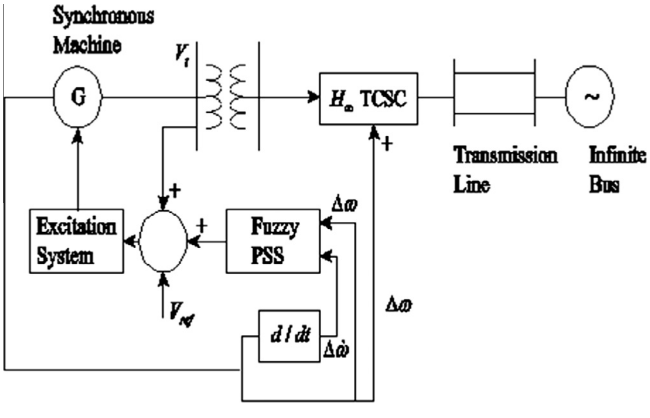

Fig. 1. TCSC and fuzzy PSS installed in a SMIB system.

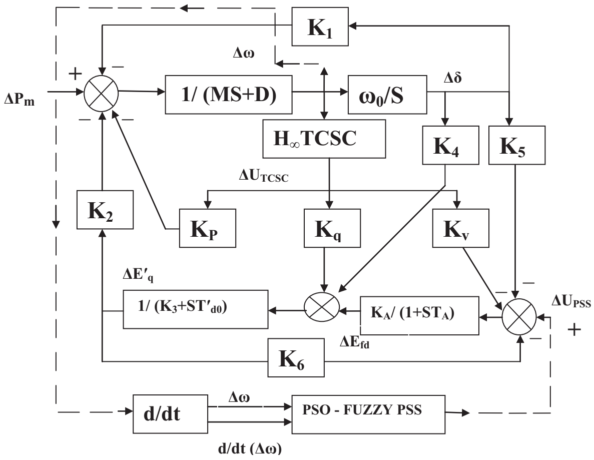

Fig. 2. P–H model of SMIB system connected with H_∞ TCSC and Fuzzy PSS.

Table 1
K Constants at different operating points.

P (pu)	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9
0.1	0.8	0.6	0.19	0.70	0.030	0.29	−0.04	0.15	0.4
0.2	1	1	0.19	1.00	0.045	0.285	−0.08	0.25	0.8
0.3	1.2	1.3	0.19	1.20	0.050	0.280	−0.12	0.4	1.2
0.4	1.5	1.5	0.19	1.50	0.06	0.276	−0.16	0.7	1.6
0.5	1.8	1.7	0.19	1.75	0.06	0.270	−0.20	1.0	2.1
0.6	1.9	1.8	0.19	1.90	0.05	0.264	−0.24	1.3	2.7
0.7	2	2.0	0.19	2.00	0.048	0.258	−0.28	1.6	3.1
0.8	2.1	2.2	0.19	2.15	0.040	0.252	−0.31	1.9	3.6
0.9	2.2	2.25	0.19	2.20	0.03	0.246	−0.35	2.1	4.1
1.0	2.2	2.35	0.19	2.25	0.025	0.24	−0.38	2.3	4.3

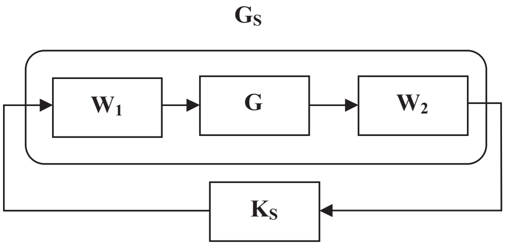

Fig. 3. Shaped plant (Gs) with H_∞ controller (Ks).

The plant G_S is known as shaped plant. It is represented by normalized left co prime factorization $G_S = M^{-1}N$ then the plant perturbed model G_Δ is expressed as

$$G_\Delta = (M + \Delta M)^{-1}(N + \Delta N)$$

where ΔM and ΔN represent the uncertainty in the power system nominal model G. The objective of robust stabilisation is to stabilise a family of perturbed plants defined by:

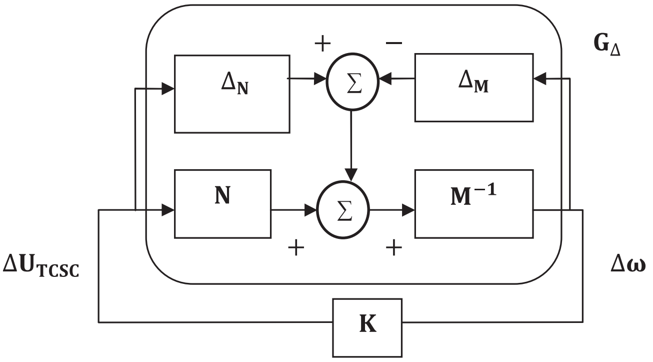

Fig. 4. H_∞ Robust stabilization.

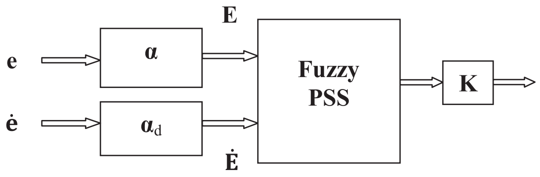

Fig. 5. Basic structure of a fuzzy logic power system stabiliser.

$$G_\Delta = \{(M + \Delta M)^{-1}(N + \Delta N) : ||\Delta N \quad \Delta M||_\infty < 1/\gamma\} \tag{1}$$

By the definition in (1) the problem of H_∞ stabilization via NCF approach can be formed by K and a perturbed plants family G_Δ as shown in Fig. 4. In (1), the term $1/\gamma$ is defined as the robust stability margin. In the presence of system uncertainties, the maximum stability margin ($1/\gamma_{min}$) is specified by the lowest possible value of γ, i.e. γ_{min}. The value of γ_{min}, can be calculated by (2),

$$\gamma_{min} = \sqrt{(1 + \lambda_{max}(XZ))} \tag{2}$$

where $\lambda_{max}(XZ)$ represents the greatest eigenvalue of XZ. For a minimal state-space realization (A, B, C, D) of G_S, the X and Z values are the unique positive definite solutions to the algebraic Riccati equations

$$(A - BS^{-1}D^TC)^TX + X(A - BS^{-1}D^TC) - XBS^{-1}X + C^TR^{-1}C = 0$$

$$(A - BS^{-1}D^TC)Z + Z(A - BS^{-1}D^TC)^T - ZC^TR^{-1}CZ + BS^{-1}B^T = 0$$

where $R = I + DD^T$, $S = I + D^TD$.

γ gives a good indication of robustness of stability to a wide class of plant variations. The nominal plant robust stability is determined by the selection of weighting function such that $\gamma_{min} \leqslant 4.0$ for most typical control system designs [25]. If γ_{min} is not satisfied, then we have to alter the weighting function. The H_∞ Controller can be find out by

$$H_\infty = \begin{bmatrix} A + BF + \gamma^2(L^T)^{-1}ZC^T(C + DF) & \gamma^2(L^T)^{-1}ZC^T \\ B^TX & -D^T \end{bmatrix} \tag{3}$$

where $\mathbf{F} = -S^{-1}(D^TC + B^TX)$ and $L = (1 - \gamma^2)I + XZ$.

Now, the TCSC controller $K = W_1 * K_\infty * W_2$ is find out that satisfies the required condition-

$$||[\mathrm{I} \quad \mathrm{K}_\infty]^T(I - G_sK_\infty)^{-1}[\mathrm{I} \quad \mathrm{G}_s]||_\infty < \gamma$$

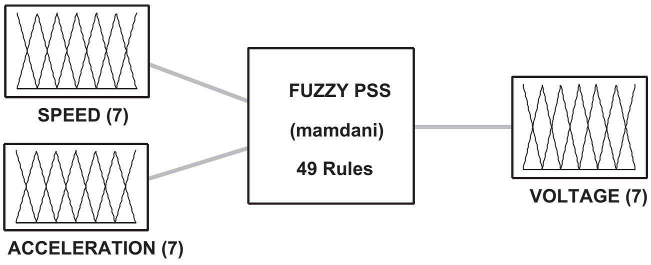

Fig. 6. FIS editor fuzzy PSS.

Table 2
Design parameters of fuzzy PSS.

Speed Dev.	Acceleration						
	NB	NM	NS	ZR	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	NS
NM	NB	NM	NM	NM	NS	NS	ZR
NS	NB	NM	NM	NM	NS	NS	ZR
ZR	NM	NS	NS	ZR	PS	PS	PM
PS	NS	ZR	ZR	PS	PS	PM	PM
PM	ZR	PS	PS	PM	PM	PM	PB
PB	PS	PM	PM	PB	PB	PB	PB

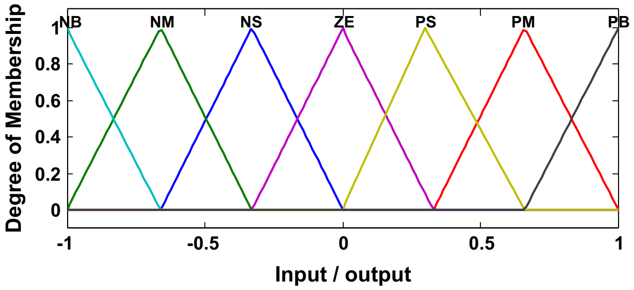

Fig. 7. Membership functions for fuzzy PSS for input and output variables.

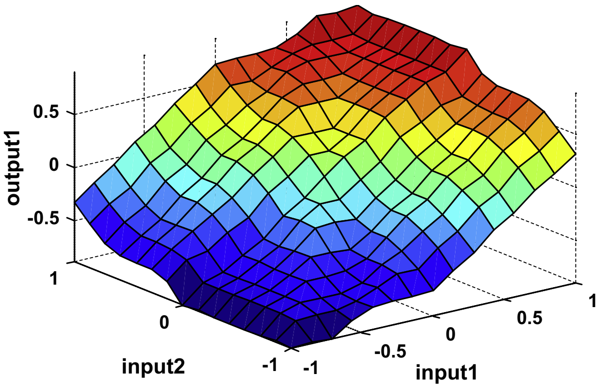

Fig. 8. Surface viewer.

PSO–fuzzy PSS design

To design Fuzzy PSS, Takagi–Sugeno and Mamdani type fuzzy inference engine were chosen (see Fig. 5).

Fig. 6 shows a FIS Editor with two input variable blocks, one output variable block and Mamdani FLC [23,26], [31,5,19,30] block. Fuzzy controller Design process involves 3 steps: fuzzification, fuzzy rules and defuzzification.

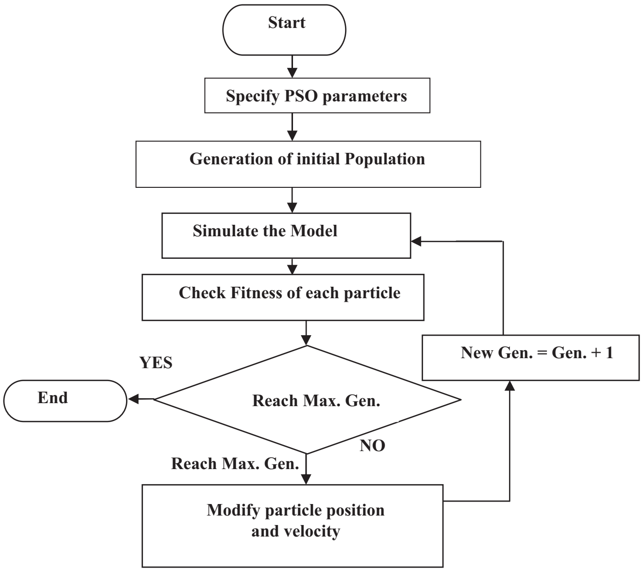

Fig. 9. Flow chart of particle swarm optimization algorithm.

Table 3
Parameters adopted for PSO.

Particle swarm optimization (PSO) parameters	
Population size	40
Initial inertia weight (w_{max})	0.9
Final inertia weight (w_{min})	0.4
Maximum iteration number (it_{max})	1000
Acceleration constants($C1$, $C2$)	1.4455, 1.4455

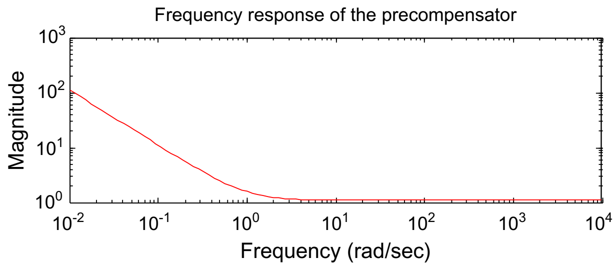

Fig. 10. Frequency response of the pre-compensator.

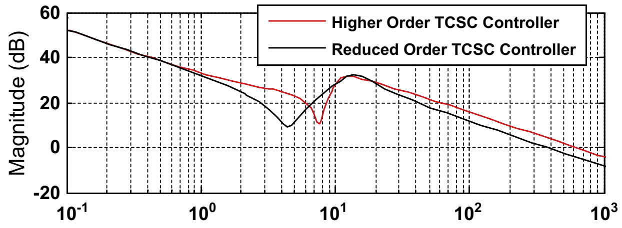

Fig. 11. Bode plot of original higher order and reduced order controllers.

Fuzzification

Fuzzification process is used for converting speed and its derivative to the fuzzy values. Seven membership functions to generate better results are defined in Table 2. The linguistic labels of membership functions are marked as in Fig. 7, NB (Negative Big), NM (Negative-Medium), NS (Negative-Small), ZR (Zero), PS (Positive-Small), PM (Positive-Medium), PB (Positive-Big) Membership functions are used to convert the fuzzy values between 0 and 1 for inputs and output value both.

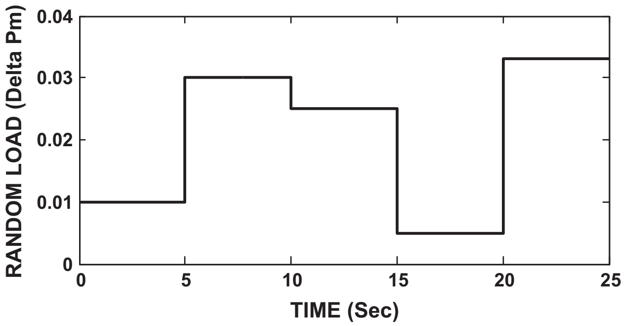

Fig. 12. Random mechanical power input (ΔP_m).

Fuzzy rules

Fuzzy rules are defined to reduce the error in the system after analysing the function of controller. For each fuzzy value there are seven membership functions, so 49 combinations of speed and acceleration are generated. However, rule base may also be generated automatically [28]. There is an output for each of the membership functions and the linguistic label can be determined by using IF–THEN fuzzy rules in the following form: ***If speed deviation is a_i and acceleration deviation is b_j then fuzzy output is*** c_{ij}. Where a_i, b_j and c_{ij} are fuzzy subsets defined in Table 2. In a Takagi–Sugeno FPSS the output $\mathbf{c_{ij}}$ is linear or constant.

Defuzzification

At last Defuzzification is done. In this step the fuzzy values which are obtained from inference engine converts into the specific values. For the inference Mamdani's minimum fuzzy implication and Max–Min compositional rule are used. For the defuzzification centroid method is used. At first, we design a parameters satisfying FLC, according to design rules and with assumption given in previous section. The dependency of the output variable on the input variable is shown by the surface viewer in Fig. 8.

Particle swarm optimization

Particle Swarm Optimization was first proposed by Kennedy and Eberhart in 1995 [11]. The PSO is an evolutionary search algorithm Inspired by the social behaviour of bird flocking and fish schooling. The system under study is initialized with a population of particles that "fly" through a multi-dimensional search space with given velocities. Each particle encodes a single intersection of all search dimensions. The associated position and velocity of each particle are randomly generated [13,27]. At each generation, the velocity of the particle is stochastically adjusted according to the historical best position for the particle itself and the neighbourhood best position. This is accomplished by using some fitness evaluation function. The movement of each particle evolves to an optimal or near-optimal solution. The position corresponding to the best fitness is known as p_{best} and the overall best out of all the particles in the population is called g_{best}.

Synthesis of fuzzy PSS using particle swarm optimization

Fuzzy PSS and TCSC are installed in the SMIB power system to minimize the power system oscillations after a sudden disturbance so as to improve the stability. These oscillations are reflected in the deviation in the generator rotor speed ($\Delta\omega$). This section studies the use of PSO for the tuning of Fuzzy PSS scaling factors.

To improve the system response in terms of the settling time (t_s) and overshoot (M_p) the objective function is formulated as

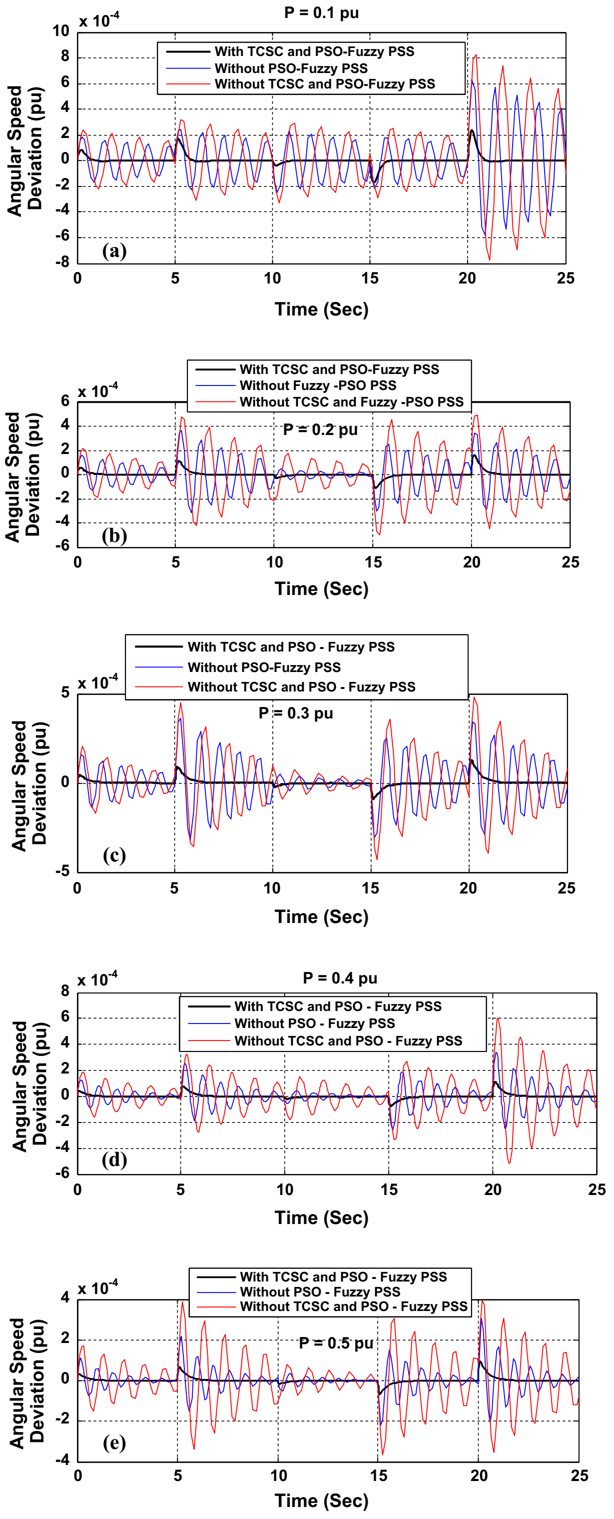

Fig. 13. (a)-(j) Angular speed deviation ($\Delta\omega$) with/without H_∞ TCSC and PSO – mamdani fuzzy PSS.

the minimization of the performance Index (PI) Integral of Time multiplied by the absolute value of error (ITAE) i.e.

$$J = \int_0^t t \cdot |\omega(t)| dt \tag{4}$$

Here t is the simulation time. The time-domain simulations of the SMIB power system are carried out to create the objective function in Matlab workspace. Smaller the value of J better is the control system. Therefore the integral criterion requires minimising J by adjusting the Fuzzy PSS scaling factors. The solution of this optimization problem using PSO is proposed as below:

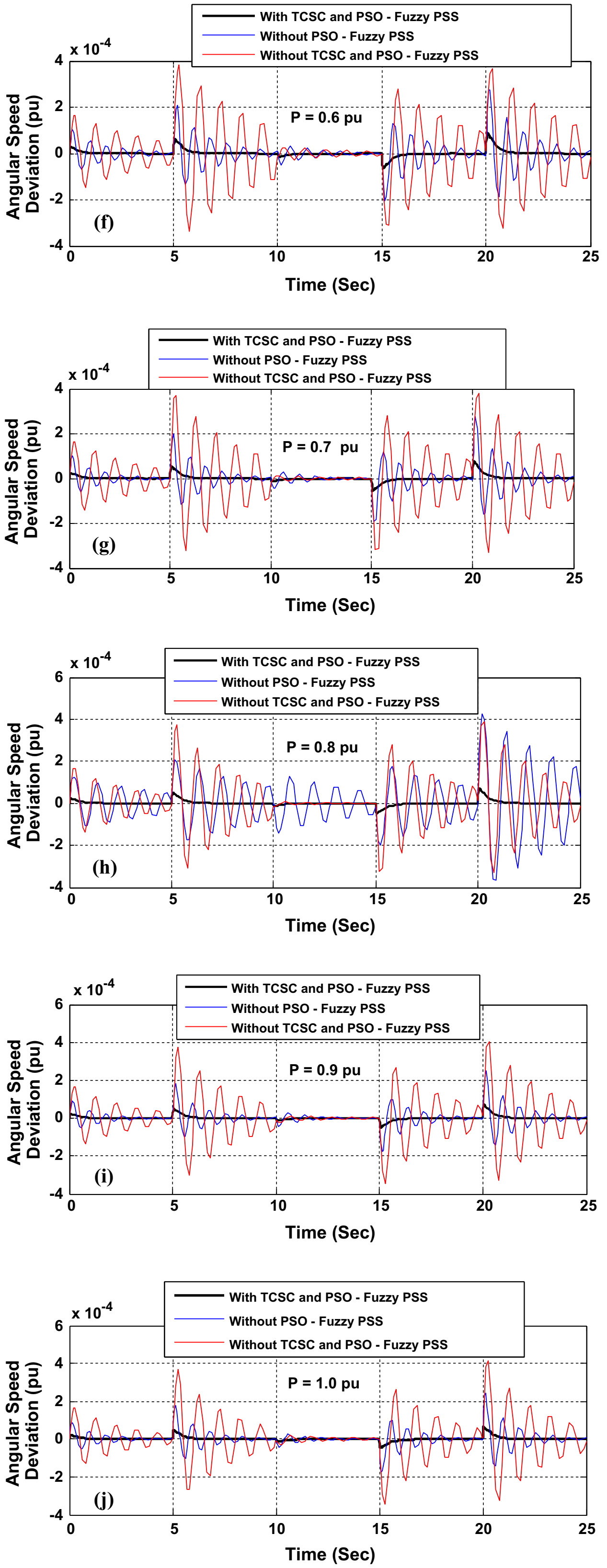

Fig. 13 (*continued*)

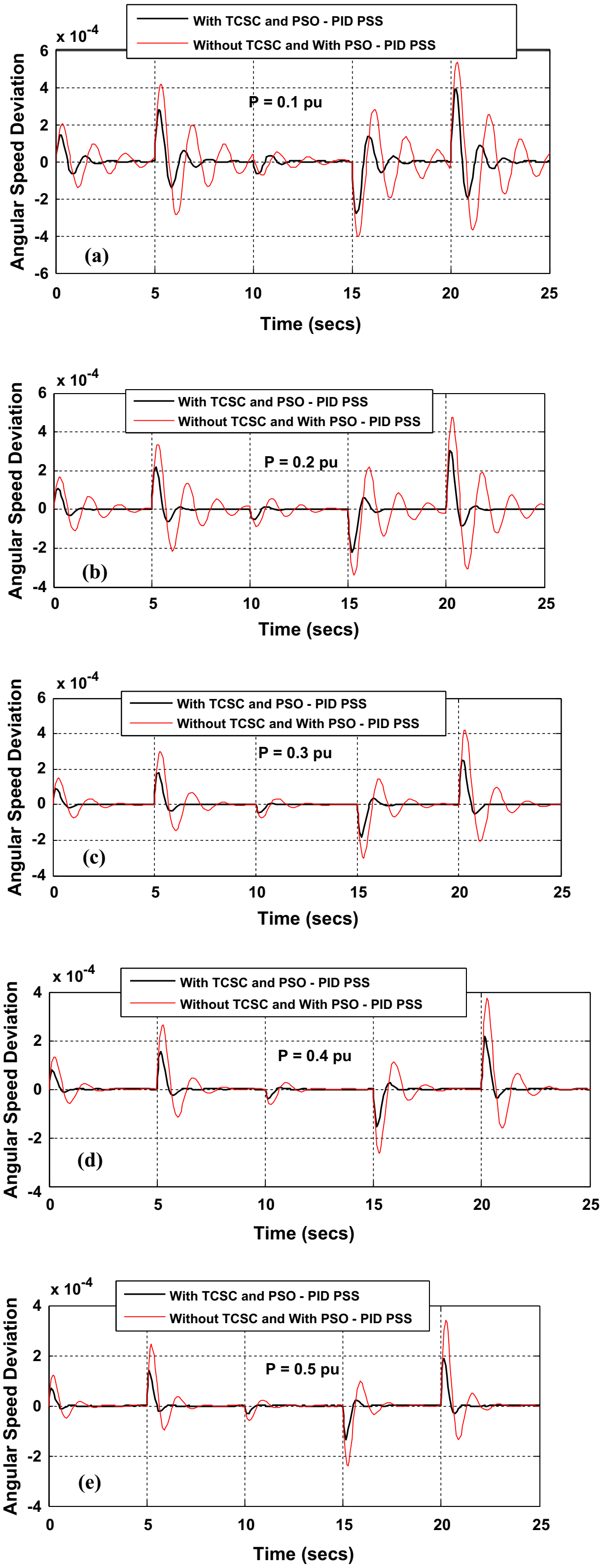

Fig. 14. (a)-(j) Angular speed deviation ($\Delta\omega$) with/without H_∞ TCSC and with/without PSO-PID PSS.

Step 1: Initialize the population of random solutions i.e. the Fuzzy PSS scaling factors in the multidimensional space.
Step 2: For each solution set, calculate the objective function value i.e. Integral of time multiplied by the Absolute value of Error.

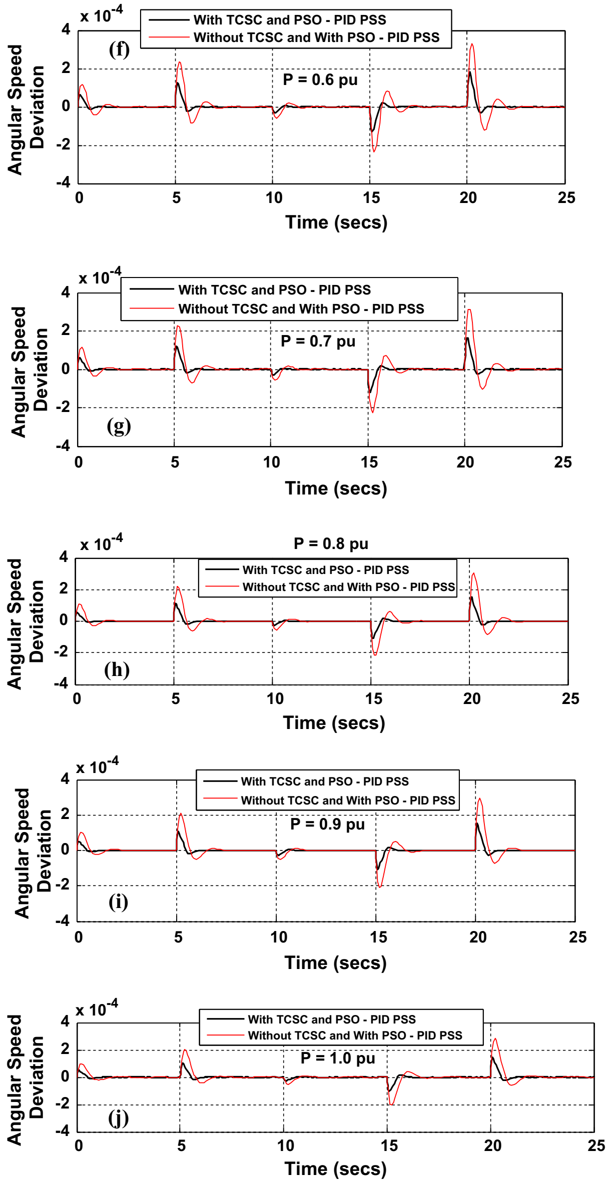

Fig. 14 (*continued*)

Step 3: Based on the objective function value, the solution population is updated using specific modification equations of the PSO and the range of space specified for the new solution sets.
Step 4: The step 2 and step 3 are repeated until the stopping criterion is met, i.e. a fixed number of iterations or a minimum value of objective function is reached.

The computational flow chart of PSO algorithm is shown in Fig. 9.

Simulation studies

To demonstrate the robustness of proposed hybrid control design, the single machine infinite Bus (SMIB) power system is simulated in Matlab. In this study, proper fine tuning of fuzzy PSS and PID PSS parameters is evaluated by PSO experimental studies examining the effect of each parameter on the final results. The parameters adopted for PSO are tabulated in Table 3. As a result, the values of Mamdani fuzzy input scaling parameters α_d and α are taken as 3.5225 and 9.1905 respectively. The output scaling parameter is set as: $K = 204$. The Takagi–Sugeno fuzzy PSS

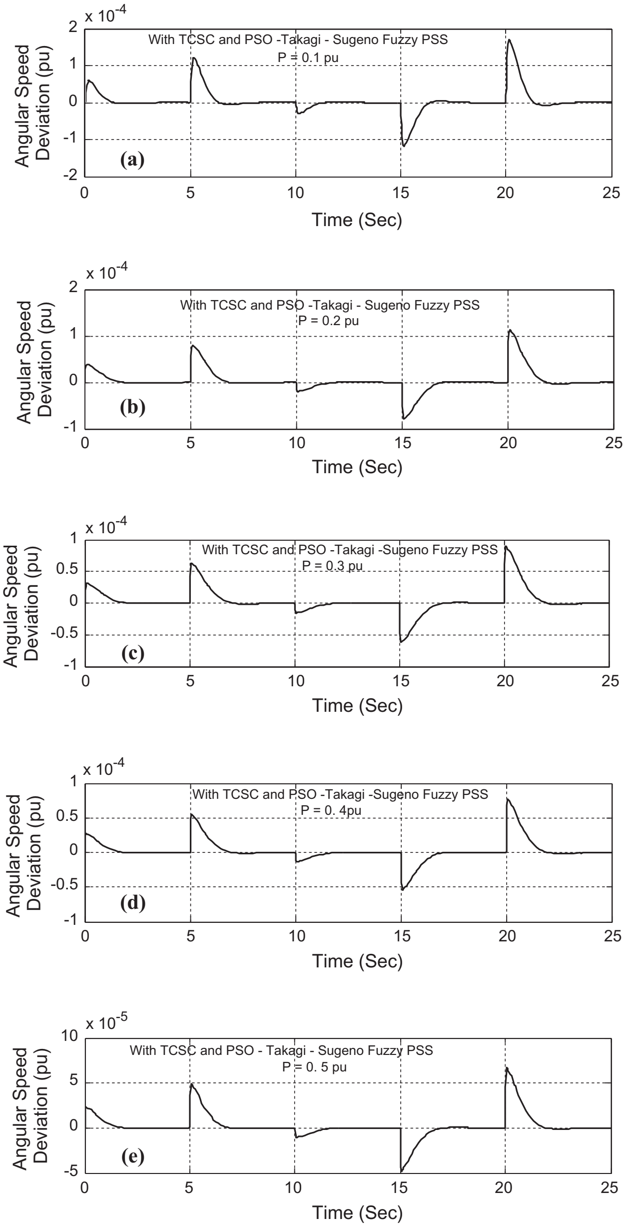

Fig. 15. (a)-(j) Angular speed deviation ($\Delta\omega$) with H_∞ TCSC and PSO-Takagi–Sugeno fuzzy PSS.

input and output scaling parameters obtained using PSO are $\alpha = 26.5512$, $\alpha_d = 17.2718$ and $K = 79.4163$. The PID PSS parameters obtained by PSO are $K_p = 35.4552$, $K_d = 294.1160$ and $K_i = 133.2334$.

The Weighting Functions for H_∞ TCSC controller are selected as $W_1 = (S+1)/0.9S$ and $W_2 = I$ so that robust stability condition is ensured ($\gamma_{min} \leqslant 4.0$). The frequency response of the pre-compensator is shown in Fig. 10. As a result, the shaped plant G_s can be established and the controller K_∞ can be determined by (3). Consequently, the sixth order robust TCSC controller K_∞ is obtained.

$$K_\infty = (614.7S^5 + 1.627\times10^4S^4 + 1.337\times10^5S^3 + 1.057\times10^6S^2 + 6.441\times10^6S + 9.84\times10^6)/(S^6 + 46.53S^5 + 875.6S^4 + 9748S^3 + 7.459\times10^4S^2 + 2.398\times10^5S)$$

To reduce the computational resources and time for cost-effective simulation, the Schur balanced truncation model reduction is applied.

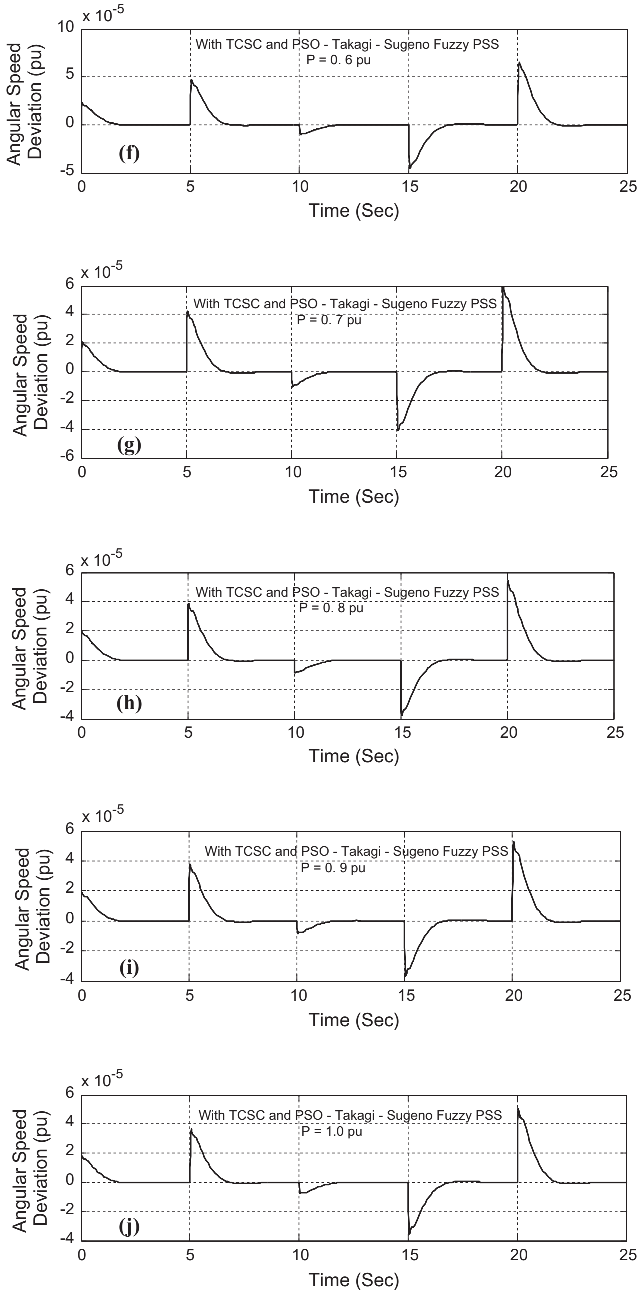

Fig. 15 (*continued*)

This result in a dimensionally reduced TCSC controller as –

$$K_{\infty Reduced\ Order} = \frac{373.9S^2 + 492.7S + 7566}{S^3 + 8.435S^2 + 184.4S + 3.343\times10^{-17}}$$

Fig. 11 shows the bode plot of the higher order and the reduced order TCSC controllers. Bode diagrams of both controllers are almost similar which means that both controllers will have nearly the same performance.

To ensure the robustness of the hybrid control scheme in a wide range, the Power system shown in Fig. 1 is studied through the computer simulation at different operating points i.e. at real power $P = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$ and 1.0 pu. The system is applied a random mechanical power input (ΔP_m) as shown in Fig. 12. By changing the mechanical input of the generator, the disturbance is created in the system at $t = 5$, 10, 15, and 20 s. To illustrate the efficiency of the hybrid controllers, five different cases are

Table 4
Rotor angular speed deviation ($\Delta\omega$) with different hybrid controllers.

Real power (pu)	Angular speed deviation-peak value(10^{-4} pu)														
	H_∞ TCSC and PSO-PID PSS					H_∞ TCSC and PSO – Mamdani fuzzy PSS					H_∞ TCSC and PSO-Takagi–Sugeno Fuzzy PSS				
	$t = 0$ s	$t = 5$ s	$t = 10$ s	$t = 15$ s	$t = 20$ s	$t = 0$ s	$t = 5$ s	$t = 10$ s	$t = 15$ s	$t = 20$ s	$t = 0$ s	$t = 5$ s	$t = 10$ s	$t = 15$ s	$t = 20$ s
0.1	1.5	2.8	−0.8	−2.8	4.0	0.8	1.8	−0.3	−1.8	2.2	0.59	1.2	−0.24	−1.1	1.7
0.2	1.0	2.25	−0.5	−2.4	3.0	0.5	1.0	−0.2	−1.0	1.8	0.38	0.79	−0.15	−0.78	1.1
0.3	1.0	1.9	−0.4	−1.9	2.4	0.4	0.95	−0.18	−0.9	1.0	0.30	0.63	−0.11	−0.58	0.89
0.4	0.9	1.8	−0.3	−1.8	2.1	0.3	0.9	−0.15	−0.8	1.0	0.27	0.55	−0.12	−0.51	0.76
0.5	0.9	1.7	−0.25	−1.6	2.0	0.3	0.8	−0.15	−0.7	1.0	0.22	0.49	−0.10	−0.48	0.67
0.6	0.8	1.6	−0.2	−1.5	2.0	0.3	0.75	−0.14	−0.7	0.9	0.22	0.46	−0.099	−0.45	0.64
0.7	0.7	1.4	−0.19	−1.4	1.8	0.2	0.70	−0.10	−0.65	0.85	0.20	0.42	−0.092	−0.41	0.58
0.8	0.5	1.3	−0.15	−1.3	1.7	0.21	0.65	−0.10	−0.65	0.75	0.19	0.39	−0.090	−0.37	0.54
0.9	0.4	1.2	−0.15	−1.2	1.7	0.20	0.47	−0.09	−0.6	0.70	0.18	0.37	−0.080	−0.36	0.53
1.0	0.3	1.1	−0.15	1.0	1.6	0.20	0.5	−0.08	−0.5	0.65	0.18	0.35	−0.070	−0.34	0.49

presented; with H_∞ TCSC and PSO – Mamdani Fuzzy PSS, with H_∞ TCSC and without PSO – Fuzzy PSS, without H_∞ TCSC and PSO–Fuzzy PSS and with H_∞ TCSC and PSO-PID PSS and with H_∞ TCSC and PSO – T–S Fuzzy PSS. The dynamic time responses of rotor angular speed deviation ($\Delta\omega$) are shown in Figs. 13(a)–(j), 14(a)–(j) and 15(a)–(j) and quantitatively compared (Table 4) at every operating point for the different cases.

The simulation results show that H_∞ TCSC and PSO-Takagi–Sugeno Fuzzy PSS combination has much lesser Peak overshoot (Mp) as well as settling time (t_s) at every operating point, thus have far better oscillations damping capabilities as compared to H_∞ TCSC and PSO-PID PSS, and H_∞ TCSC and PSO – Mamdani Fuzzy PSS control schemes. Further, in the absence of PSO – Mamdani/T–S Fuzzy or /and H_∞ TCSC Controller in hybrid control scheme there are substantial oscillations in the system at each operating point. In contrast, the designed H_∞ TCSC and T–S Fuzzy PSS hybrid controllers are able to significantly damp these oscillations with substantial improvement in system response in terms of the settling time (t_s) and overshoot (M_p) for all cases i.e. for $P = 0.1$ pu,0.2 pu…1.0 pu.

Conclusions

The hybrid H_∞ loop shaping TCSC and PSO tuned Mamdani/Takagi–Sugeno fuzzy PSS design for SMIB system in a wide range has been proposed in this paper. The generator rotor speed deviation ($\Delta\omega$) and acceleration ($\Delta\dot{\omega}$) have been used as the feedback signal inputs. The proposed H_∞ TCSC and PSO – T–S Fuzzy PSS hybrid controllers have been compared with H_∞ TCSC and PSO-PID PSS, and H_∞ TCSC and PSO–Mamdani Fuzzy PSS. Due to the complex nature of power system the H_∞ TCSC and PSO – T–S Fuzzy PSS control scheme gives much better performance as compared to TCSC and PSO tuned Mamdani Fuzzy PSS/PID PSS combinations. The proposed controllers combine the advantages of H_∞ TCSC and PSO optimized T–S Fuzzy Logic Controller and have an excellent capability in damping power system oscillations and enhance greatly the dynamic stability of the power system. The simulation results show the robustness and superiority of the proposed control. It has been observed from the Fig. 13(a)–(j) that the system without fuzzy PSS or/and H_∞ TCSC is unstable but with hybrid H_∞ TCSC controller and PSO – Mamdani/T–S fuzzy PSS the system gains stability quickly and robust stability of the test power system in the presence of system uncertainties in a wide range is ensured.

Appendix A

Parameter values
Generator: $M = 9.26$ s., $D = 0$, $T'_{do} = 7.76$, $W_b = 377$
Exciter: (IEEE Type ST1): $K_A = 50$, $T_A = 0.05$ s.

References

[1] Abido MA. Pole placement technique for PSS and TCSC-based stabilizer design using simulated annealing. Electr power Energy Syst 2000;22:543–54.
[2] Boukarim GE, Wang S, Chow JH, Taranto GN, Martins N. A comparison of classical, robust, and decentralized control designs for multiple power system stabilizers. IEEE Trans Power Apparatus Syst 2000;15(4):1287–92.
[3] Colman LRS, Araujo PB. Effects of the Thyristor Controlled Series Capacitor on the Electric Power System. IEE/PES transmission & distribution conference & exposition: Latin America; 2004. p. 481–86.
[4] DeMello FP, Concordia C. Concepts of synchronous machine stability as affected by excitation control. IEEE Trans PAS 1969;88(4):316–29.
[5] Friedland B. Advanced Control System Design. Englewood Cliffs, NJ: Prentice-Hall; 1996.
[6] Gyugyi L. A Unified power-flow control concept for Flexible AC Transmission Systems. IEE Proc-C 1992;139(4):323–31.
[7] Hingorani NG, Gyugyi L. Understanding FACTS: Concepts and technology of Flexible AC Transmission System. IEEE Press; 2000.
[8] Hassan MO, Zakaria ZA, Cheng SJ. Impact of TCSC on enhancing power system stability, IEEE Power and Energy Conference, APPEEC; 2009. p. 1–6.
[9] Kundur P. Power system stability and control. New York: McGraw-Hill; 1994.
[10] Kundur P, Klein M, Rogers GJ, Zywno S. Application of power system stabilizers for enhancement of overall system stability. IEEE Trans Power Syst 1989;4(2):614–26.
[11] Kennedy J, Eberhart R. Particle swarm optimization. Proc IEEE Int Conf Neural Networks 1995;4:1942–8.
[12] Larsen E, Swarm D. Applying power system stabilizers IEEE Trans. PAS 100; 1981. p. 3017–3046.
[13] Lim CP, Jain LC LC. Innovations in Swarm Intelligence, vol. 248. Springer verlag; 2009. p. 1–7.
[14] Magid Abdel YL, Abido MA. Robust coordinated design of excitation and TCSC-based stabilizer using genetic algorithms. Electr Power Energy Syst 2004;69:129–41.
[15] Mahran AR, Hogg BW, Al-Sayed ML. Coordinated control of synchronous generator excitation and static var compensator. IEEE Trans Energy Convers 1992;7(4):615–22.
[16] Martins N, Lima L. Eigen value and frequency domain of small-signal electro mechanical stability problems. In: IEEE Symposium on application of eigen analysis and frequency domain methods for system dynamic performance. Special publication 90TH0292-3 PWR; 1990. p. 17–33.
[17] McFarlane DC, Glover K. Robust Controller Design using Normalised Co-prime Factor Plant Descriptions. Springer Verlag, Lecture Notes in Control and Information Sciences; 1989. pp. 138.
[18] McFarlane DC, Glover K. A loop shaping design procedure using synthesis. IEEE Trans Automat Contr 1992;37(6):759–69.
[19] Mamdani EH. Application of fuzzy algorithms for simple dynamic plant. Proc Inst Electr Eng 1974;121:1585–8.
[20] Pal BC. Robust pole placement versus root-locus approach in the context of damping inter area oscillations in power systems. IEE Proc Generat, Trans Distrib 2002;149(6):739–45.
[21] Rahim A, Nassimi S. Synchronous generator damping enhancement through coordinated control of exciter and SVC. IEE Proc -Generat Transm Distrib 1996;143(2):211–8.
[22] Rouco L, Pagola FL. An eigen value sensitivity approach to location and controller design of controllable series capacitor for damping power system oscillations. IEEE Trans Power Syst 1997;12(4):1660–6.
[23] Ramaswamy P, Edwards RM, Lee KY. An automatic tuning method of a fuzzy logic controller for nuclear reactors. IEEE Trans Nucl Sci 1993;40(4):1253–62.
[24] Sadikovic R, Korba P, Andersson G. Application of FACTS devices for damping of power system oscillations. In: Proceedings of IEEE power Tech Conference; 2005. p. 1–6.
[25] Skogestad S, Postlethwaite I. Multivariable feedback control: analysis and design. John Wiley; 2005.
[26] Shao S. Fuzzy self-organizing controller and its application for dynamic processes. Fuzzy Sets Syst 1998;26:151–64.

[27] Sharma KD, Chatterjee A, Rakshit A. A hybrid approach for design of stable adaptive fuzz controllers employing lyapunov theory and particle swarm optimization. IEEE Trans Fuzzy Syst 2009;17(2):329–42.
[28] Sharma KD. A systematic design methodology of pd fuzzy logic controller using cellular fuzzy logic concept. Int J Automat Contr, Inderscience Pub 2012;6(3/4):231–45.
[29] Supriyadi ANC, Ngamroo I, Kaitwanidvilai S, Kunakorn A, Hashiguchi T, Goda T. H_∞ loop shaping-based robust control design of PSS and TCSC for dynamic stability enhancement. In: IEEE International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, (ECTI-CON), vol. 2; 2008. p. 965–68.
[30] Tayal VK, Lather JS. Digital simulation of reduced rule fuzzy logic power system stabilizer for analysis of power system stability enhancement. Int J Comput Appl 2012;47(7):888–975.
[31] Yi SY, Chung MJ. Systematic design and stability analysis of a fuzzy logic controller. Fuzzy Sets Syst 1995;72:271–98.
[32] Wang Y, Hill D, Middleton R, Gao L. Transient stability enhancement and voltage regulation of power systems. IEEE Trans Power Syst 1993;8(2):620–7.
[33] Wang HF, Swift FJ. Multiple stabilizers setting in multi-machine power systems by the phase compensation method. Electr Power Energy Syst 1998;20(4):241–6.