Robust design of multimachine power system stabilisers using tabu search algorithm

M.A.Abido and Y.L.Abdel-Magid

Abstract: Robust design of multimachine power system stabilisers (PSSs) using the tabu search (TS) optimisation technique is presented. The proposed approach employs TS for optimal parameter settings of a widely used conventional fixed-structure lead-lag PSS (CPSS). The parameters of the proposed stabilisers are selected using TS in order to shift the system poorly damped electromechanical modes at several loading conditions and system configurations simultaneously to a prescribed zone in the left hand side of the s-plane. Incorporation of TS as a derivative-free optimisation technique in PSS design significantly reduces the computational burden. In addition, the quality of the optimal solution does not rely on the initial guess. The performance of the proposed PSSs under different disturbances and loading conditions is investigated for multimachine power systems. The eigenvalue analysis and the nonlinear simulation results show the effectiveness of the proposed PSSs in damping out the local, as well as the interarea, modes and enhance greatly the system stability over a wide range of loading conditions and system configurations.

1 Introduction

In the past two decades, the utilisation of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention [1–18]. Nowadays, the conventional power system stabiliser (CPSS) is widely used by power system utilities. Recently, several approaches based on modern control theory have been applied to the PSS design problem. These include optimal, adaptive, variable structure, and intelligent control [2–5]. Despite the potential of modern control techniques with different structures, power system utilities still prefer the CPSS structure [6]. The reasons behind that might be the ease of on-line tuning and the lack of assurance of the stability related to some adaptive or variable structure techniques.

Different techniques of sequential design of PSSs are presented to damp out one of the electromechanical modes at a time [7]. However, this approach may not finally lead to an overall optimal choice of PSS parameters. Moreover, the stabilisers designed to damp one mode can produce adverse effects in other modes. Also, the optimal sequence of design is a very involved question. The sequential design of PSSs is avoided in [8, 9]. Unfortunately, the proposed techniques are iterative and require a heavy computation burden due to the system reduction procedure. In addition, the initialisation step of these algorithms is crucial and affects the final dynamic response of the controlled system. Therefore, a final selection criterion is required to avoid long runs of validation tests on the nonlinear model.

Generally, it is important to recognise that machine parameters change with loading, making the machine behaviour quite different for different operating conditions. Since these parameters change in a rather complex manner, a set of CPSS parameters which stabilises the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations. Hence, PSSs should provide some degree of robustness to the variations in system parameters, loading conditions and configurations.

H_∞ optimisation techniques [10, 11] have been applied to the robust PSS design problem. However, the importance and difficulties in the selection of weighting functions of the H_∞ optimisation problem have been reported. In addition, the additive and/or multiplicative uncertainty representation cannot treat situations where a nominal stable system becomes unstable after being perturbed [12]. Moreover, the pole-zero cancellation phenomenon associated with this approach produces closed loop poles whose damping is directly dependent on the open loop system (nominal system) [13]. On the other hand, the order of the H_∞-based stabiliser is as high as that of the plant. This gives rise to the complex structure of such stabilisers and reduces their applicability. Although the sequential loop closure method [14] is well suited for on-line tuning, there is no analytical tool to decide the optimal sequence of the loop closure.

On the other hand, Kundur *et al.* [15] have presented a comprehensive analysis of the effects of the different CPSS parameters on the overall dynamic performance of the power system. It is shown that the appropriate selection of CPSS parameters results in satisfactory performance during system upsets. In addition, Gibbard [16] demonstrated that the CPSS provides satisfactory damping performance over a wide range of system loading conditions. The robust nature of the CPSS is due to the fact that the torque reference voltage transfer function remains approximately invariant over a wide range of operating conditions.

For the robust design of the CPSS, several operating conditions and system configurations are simultaneously considered in the CPSS design process [16, 17]. A genetic

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The authors are with the Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

algorithm-based approach to robust CPSS design is presented in [17]. It is shown that the optimal selection of PSS parameters results in a robust performance of the CPSS. However, there exist some structural problems in the conventional genetic algorithm such as premature convergence and duplications among strings as evolution is processing. A gradient procedure for optimisation of PSS parameters at different operating conditions is presented in [18]. Unfortunately, the optimisation process requires the computation of sensitivity factors and eigenvectors at each iteration. This gives rise to a heavy computational burden and slow convergence. In addition, the search process is susceptible to becoming trapped in local minima and the solution obtained will not be optimal. Therefore, a TS-based approach to robust PSS design is proposed in this paper.

In the last few years, the tabu search algorithm [19–23] appeared as another promising heuristic algorithm for handling combinatorial optimisation problems. The tabu search algorithm uses a flexible memory of search history to prevent cycling and to avoid entrapment in local optima. It has been shown that, under certain conditions, the tabu search algorithm can yield a global optimal solution with probability 1 [22].

In this paper, the problem of robust PSS design is formulated as an optimisation problem and the TS algorithm is employed to solve this problem. The proposed design approach has been applied to different examples of multimachine power systems. The eigenvalue analysis and the nonlinear simulation results have been carried out to assess the effectiveness of the proposed PSSs under different disturbances, loading conditions and system configurations.

2 Problem statement

2.1 Power system model

A power system can be modelled by a set of nonlinear differential equations as:

$$\dot{X} = f(X, U) \tag{1}$$

where X is the vector of the state variables and U is the vector of input variables. In this study $X = [\delta, \omega, E'_q, E_{fd}]^T$ and U is the PSS output signals. Here, δ and ω are the rotor angle and speed, respectively. Also, E'_q and E_{fd} are the internal and field voltages, respectively.

In the design of PSSs, the linearised incremental models around an equilibrium point are usually employed [24]. Therefore, the state equation of a power system with n machines and m stabilisers can be written as:

$$\dot{X} = AX + BU \tag{2}$$

where A is a $4n \times 4n$ matrix and equals $\partial f/\partial X$ while B is a $4n \times m$ matrix and equals $\partial f/\partial U$. Both A and B are evaluated at a certain operating point. X is a $4n \times 1$ state vector and U is an $m \times 1$ input vector.

2.2 PSS structure

A widely used conventional lead-lag PSS is considered in this study. It can be described as

$$U_i = K_i \frac{sT_w}{1 + sT_w} \frac{(1 + sT_{1i})}{(1 + sT_2)} \frac{(1 + sT_{3i})}{(1 + sT_4)} \Delta\omega_i \tag{3}$$

where T_w is the washout time constant, U_i is the PSS output signal at the ith machine, and $\Delta\omega_i$ is the speed deviation of this machine. The time constants T_w, T_2 and T_4 are usually prespecified. The stabiliser gain K_i and time constants T_{1i} and T_{3i} are the parameters to be determined.

2.3 Objective function

To increase the system damping, two eigenvalue-based objective functions are considered:

$$J_1 = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} (\sigma_0 - \sigma_{i,j})^2 \tag{4}$$

$$J_2 = \sum_{j=1}^{np} \sum_{\zeta_{i,j} \leq \zeta_0} (\zeta_0 - \zeta_{i,j})^2 \tag{5}$$

where np is the number of operating points considered in the design process. $\sigma_{i,j}$ and $\zeta_{i,j}$ are the real part and the damping ratio of the ith eigenvalue of the jth operating point, respectively. Also, σ_0 and ζ_0 are chosen thresholds. Here, J_1 and J_2 reflect the system response settling time and overshoot, respectively. The value of σ_0 represents the desirable level of system damping. This level can be achieved by shifting the dominant eigenvalues to the left of the $s = \sigma_0$ line in the s-plane. This insures some degree of relative stability. Also, the value of ζ_0 represents the desirable damping ratio which can be achieved by shifting the dominant eigenvalues to the left of the $\zeta = \zeta_0$ line in the s-plane. This ensures a good time-domain response in terms of overshoots and settling time. The conditions $\sigma_{i,j} \geq \sigma_0$ and $\zeta_{i,j} \leq \zeta_0$ are imposed to consider only the unstable or poorly damped modes which mainly belong to the electromechanical ones. The problem constraints are the CPSS parameter bounds. It is worth noting that it is also possible to use a combination of eqns. 4 and 5 in the form of $J_1 + \eta J_2$ [17]. Loading-dependent σ_0 and ζ_0 can also be used. The design problem can be formulated as the following optimisation problem:

$$Minimize\ J \tag{6}$$

Subject to

$$K_i^{\min} \leq K_i \leq K_i^{\max} \tag{7}$$

$$T_{1i}^{\min} \leq T_{1i} \leq T_{1i}^{\max} \tag{8}$$

$$T_{3i}^{\min} \leq T_{3i} \leq T_{3i}^{\max} \tag{9}$$

The proposed approach employs the TS algorithm to solve this optimisation problem and search for an optimal or near optimal set of PSS parameters, $\{K_i, T_{1i}, T_{3i}, i = 1, 2, \ldots, m\}$.

3 Tabu search algorithm

3.1 Overview

The tabu search is a higher level heuristic algorithm for solving combinatorial optimisation problems. It is an iterative improvement procedure that starts from any initial solution and attempts to determine a better solution. TS was proposed in its present form a few years ago by Glover [20–23]. It has now become an established optimisation approach that is rapidly spreading to many new fields. Together with other heuristic search algorithms such as GA, TS has been singled out as 'extremely promising' for the future treatment of practical applications [20]. Generally, TS is characterised by its ability to avoid entrapment in a local optimal solution and prevent cycling by using flexible memory of search history.

3.2 TS algorithm

The basic elements of TS are briefly stated and defined as follows:

• *Current solution*, $x_{current}$: A set of the optimised parameter values at any iteration. It plays a central role in generating the neighbour trial solutions.

• *Moves:* They characterise the process of generating trial solutions that are related to $x_{current}$.

• *Set of candidate moves, $N(x_{current})$:* The set of all possible moves or trial solutions, x_{trial}, in the neighbourhood of $x_{current}$. In case of continuous variable optimisation problems, this set is too large or even an infinite set. Therefore, one could operate with a subset, $S(x_{current})$ with a limited number of trial solutions nt, of this set, i.e. $S \subset N$ and $x_{trial} \in S(x_{current})$.

• *Tabu restrictions:* These are certain conditions imposed on moves that make some of them forbidden. These forbidden moves are listed to a certain size and known as tabu. This list is called the tabu list. The reason behind classifying a certain move as forbidden is basically to prevent cycling and avoid returning to the local optimum just visited. The tabu list size plays a great role in the search for high-quality solutions. The way to identify a good tabu list size is simply watch for the occurrence of cycling when the size is too small, and the deterioration in solution quality when the size is too large caused by forbidding too many moves. In some applications a simple choice of the tabu list size in a range centred at 7 seems to be quite effective [21]. Generally, the tabu list size should grow with the size of the given problem. In our implementation, the size 7 is found to be quite satisfactory.

• *Aspiration criterion (Level):* A rule that overrides tabu restrictions, i.e. if a certain move is forbidden by tabu restriction, the aspiration criterion, when satisfied, can make this move allowable. Different forms of aspiration criterion are used in the literature [19–23]. The one considered here is to override the tabu status of a move if this move yields a solution which has better objective function, J, than the one obtained earlier with the same move. The importance of using an aspiration criterion is to add some flexibility to the tabu search by directing it towards the attractive moves.

• *Stopping criteria:* These are the conditions under which the search process will terminate. In this study, the search will terminate if one of the following criteria is satisfied: (*a*) the number of iterations since the last change of the best solution is greater than a prespecified number; (*b*) the number of iterations reaches the maximum allowable number; or (*c*) the value of the objective function reaches zero. The general algorithm of TS can be described in steps as follows:

Step 1: Set the iteration counter $k = 0$ and randomly generate an initial solution $x_{initial}$. Set this solution as the current solution as well as the best solution, x_{best}, i.e. $x_{initial} = x_{current} = x_{best}$.

Step 2: Randomly generate a set of trial solutions x_{trial} in the neighbourhood of the current solution, i.e. create $S(x_{current})$. Sort the elements of S based on their objective function values in ascending order as the problem is a minimisation one. Let us define x_{trial}^i as the ith trial solution in the sorted set, $1 \leq i \leq nt$. Here, x_{trial}^1 represents the best trial solution in S in terms of the objective function value associated with it.

Step 3: Set $i = 1$. If $J(x_{trial}^i) > J(x_{best})$ go to step 4, else set $x_{best} = x_{trial}^i$ and go to step 4.

Step 4: Check the tabu status of x_{trial}^i. If it is not in the tabu list then put it in the tabu list, set $x_{current} = x_{trial}^i$, and go to step 7. If it is in the tabu list go to step 5.

Step 5: Check the aspiration criterion of x_{trial}^i. If satisfied then override the tabu restrictions, update the aspiration level, set $x_{current} = x_{trial}^i$, and go to step 7. If not, set $i = i + 1$ and go to step 6.

Step 6: If $i > nt$ go to step 7, else go back to step 4.

Step 7: Check the stopping criteria. If one of them is satisfied then stop, else set $k = k + 1$ and go back to step 2.

3.3 Application of TS to PSS design

In the proposed design approach, several operating points are simultaneously considered, namely, the base case and other points that represent extreme loading conditions and system configurations. After the initialisation step, the system model is linearised at each operating point. The above-described TS algorithm is excited by generating random initial values of the optimised parameters, i.e. initial solution. Then, the closed-loop system eigenvalues at each operating point are computed and the objective function is evaluated. The search for the optimal set of the CPSS parameters will continue until one of the stopping criteria is satisfied. In addition to the above-mentioned stopping criteria, another criterion has been implemented in this study to avoid undue and excessive computations. This criterion will terminate the search if the objective function value reaches zero, i.e. all the dominant eigenvalues are completely shifted to the desired zone in the left side of the s-plane.

In the following two examples, the eigenvalues associated with the electromechanical modes of all operating points considered in the design process have been shifted simultaneously to the desired zone.

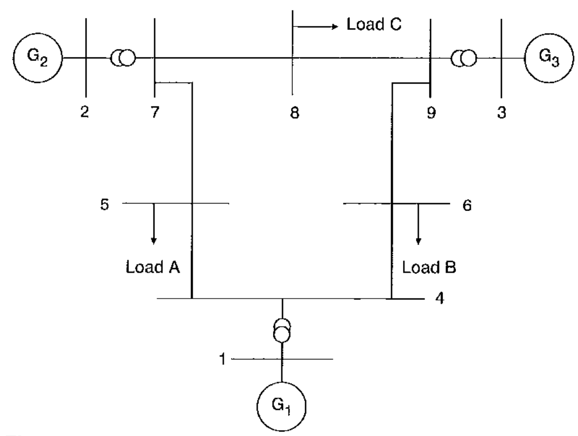

Fig. 1 *Three-machine nine-bus power system*

Table 1: Generator operating conditions of example 1

Generator	Base case		Case 1		Case 2		Case 3	
	P	*Q*	*P*	*Q*	*P*	*Q*	*P*	*Q*
G_1	0.72	0.27	2.21	1.09	0.36	0.16	0.33	1.12
G_2	1.63	0.07	1.92	0.56	0.80	−0.11	2.00	0.57
G_3	0.85	−0.11	1.28	0.36	0.45	−0.20	1.50	0.38

Table 2: Loads of example 1

Load	Base case		Case 1		Case 2		Case 3	
	P	*Q*	*P*	*Q*	*P*	*Q*	*P*	*Q*
A	1.25	0.50	2.00	0.80	0.65	0.55	1.50	0.90
B	0.90	0.30	1.80	0.60	0.45	0.35	1.20	0.80
C	1.00	0.35	1.50	0.60	0.50	0.25	1.00	0.50

4 Example 1: Three machine power system

4.1 Test system

In this example, the 3-machine 9-bus system shown in Fig. 1 is considered. Details of the system data are given in

Table 3: Eigenvalues and damping ratios of example 1 without PSSs

Base case	Case 1	Case 2	Case 3
$-0.01 \pm j9.07$, 0.001	$-0.021 \pm j8.91$, 0.002	$-0.30 \pm j8.95$, 0.034	$0.38 \pm j8.87$, -0.034
$-0.78 \pm j13.86$, 0.056	$-0.52 \pm j13.83$, 0.038	$-0.84 \pm j13.72$, 0.061	$-0.34 \pm j13.69$, 0.025

[24]. The participation factor method [25] and the sensitivity of PSS effect method [26] were used to identify the optimum locations of PSSs. The results of both methods indicate that G_2 and G_3 are the optimum locations for installing PSSs.

4.2 PSS design

To design the proposed PSSs, four operating cases are considered. The generator operating conditions and the loads at these cases are given in Tables 1 and 2, respectively. The electromechanical modes eigenvalues and their damping ratios without PSSs are given in Table 3. It is clear that the electromechanical modes are poorly damped and some of them are unstable. In this example, the optimised parameters are K_i, T_{1i} and T_{3i}, $i = 2, 3$. T_w, T_2 and T_4 are set to be 5s, 0.05s and 0.05s, respectively [24].

Table 4: Optimal values of proposed PSS parameters for example 1

Generator	Objective function J_1			Objective function J_2		
	k	T_1	T_3	k	T_1	T_3
G_2	11.833	0.140	0.133	5.821	0.118	0.300
G_3	0.438	0.238	0.150	0.138	0.340	0.374

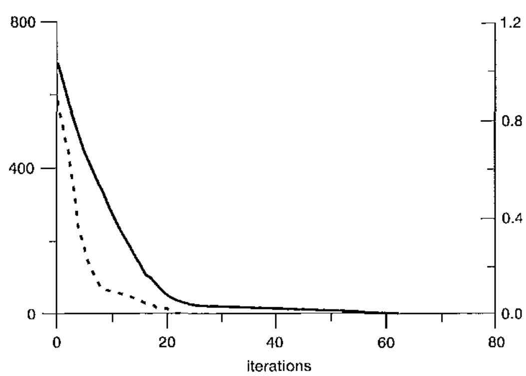

Fig. 2 *Objective function variations of example 1*
-- —— objective function J_1
··· objective function J_2

In the case of J_1, σ_0 is chosen to be -3.0, while ζ_0 is chosen to be 0.25 in the case of J_2. With each case, the TS algorithm has been applied to search for the optimised parameter settings so as to shift simultaneously the poorly damped eigenvalues of the four cases to the left of the s-plane. The final values of the optimised parameters in each case are given in Table 4. The convergence rates of the objective functions are shown in Fig. 2. With the optimal values of the proposed PSSs, the system eigenvalues with J_1 and J_2 settings are given in Tables 5 and 6, respectively. It is quite clear that the system damping with the proposed PSSs is greatly enhanced.

4.3 Nonlinear time-domain simulation

To demonstrate the effectiveness of the proposed PSSs over a wide range of loading conditions, two different disturbances are considered as follows:

(*a*) A 6-cycle fault disturbance at bus 7 at the end of line 5-7 with case 3. The fault has been cleared without tripping.

(*b*) A 6-cycle fault disturbance at bus 7 at the end of line 5-7 with case 1. The fault is cleared by tripping the line 5-7 with successful reclosure after 1.0s.

The system responses to the considered faults with and without the proposed PSSs are shown in Figs. 3–8. It is clear that the proposed PSSs provide good damping characteristics to low-frequency oscillations and greatly enhance the dynamic stability of power systems.

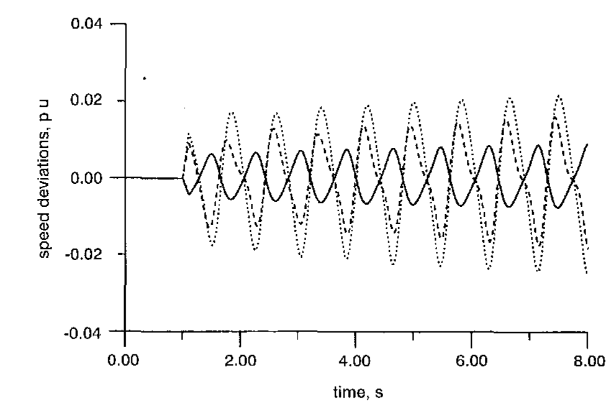

Fig. 3 *System response of example 1 with disturbance (a): without PSSs*
-—- · $\Delta\omega_1$
·········· $\Delta\omega_2$
· - · - - $\Delta\omega_3$

Table 5: Eigenvalues and damping ratios of example 1 with proposed PSSs (J_1 settings)

Base case	Case 1	Case 2	Case 3
$-3.00 \pm j18.40$, 0.161	$-3.39 \pm j18.47$, 0.181	$-3.63 \pm j16.71$, 0.212	$-3.16 \pm j18.15$, 0.172
$-4.47 \pm j8.27$, 0.457	$-3.06 \pm j7.60$, 0.373	$-3.01 \pm j8.65$, 0.329	$-3.57 \pm j8.32$, 0.394

Table 6: Eigenvalues and damping ratios of example 1 with proposed PSSs (J_2 settings)

Base case	Case 1	Case 2	Case 3
$-4.13 \pm j18.09$, 0.223	$-4.64 \pm j18.32$, 0.246	$-5.24 \pm j16.34$, 0.305	$-4.41 \pm j17.88$, 0.239
$-2.63 \pm j7.86$, 0.317	$-1.98 \pm j7.56$, 0.253	$-2.06 \pm j8.06$, 0.250	$-1.96 \pm j7.96$, 0.239

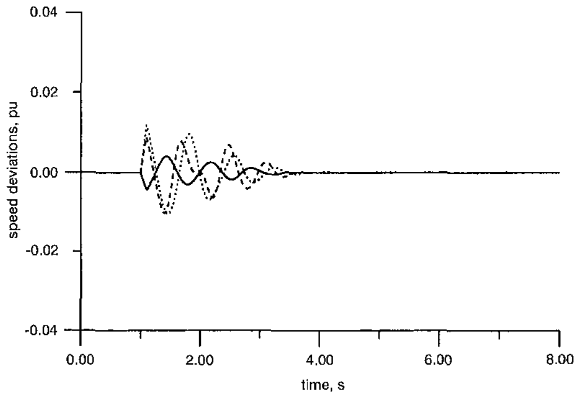

Fig. 4 *System response of example 1 with disturbance (a): proposed PSSs with J_1 settings*
- ——— $\Delta\omega_1$
·········· $\Delta\omega_2$
— — ·· $\Delta\omega_3$

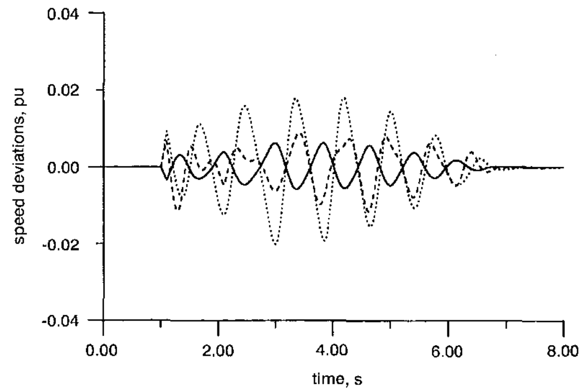

Fig. 7 *System response of example 1 with disturbance (b): proposed PSSs with J_1 settings*
— - $\Delta\omega_1$
·········· $\Delta\omega_2$
· · - ·· $\Delta\omega_3$

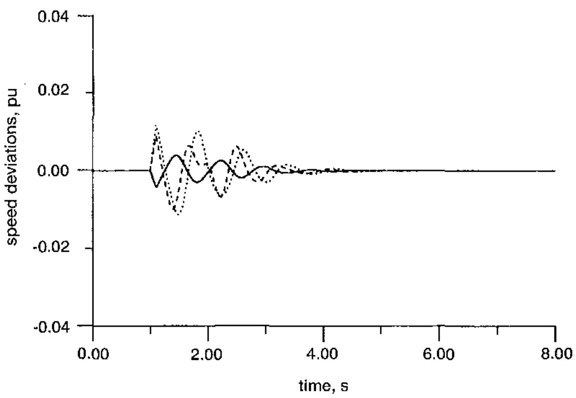

Fig. 5 *System response of example 1 with disturbance (a): proposed PSSs with J_2 settings*
$\Delta\omega_1$
·········· $\Delta\omega_2$
· -··· – $\Delta\omega_3$

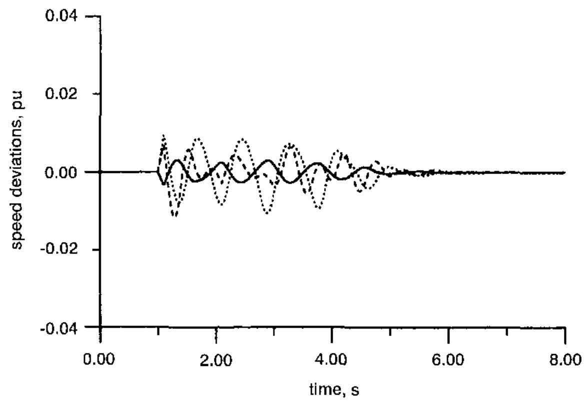

Fig. 8 *System response of example 1 with disturbance (b): proposed PSSs with J_2 settings*
· ——— $\Delta\omega_1$
·········· $\Delta\omega_2$
– – – – $\Delta\omega_3$

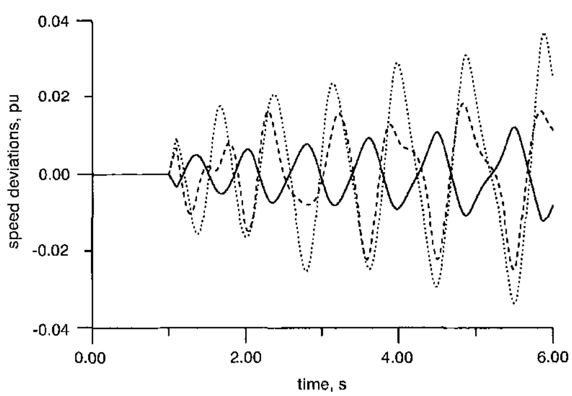

Fig. 6 *System response of example 1 with disturbance (b): without PSSs*
– – ——— $\Delta\omega_1$
·········· $\Delta\omega_2$
- $\Delta\omega_3$

5 Example 2: New England power system

5.1 Test system

In this example, the 10-machine 39-bus New England power system shown in Fig. 9 is considered. Generator G_1 is an equivalent power source representing parts of the US-Canadian interconnection system. Details of the system data are given in [27]. Although the number and location of PSSs required can be investigated [25, 26], it is assumed here that all generators except G_1 are equipped with PSSs for illustration and comparison purposes.

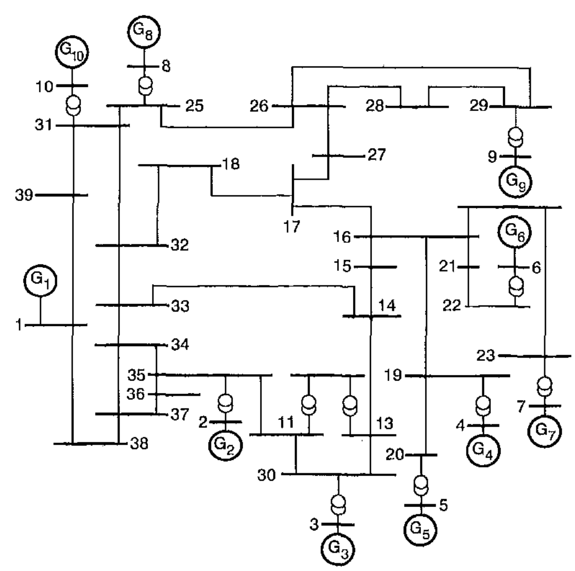

Fig. 9 *Single line diagram for New England system*

5.2 PSS design

To design the proposed TSPSS, three different operating conditions that represent the system under severe loading conditions and critical line outages in addition to the base case are considered. These conditions are extremely harsh

Table 7: Eigenvalues and damping ratios of example 2 without PSSs

Base case	Case 1	Case 2	Case 3
0.191 ± *j*5.808, −0.033	0.195 ± *j*5.716, −0.034	0.189 ± *j*5.811, −0.033	0.205 ± *j*5.638, −0.036
0.088 ± *j*4.002, −0.022	0.121 ± *j*3.798, −0.032	0.006 ± *j*3.113, −0.002	0.152 ± *j*3.714, −0.041
−0.028 ± *j*9.649, 0.003	0.097 ± *j*6.006, −0.016	0.001 ± *j*6.180, −0.0002	0.126 ± *j*5.964, −0.021
−0.034 ± *j*6.415, 0.005	−0.032 ± *j*9.694, 0.003	−0.028 ± *j*9.650, 0.003	0.051 ± *j*9.648, −0.005
−0.056 ± *j*7.135, 0.008	−0.104 ± *j*8.015, 0.013	−0.032 ± *j*7.105, 0.005	−0.098 ± *j*8.013, 0.012
−0.093 ± *j*8.117, 0.011	−0.109 ± *j*6.515, 0.017	−0.091 ± *j*8.115, 0.011	−0.101 ± *j*6.512, 0.016
−0.172 ± *j*9.692, 0.018	−0.168 ± *j*9.715, 0.017	−0.172 ± *j*9.693, 0.018	−0.167 ± *j*9.727, 0.017
−0.220 ± *j*8.013, 0.027	−0.204 ± *j*8.058, 0.025	−0.218 ± *j*8.024, 0.027	−0.202 ± *j*8.079, 0.025
−0.270 ± *j*9.341, 0.029	−0.250 ± *j*9.268, 0.027	−0.269 ± *j*9.342, 0.029	−0.238 ± *j*9.296, 0.026

from the stability point of view [28]. They can be described as:

(i) Base case;

(ii) Case 1; outage of line 21-22;

(iii) Case 2; outage of line 1-38.

(iv) Case 3; outage of line 21-22, 25% increase in loads at buses 16 and 21, and 25% increase in generation of G_7.

The electromechanical modes and damping ratios without PSSs for these conditions are given in Table 7. It is clear that these modes are poorly damped and some of them are unstable. In this example, the optimised parameters are K_i, T_{1i} and T_{3i}, $i = 2, 3, ..., 10$, i.e. the number of optimised parameters is 27. T_w, T_2 and T_4 are set to be 5s [18], 0.05s and 0.05s, respectively.

In this case, σ_0 and ζ_0 are chosen to be −1.0 and 0.2, respectively. The final values of the optimised parameters with both objective functions are given in Table 8. The convergence rate of the objective functions are shown in Fig. 10. With the optimal values of the proposed PSSs, the system eigenvalues with J_1 and J_2 settings are given in Tables 9 and 10, respectively. It is quite clear that the system eigenvalues associated with the electromechanical modes have been shifted to the left of the *s*-plane with the proposed PSSs. This demonstrates that the system damping with the proposed PSSs is greatly improved.

Table 8: Optimal values of proposed PSS parameters for example 2

Generator	Objective function J_1			Objective function J_2		
	k	T_1	T_3	k	T_1	T_3
G_2	26.963	0.399	0.880	25.465	0.865	0.993
G_3	15.733	0.650	0.826	49.336	0.848	0.986
G_4	26.842	0.425	0.966	42.820	0.632	0.924
G_5	43.727	0.102	0.427	29.322	0.202	0.347
G_6	18.260	0.974	0.393	49.384	0.409	0.642
G_7	2.737	0.460	0.202	10.328	0.236	0.151
G_8	0.278	0.734	0.743	26.630	0.948	0.998
G_9	18.732	0.171	0.337	31.461	0.291	0.176
G_{10}	26.598	0.945	0.871	48.940	1.000	0.962

5.3 Nonlinear time-domain simulation

To demonstrate the effectiveness of the proposed PSSs over a wide range of operating conditions, the following disturbances are considered for nonlinear time simulations:

(*a*) A 6-cycle fault disturbance at bus 29 at the end of line 26-29. The fault is cleared by tripping the line 26-29 with successful reclosure after 1.0s.

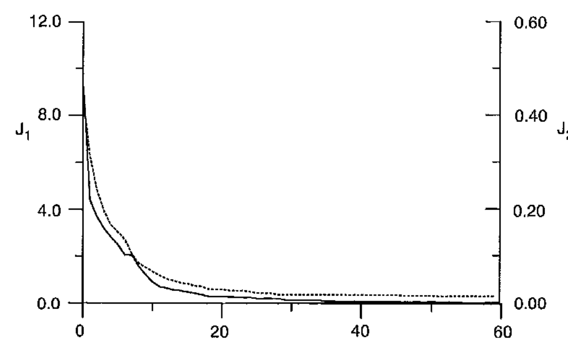

Fig. 10 *Objective function variations of example 2*
——— objective function J_1
········ objective function J_2

(*b*) A 6-cycle fault disturbance at bus 14 at the end of line 14-15. The fault is cleared by tripping the line 14-15 with successful reclosure after 1.0s.

The performance of the proposed PSSs is compared to that of PSSs with the settings given in [18], where the stabilisers were designed using gradient methods with the same conditions considered in this study. For disturbance (*a*), the speed deviation of G_9, as the nearest generator to the fault location, is shown in Fig. 11. It is clear that the system response with the proposed PSSs is stable, while with PSSs of [18] the system is unstable. Additionally, PSSs of [18] fail to stabilise the system with disturbance (*b*), the proposed PSSs provide good damping characteristics and the system is stable under this severe disturbance as shown in Fig. 12. In addition, the proposed PSSs are quite efficient in damp-

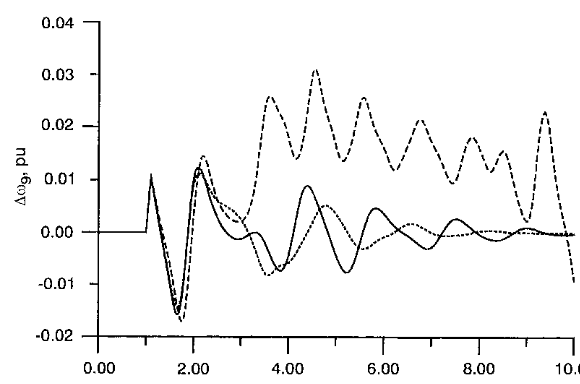

Fig. 11 *System response of example 2 with disturbance (a)*
– – – – with PSSs [18]
——— with proposed PSSs (J_1 settings)
········ with proposed PSSs (J_2 settings)

Table 9: Eigenvalues and damping ratios of example 2 with proposed PSSs (J_1 settings)

Base case	Case 1	Case 2	Case 3
$-1.236 \pm j14.83$, 0.083	$-1.321 \pm j14.54$, 0.090	$-1.239 \pm j14.83$, 0.083	$-1.234 \pm j14.60$, 0.084
$-1.148 \pm j11.13$, 0.103	$-1.129 \pm j11.12$, 0.101	$-1.145 \pm j11.13$, 0.102	$-1.116 \pm j11.11$, 0.100
$-2.064 \pm j10.94$, 0.185	$-2.004 \pm j10.87$, 0.181	$-2.040 \pm j10.91$, 0.184	$-1.982 \pm j10.83$, 0.180
$-1.160 \pm j10.99$, 0.105	$-1.029 \pm j10.75$, 0.095	$-1.159 \pm j10.99$, 0.105	$-1.000 \pm j10.73$, 0.093
$-1.787 \pm j9.507$, 0.185	$-1.082 \pm j8.927$, 0.120	$-1.777 \pm j9.466$, 0.185	$-1.082 \pm j8.903$, 0.121
$-1.101 \pm j9.159$, 0.119	$-1.785 \pm j8.603$, 0.203	$-1.056 \pm j9.137$, 0.115	$-1.728 \pm j8.556$, 0.198
$-1.730 \pm j7.925$, 0.213	$-1.974 \pm j7.223$, 0.264	$-1.803 \pm j7.526$, 0.233	$-1.971 \pm j7.036$, 0.270
$-1.096 \pm j5.569$, 0.193	$-1.047 \pm j5.479$, 0.188	$-1.000 \pm j5.584$, 0.176	$-1.028 \pm j5.429$, 0.186
$-1.008 \pm j3.864$, 0.252	$-1.035 \pm j3.614$, 0.275	$-1.000 \pm j2.333$, 0.394	$-1.069 \pm j3.443$, 0.297

Table 10: Eigenvalues and damping ratios of example 2 with the proposed PSSs (J_2 settings)

Base case	Case 1	Case 2	Case 3
$-3.035 \pm j14.72$, 0.202	$-3.076 \pm j14.61$, 0.206	$-3.040 \pm j14.72$, 0.202	$-3.100 \pm j14.55$, 0.208
$-2.482 \pm j13.16$, 0.185	$-2.444 \pm j12.98$, 0.185	$-2.490 \pm j13.15$, 0.186	$-2.417 \pm j12.91$, 0.184
$-3.330 \pm j12.74$, 0.253	$-3.342 \pm j12.74$, 0.254	$-3.339 \pm j12.73$, 0.254	$-3.394 \pm j12.73$, 0.258
$-2.317 \pm j12.74$, 0.179	$-2.206 \pm j12.64$, 0.172	$-2.300 \pm j12.74$, 0.178	$-2.189 \pm j12.62$, 0.171
$-2.216 \pm j11.95$, 0.182	$-2.363 \pm j11.67$, 0.194	$-2.148 \pm j11.86$, 0.178	$-2.185 \pm j11.73$, 0.183
$-3.351 \pm j11.48$, 0.280	$-2.962 \pm j11.12$, 0.257	$-3.351 \pm j11.46$, 0.281	$-2.923 \pm j11.01$, 0.257
$-2.335 \pm j11.06$, 0.207	$-2.149 \pm j11.17$, 0.189	$-2.439 \pm j10.99$, 0.217	$-2.242 \pm j11.09$, 0.198
$-1.915 \pm j9.553$, 0.197	$-1.954 \pm j5.105$, 0.357	$-1.923 \pm j9.520$, 0.198	$-1.825 \pm j4.847$, 0.352
$-0.764 \pm j2.912$, 0.254	$-0.660 \pm j2.927$, 0.220	$-0.471 \pm j2.195$, 0.210	$-0.605 \pm j2.936$, 0.202

ing out the local modes as well as the inter-area modes of oscillations. This illustrates the superiority of the proposed TSPSS design approach to get optimal or near optimal PSS parameters.

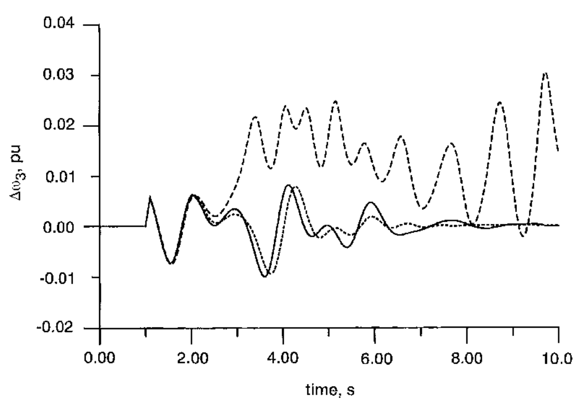

Fig. 12 *System response of example 2 with disturbance (b)*
- - - - with PSSs [18]
——— with proposed PSSs (J_1 settings)
.... with proposed PSSs (J_2 settings)

Due to space limitations and to give a clear perceptive of the system responses, two performance indices that reflect the settling time and overshoots are introduced and evaluated. These indices are defined as:

$$PI_1 = \sum_{i=1}^{n} \int_{t=0}^{t=t_{sim}} (t\Delta\omega_i)^2 dt \qquad (10)$$

$$PI_2 = \sum_{i=1}^{n} \int_{t=0}^{t=t_{sim}} (\Delta\omega_i)^2 dt \qquad (11)$$

where n is the number of machines and t_{sim} is the simulation time. The values of these indices with the disturbances (a) and (b) are given in Table 11. It is clear that the values of these indices with the proposed PSSs are much smaller. This demonstrates that the settling time and the speed deviations of all units are much reduced by applying the proposed PSSs.

Table 11: Values of performance indices for example 2

	PI_1			PI_2		
Fault	PSSs [18]	Proposed PSSs		PSSs [18]	Proposed PSSs	
		J_1 settings	J_2 settings		J_1 settings	J_2 settings
a	4964	74.382	78.592	191.8	8.233	9.034
b	4944	78.828	49.307	163.6	8.488	7.543

6 Discussion

Some comments on the proposed approach are now in order:

Unlike the methods of [7, 8], the proposed TS based approach does not rely on the initial solution. Starting anywhere in the search space, the TS algorithm ensures the convergence to the optimal solution. Example 1 is reconsidered to demonstrate this point. In this case, the main target is to shift the dominant eigenvalues as far as possible to the left of the s-plane. Different initial solutions are considered by changing the seed of the random number generator that generates the initial solution. The convergence of the objective functions with different initial solutions is shown in Fig. 13. The results emphasise that the proposed TS-based approach finally leads to the optimal solution regardless of the initial one.

Based on the above conclusion, the proposed approach can be used to improve the solution quality of other methods described in [5–8].

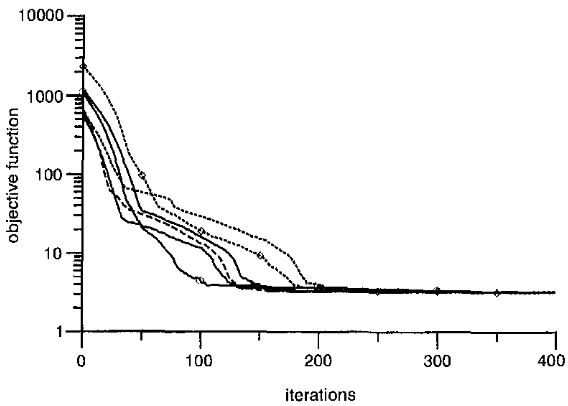

Fig. 13 *Objective function J_I of example 1 with different initialisations*

7 Conclusions

In this study, the tabu search algorithm is proposed for the robust PSS design problem. The proposed design approach employs TS to search for optimal settings of CPSS parameters. The proposed objective function shifts simultaneously the electromechanical mode eigenvalues of different operating conditions to the left in the s-plane. The proposed approach has been applied to two different multimachine power systems with different loading conditions and system configurations. The main features of the proposed approach can be summarised as:

(i) The solution quality of the proposed approach is independent of the initial guess. Hence, the proposed approach can be used to improve the quality of the solutions of other classical optimisation methods.

(ii) Since eigenvector calculations and sensitivity analysis are not required to evaluate the proposed objective functions, heavy computations of the design process are avoided.

(iii) The eigenvalue analysis reveals the effectiveness of the proposed PSSs to damp out local as well as inter-area modes of oscillations.

(iv) The nonlinear time-domain simulation results show that the proposed PSSs work effectively over a wide range of loading conditions and system configurations.

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