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Eigenvalue assignments in multimachine power systems using tabu search algorithm

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Abstract

Applying tabu search (TS) optimization technique to multimachine power system stabilizer (PSS) design is presented in this paper. The proposed approach employs TS to search for optimal or near optimal settings of PSS parameters that shift the system eigenvalues associated with the electromechanical modes to the left of a vertical line in the *s*-plane. Incorporation of TS algorithm in PSS design significantly reduces the computational burden. One of the main advantages of the proposed approach is its robustness to the initial guess. The performance of the proposed PSS 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 to damp out the local as well as the interarea modes of oscillations and work effectively over a wide range of loading conditions and system configurations.

Keywords: Power system stabilizer; Tabu search algorithm; Dynamic stability

1. Introduction

Power systems experience low frequency oscillations when subjected to disturbances. The oscillations may sustain and grow to cause system separation if no adequate damping is available. To enhance system damping, the generators are equipped with power system stabilizers (PSSs) that provide supplementary feedback stabilizing signals in the excitation systems. PSSs extend the power system stability limit by enhancing the system damping of low frequency oscillations associated with the electromechanical modes [1–3].

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The concepts of synchronous machine stability as affected by excitation control presented in Refs. [2,3] where an understanding of the stabilizing requirements for static excitation systems has been established. In recent years, several approaches based on modern control theory have been applied to PSS design problem. These include optimal control, adaptive control, variable structure control, and intelligent control [4–7].

Despite the potential of modern control techniques with different structures, power system utilities still prefer the conventional lead-lag power system stabilizer (CPSS) structure [8–10]. 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.

Kundur et al. [10] 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.

A lot of different techniques has been reported in the literature pertaining to coordinated design problem of CPSS. Different techniques of sequential design of PSSs are presented [11,12] to damp out one of the electromechanical modes at a time. Generally, the dynamic interaction effects among various modes of the machines are found to have significant influence on the stabilizer settings. Therefore, considering the application of stabilizer to one machine at a time may not finally lead to an overall optimal choice of PSS parameters. Moreover, the stabilizers 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 Refs. [13–16] where various methods for simultaneous tuning of PSSs in multimachine power systems are proposed. Unfortunately, the proposed techniques are iterative and require heavy computation burden due to system reduction procedure. This gives rise to time consuming computer codes. In addition, the initialization step of these algorithms is crucial and affects the final dynamic response of the controlled system. Hence, different designs assigning the same set of eigenvalues were simply obtained by using different initializations. Therefore, a final selection criterion is required to avoid long runs of validation tests on the nonlinear model. Other techniques such as mathematical programming [17] have been applied to the problem of tuning of PSSs. The problem has been formulated as both a quadratic and a linear programming problem. However, this formulation is carried out at the expense of some conservativeness and the number of constraints becomes unduly large. A gradient procedure for optimization of PSS parameters is presented in Ref. [18]. The optimization process requires computations of sensitivity factors and eigenvectors at each iteration. This gives rise to heavy computational burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained will not be optimal. To overcome the shortcomings of the previous methods and to avoid computations of sensitivity factors and eigenvectors, tabu search (TS) based approach to PSS design is proposed.

Recently, genetic algorithm (GA) has received much attention and has been successfully applied to PSS design problem [19–21]. Even though several successful applications have been reported, recent research has identified some inefficiencies in GA performance [22]. This degradation in efficiency is apparent in applications with highly epistatic objective functions, i.e., where the parameters being optimized are highly correlated. Also, the encoding and decoding processes of each solution use a lot of computing time. The new generation of GA after mutation and crossover may lose advantages obtained in the last generation. In addition, the premature convergence of GA represents a major problem. This problem occurs when the population of chromosomes reaches a configuration such that crossover no longer produces offspring that can outperform their parents. Under such circumstances, all standard forms of crossover simply regenerate the current parents. Any further optimization relies solely on bit mutation and can be quite slow. At this stage, hill-climbing heuristics should be employed to search for improvement [23].

In the last few years, TS algorithm [24–28] appeared as another promising heuristic algorithm for handling the combinatorial optimization problems. Unlike GA and other heuristic techniques, TS 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 TS algorithm can yield global optimal solution with probability one [27].

In this paper, PSS design by eigenvalue shift technique using TS algorithm is proposed. The problem of PSS design is formulated as an optimization problem. Then, TS algorithm is employed to solve this optimization problem with the aim of getting optimal settings of PSS parameters. 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 modeled by a set of nonlinear differential equations. In this work, the following third order model of the ith machine is used. The following model is widely considered to be sufficiently accurate to analyze electromechanical dynamics [2].

$$\rho\delta_i = \omega_b(\omega_i - 1) \tag{1}$$

$$\rho\omega_i = (T_{mi} - T_{ei} - D_i(\omega_i - 1))/M_i \tag{2}$$

$$\rho E'_{qi} = (E_{fdi} - (x_{di} - x'_{di})i_{di} - E'_{qi})/T'_{doi} \tag{3}$$

$$T_{ei} = E'_{qi}i_{qi} + (x_{qi} - x'_{di})i_{di}i_{qi} \tag{4}$$

where ρ is the first derivative with respect to time; δ and ω are the rotor angle and speed respectively; M and D are machine inertia constant and damping coefficient respectively; ω_b is the synchronous speed; E'_q is the internal voltage behind x'_d; i_d and i_q are stator currents in d- and q-axis circuits respectively; x_d and x_q are d- and q-axis synchronous reactances respectively; x'_d is the d-axis transient reactance; E_{fd} is the equivalent excitation voltage; T'_{do} is the time constant of excitation circuit; T_m and T_e are mechanical torque and electric torque respectively.

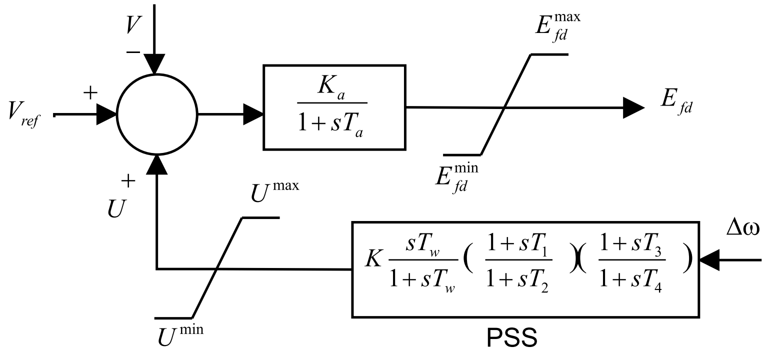

Fig. 1. IEEE Type-ST1 excitation system with PSS.

2.2. Excitation system

The IEEE Type-ST1 excitation system shown in Fig. 1 is considered in this study. It can be described as

$$\rho E_{fdi} = (K_{ai}(V_{\mathrm{ref}i} - V_i + U_i) - E_{fdi})/T_{ai} \tag{5}$$

and,

$$V = (V_d^2 + V_q^2)^{1/2} \tag{6}$$

$$V_d = x_q i_q \tag{7}$$

$$V_q = E'_q - x'_d i_d \tag{8}$$

where V and V_{ref} are terminal and reference voltages respectively; v_d and v_q are terminal voltage in d- and q-axis respectively; K_a and T_a are the regulator gain and time constant respectively; U is the PSS output signal at the machine. In Fig. 1 $E_{fd}^{\max}$ and $E_{fd}^{\min}$ are the upper and lower limits of E_{fd}. These limits are set as ± 6.0 pu.

2.3. Power system stabilizer structure

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

$$U_i = K_i \frac{sT_{\mathrm{w}}}{1 + sT_{\mathrm{w}}} \frac{(1 + sT_{1i})}{(1 + sT_2)} \frac{(1 + sT_{3i})}{(1 + sT_4)} \Delta\omega_i \tag{9}$$

where T_{w} is the washout time constant 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 stabilizer gain K_i and time constants T_{1i} and T_{3i} are remained to be determined. In Fig. 1 $U^{\max}$ and $U^{\min}$ are the upper and lower limits of U. These limits are set as ± 0.2 pu.

In short, the model can be written as

$$\dot{X} = f(X, U) \tag{10}$$

where $X = [\delta, \omega, E'_q, E_{fd}]^{\mathrm{T}}$ and U is the PSS output signals.

In the design of PSS, the linearized incremental models around an equilibrium point are usually employed [1–3]. Therefore, the state equation of a power system with n machines and m stabilizers can be written as:

$$\Delta\dot{X} = A\Delta X + BU \tag{11}$$

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

2.4. Objective function

To increase the system damping to electromechanical modes, an objective function J defined below is considered.

$$J = \sum_{\sigma_i \geqslant \sigma_0} (\sigma_0 - \sigma_i)^2 \tag{12}$$

where σ_i is the real part of the ith eigenvalue and σ_0 is a chosen threshold. 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 $s = \sigma_0$ line in the s-plane. This insures also some degree of relative stability. It is worth noting that the knowledge of the controller's structure and system conditions will dictate the choice of the value of σ_0. The condition $\sigma_i \geqslant \sigma_0$ is imposed on the evaluation of J to consider only the unstable or poorly damped modes which are mainly the electromechanical ones.

The problem constraints are the parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

$$\text{Minimize } J \tag{13}$$

Subject to

$$K_i^{\min} \leqslant K_i \leqslant K_i^{\max} \tag{14}$$

$$T_{1i}^{\min} \leqslant T_{1i} \leqslant T_{1i}^{\max} \tag{15}$$

$$T_{3i}^{\min} \leqslant T_{3i} \leqslant T_{3i}^{\max} \tag{16}$$

The proposed approach employs TS algorithm to solve this optimization problem and search for 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

TS is a higher level heuristic algorithm for solving combinatorial optimization 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 [24–28]. It has now become an established optimization 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 [24]. Generally, TS is characterized by its ability to avoid entrapment in local optimal solution and prevent cycling by using flexible memory of search history.

3.2. Tabu search algorithm

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

- *Current solution*, x_{current}: It is a set of the optimized parameter values at any iteration. It plays a central role in generating the neighbor trial solutions.
- *Moves*: They characterize the process of generating trial solutions that are related to x_{current}.
- *Set of candidate moves*, $N(x_{\text{current}})$: It is the set of all possible moves or trial solutions, x_{trial}s, in the neighborhood of x_{current}. In case of continuous variable optimization problems, this set is too large or even infinite set. Therefore, one could operate with a subset, $S(x_{\text{current}})$ with a limited number of trial solutions nt, of this set, i.e., $S \subset N$ and $x_{\text{trial}} \in S(x_{\text{current}})$.
- *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. In our implementation, the size 7 is found to be quite satisfactory.
- *Aspiration criterion* (*Level*): It is a rule that override tabu restrictions, i.e., if a certain move is forbidden by tabu restriction, the aspiration criterion, when satisfied, can make this move allowable. 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.
- *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) 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., $x_{\text{initial}} = x_{\text{current}} = x_{\text{best}}$.

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

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

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

Step 5: Check the aspiration criterion of x^i_{trial}. If satisfied then override the tabu restrictions, update the aspiration level, set $x_{\mathrm{current}} = x^i_{\mathrm{trial}}$, 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 tabu search to power system stabilizer design

The TS algorithm has been applied to search for optimal or near optimal settings of the PSS optimized parameters. In our implementation, the search will terminate if (1) best solution does not change for more than 20 iterations; (2) number of iterations reaches 100; or (3) value of the objective function reaches zero, i.e., all the dominant eigenvalues are shifted to the left of $s = \sigma_0$ line.

It is worth mentioning that the optimization process has been carried out with the system operating at the base case of the following two examples.

4. Example 1: three-machine power system

4.1. Test system

In this example, the three-machine nine-bus system shown in Fig. 2 is considered. Each machine has been represented by a fourth order nonlinear model. The rated MVA of G_1, G_2, and G_3 are 247.5, 192, and 128 respectively. Details of the system data are given in Ref. [1].

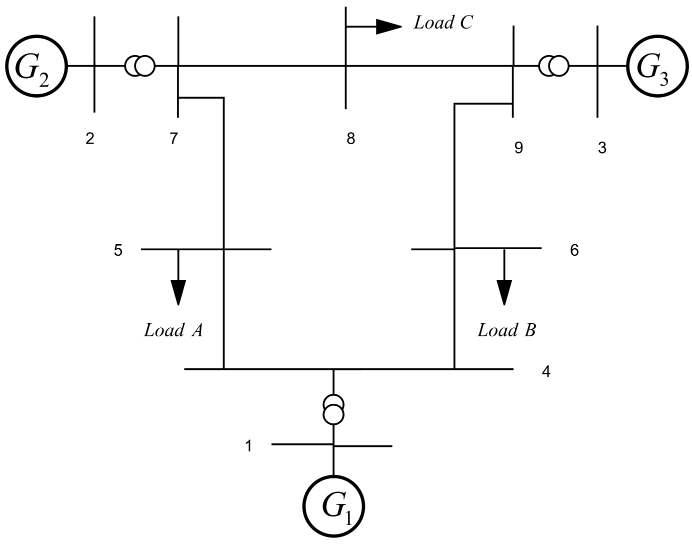

Fig. 2. Three-machine nine-bus power system.

Table 1
The optimal values of the proposed PSS parameters for example 1

Gen#	k	T_1	T_3
G_2	3.974	0.082	0.619
G_3	0.403	0.243	0.530

4.2. Power system stabilizer design

In this example, the optimized parameters are K_i, T_{1i}, and T_{3i}, $i = 2, 3$. T_w, T_2, and T_4 are set to be 5, 0.05, and 0.05 s respectively. Here σ_0 is chosen to be -3.0. TS algorithm has been applied to search for settings of the optimized parameters so as to shift the eigenvalues of electromechanical modes to the left of the line $s = -3.0$ in the s-plane. The final values of the optimized parameters are given in Table 1. The convergence rate of the objective function J with the number of iterations is shown in Fig. 3. It is worth mentioning that the computation time/iteration was 0.13 s on Pentium-I 133 MHz PC.

4.3. Simulation results

To demonstrate the effectiveness of the proposed PSSs over a wide range of loading conditions, two different operating conditions in addition to the base case are considered. The loads are given in Table 2 in per-unit on system 100-MVA base. The loading levels of the generators are given in Table 3 in per-unit on the generator own base. The electromechanical mode eigenvalues and the corresponding damping ratios without PSSs are given in Table 4. It is clear that the electromechanical modes are poorly damped and some of them are unstable. These modes with the proposed PSSs are given in Table 5. It can be shown that the dominant eigenvalues of the base case

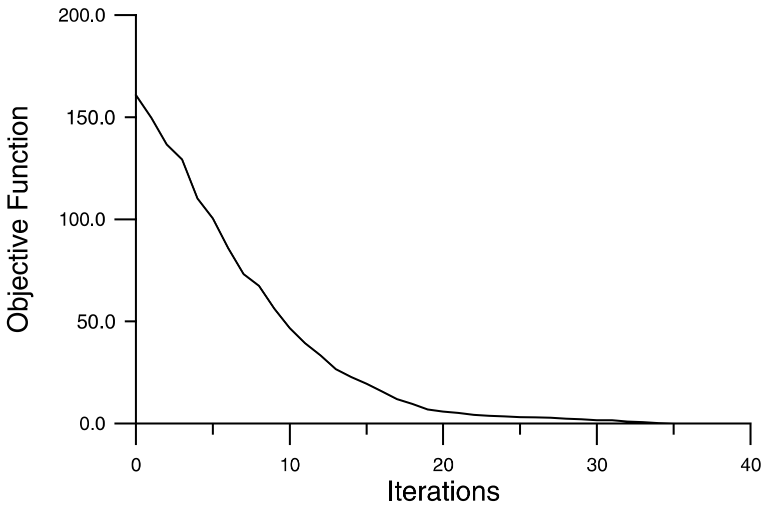

Fig. 3. Objective function variations of example 1.

Table 2
Loads of example 1 in pu on system 100-MVA base

Load	Base case		Case 1		Case 2	
	P (pu)	Q (pu)	P (pu)	Q (pu)	P (pu)	Q (pu)
A	1.250	0.500	2.000	0.800	1.500	0.900
B	0.900	0.300	1.800	0.600	1.200	0.800
C	1.000	0.350	1.500	0.600	1.000	0.500

Table 3
Generator loading levels of example 1 in pu on the generator own base

Gen#	Base case		Case 1		Case 2	
	P (pu)	Q (pu)	P (pu)	Q (pu)	P (pu)	Q (pu)
G_1	0.289	0.109	0.892	0.440	0.135	0.453
G_2	0.849	0.035	1.000	0.294	1.042	0.296
G_3	0.664	−0.085	1.000	0.280	1.172	0.298

Table 4
Eigenvalues and damping ratios of example 1 without PSSs

Base case	Case 1	Case 2
−0.011 ±j 9.068, 0.121	−0.021 ±j 8.907, 0.002	0.377 ±j 8.865, −0.042
−0.778 ±j 13.860, 0.056	−0.519 ±j 13.832, 0.037	−0.336 ±j 13.686, 0.025

Table 5
Eigenvalues and damping ratios of example 1 with the proposed PSSs

Base case	Case 1	Case 2
−3.091 ±j 8.194, 0.353	−2.155 ±j 7.247, 0.285	−2.338 ±j 7.847, 0.286
−3.222 ±j 18.707, 0.170	−3.476 ±j 18.575, 0.184	−3.324 ±j 18.453, 0.177

have been shifted to the left of $s = -3$ line. It is obvious that the system damping with the proposed PSSs is greatly improved and enhanced.

For further illustration, a six-cycle three-phase fault disturbance at bus 7 at the end of line 5–7 is considered for the nonlinear time simulations. The rotor angle responses of G_2 and G_3 with respect to G_1, δ_{21} and δ_{31}, are shown in Figs. 4–6 with the base case, case 1, and case 2 respectively. It is clear that the proposed PSSs provide good damping characteristics to low frequency oscillations and enhance greatly the dynamic stability of power systems.

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. 7 is considered. Each machine has been represented by a fourth order nonlinear model. Generator G_1 is

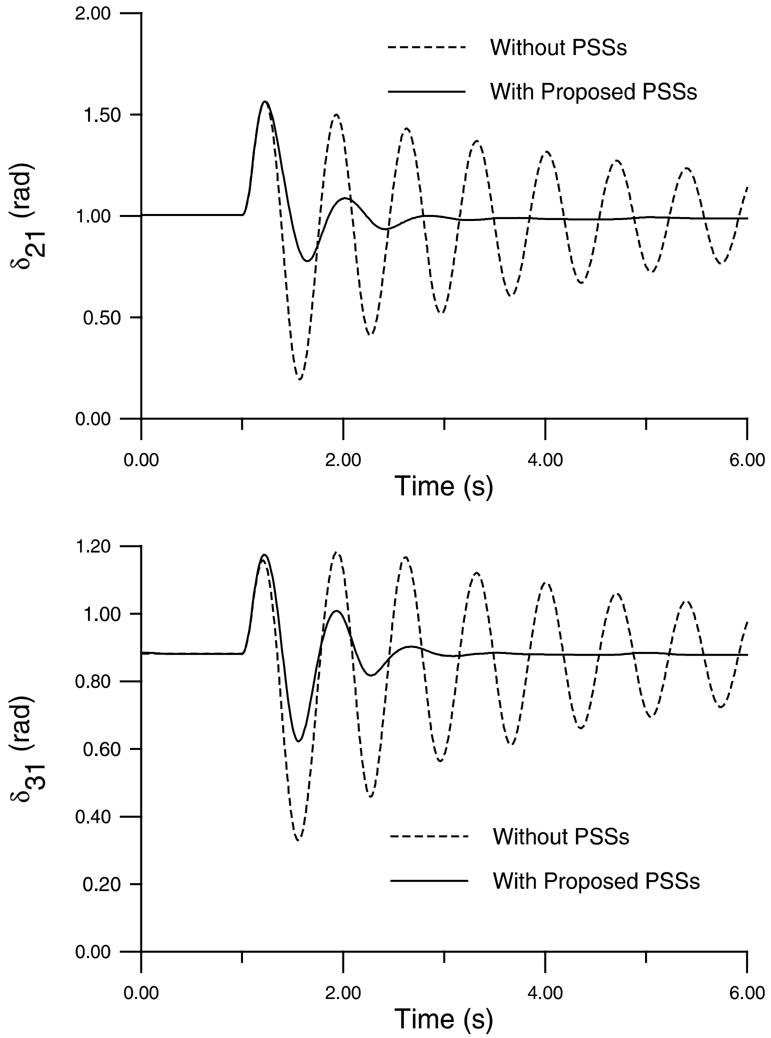

Fig. 4. System response of example 1 with the base case.

an equivalent power source representing parts of the US–Canadian interconnection system. Details of the system data are given in Ref. [29].

5.2. Power system stabilizer design

In this example, the optimized parameters are K_i, T_{1i}, and T_{3i}, $i = 2, 3, \ldots, 10$ i.e., the number of optimized parameters is 27. T_w, T_2, and T_4 are set to be 5, 0.05, and 0.05 s respectively. Here σ_0 is chosen to be -1.0. TS algorithm has been applied to search for settings of these parameters so as to shift the eigenvalues of electromechanical modes to the left of the line $s = -1.0$ in the s-plane. The final values of the optimized parameters are given in Table 6. The convergence rate of

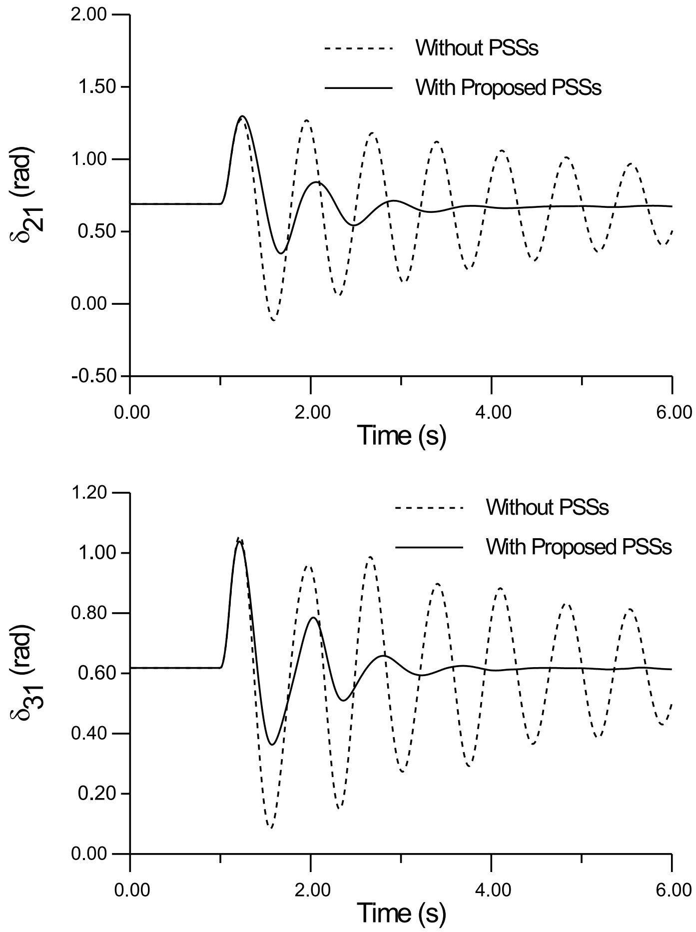

Fig. 5. System response of example 1 with the case 1.

the objective function J with the number of iterations is shown in Fig. 8. In this example, the computation time/iteration was 7 s.

5.3. Simulation results

To demonstrate the effectiveness of the proposed PSSs under severe conditions and critical line outages, two different operating conditions in addition to the base case are considered. These conditions are extremely hard from the stability point of view [30]. They can be described as

1. Base case;
2. Case 1; outage of line 21–22;
3. Case 2; outage of line 14–15.

The electromechanical modes without PSSs for the three cases are given in Table 7. It is clear that these modes are poorly damped and some of them are unstable. The electromechanical modes

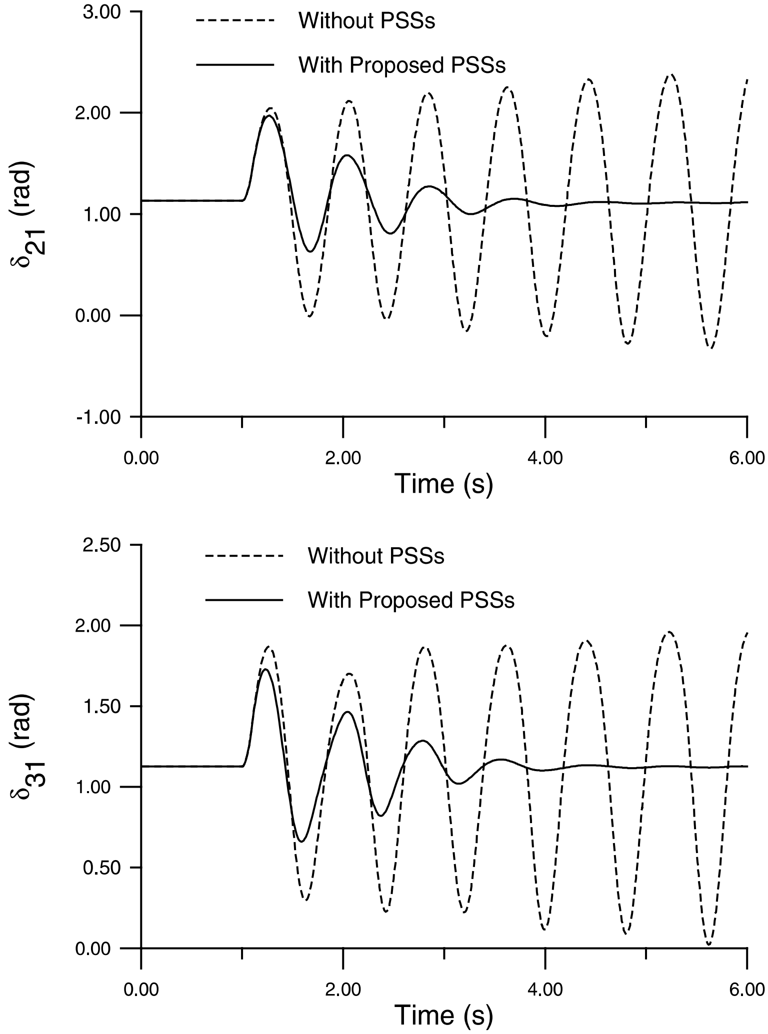

Fig. 6. System response of example 1 with the case 2.

with the proposed PSSs are given in Table 8. It can be seen that the electromechanical modes of the base case with the proposed PSSs have been shifted to the left of $s = -1$ line. It is obvious that the system damping greatly improved and enhanced for all cases.

A six-cycle three-phase fault disturbance at bus 29 at the end of line 26–29 is considered for the nonlinear time simulations. In case 2, the fault is cleared by tripping the line 26–29 and successful reclosure after 1 s. The performance of the proposed PSSs is compared to that of PSSs with the settings given in Ref. [18]. The speed deviation of G_9 as the nearest generator to the fault location is shown in Figs. 9–11 with the base case, case 1, and case 2 respectively. It is clear that the system performance with the proposed PSSs is much better and the oscillations are damped out much faster. While PSSs [18] fail to stabilize the system with the disturbance of case 2, the proposed

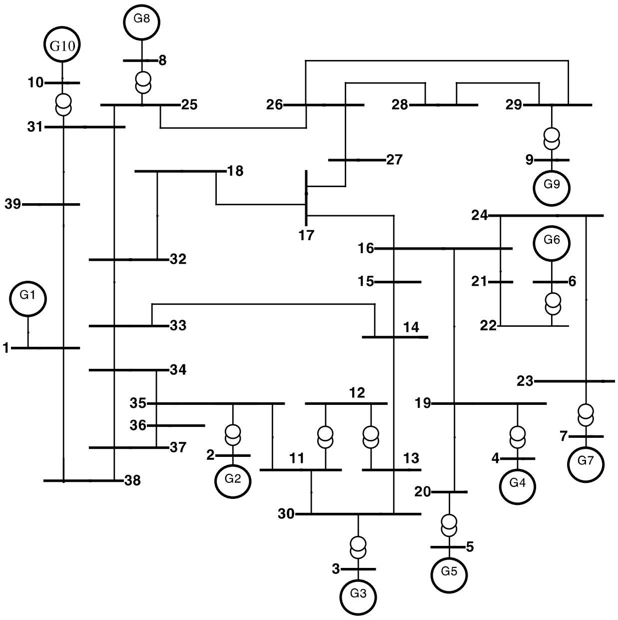

Fig. 7. Single line diagram for New England system.

Table 6
The optimal values of the proposed PSS parameters for example 2

Gen#	k	T_1	T_3
G_2	23.447	0.693	0.960
G_3	41.581	0.663	0.960
G_4	22.074	0.361	0.884
G_5	2.612	0.888	0.223
G_6	49.208	0.659	0.643
G_7	26.249	0.088	0.609
G_8	32.417	0.604	0.680
G_9	2.738	0.674	0.272
G_{10}	10.576	0.968	0.961

PSSs provide good damping characteristics and the system is stable under this sever disturbance. In addition, the proposed PSSs are quite efficient to damp out the local modes as well as the interarea modes of oscillations. This illustrates the superiority of the proposed PSS design approach to get optimal or near optimal set of PSS parameters.

Due to space limitations and to give clear perceptiveness about the system responses, two performance indices that reflect the settling time and overshoots are introduced. They are defined as

$$\mathrm{PI}_1 = \sum_{i=1}^{n} \int_{t=0}^{t=t_{\mathrm{sim}}} (t\,\Delta\omega_i)^2\,\mathrm{d}t \tag{17}$$

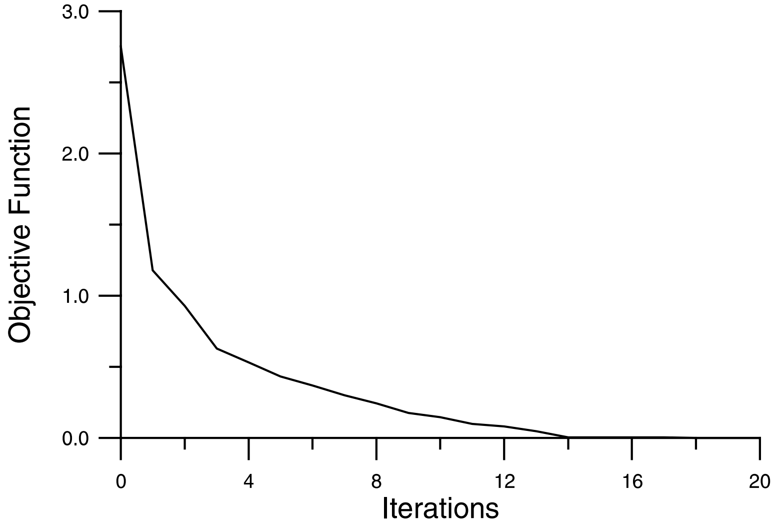

Fig. 8. Objective function variations of example 2.

Table 7
Eigenvalues and damping ratios of example 2 without PSSs

Base case	Case 1	Case 2
0.191 ±j 5.808, −0.033	0.195 ±j 5.716, −0.034	0.152 ±j 5.763, −0.026
0.088 ±j 4.002, −0.022	0.121 ±j 3.798, −0.032	0.095 ±j 3.837, −0.025
−0.028 ±j 9.649, 0.003	0.097 ±j 6.006, −0.016	0.033 ±j 6.852, −0.005
−0.034 ±j 6.415, 0.005	−0.032 ±j 9.694, 0.003	−0.026 ±j 9.659, 0.003
−0.056 ±j 7.135, 0.008	−0.104 ±j 8.015, 0.013	−0.094 ±j 8.120, 0.012
−0.093 ±j 8.117, 0.011	−0.109 ±j 6.515, 0.017	−0.100 ±j 6.038, 0.017
−0.172 ±j 9.692, 0.018	−0.168 ±j 9.715, 0.017	−0.171 ±j 9.696, 0.018
−0.220 ±j 8.013, 0.027	−0.204 ±j 8.058, 0.025	−0.219 ±j 8.000, 0.027
−0.270 ±j 9.341, 0.029	−0.250 ±j 9.268, 0.027	−0.259 ±j 9.320, 0.028

Table 8
Eigenvalues and damping ratios of example 2 with the proposed PSSs

Base case	Case 1	Case 2
−1.010 ±j 8.759, 0.115	−0.800 ±j 8.595, 0.093	−0.892 ±j 3.013, 0.284
−1.058 ±j 10.971, 0.096	−0.804 ±j 2.963, 0.262	−1.033 ±j 5.258, 0.193
−1.059 ±j 5.315, 0.195	−0.963 ±j 10.251, 0.094	−1.035 ±j 8.727, 0.118
−1.101 ±j 3.175, 0.328	−1.032 ±j 10.979, 0.094	−1.055 ±j 10.970, 0.096
−1.102 ±j 10.553, 0.103	−1.068 ±j 5.337, 0.196	−1.105 ±j 10.549, 0.104
−1.184 ±j 3.845, 0.294	−1.173 ±j 4.105, 0.275	−1.389 ±j 3.880, 0.337
−1.622 ±j 9.420, 0.174	−2.088 ±j 10.861, 0.189	−1.428 ±j 9.033, 0.156
−1.955 ±j 8.271, 0.230	−2.092 ±j 7.914, 0.256	−2.128 ±j 10.826, 0.193
−2.132 ±j 10.935, 0.191	−2.098 ±j 8.744, 0.233	−2.325 ±j 8.032, 0.278

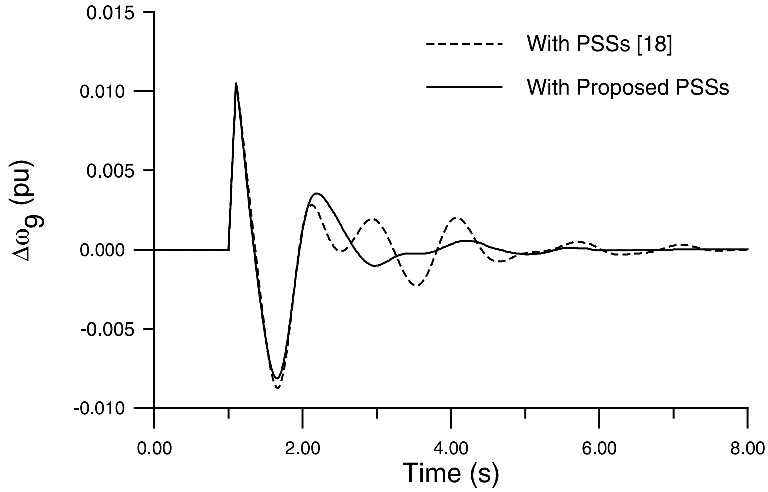

Fig. 9. System responses of example 2 with the base case.

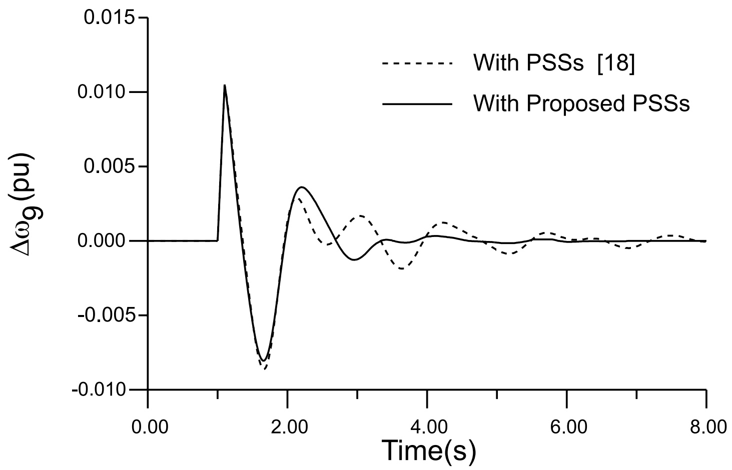

Fig. 10. System responses of example 2 with the case 1.

$$\mathrm{PI}_2 = \sum_{i=1}^{n} \int_{t=0}^{t=t_{\mathrm{sim}}} (\Delta\omega_i)^2 \, \mathrm{d}t \tag{18}$$

where n is the number of machines and t_{sim} is the simulation time. The values of these indices with the different cases are given in Table 9. It is clear that the values of these indices with the proposed PSSs are much smaller compared to the corresponding values with the PSSs given in Ref. [18].

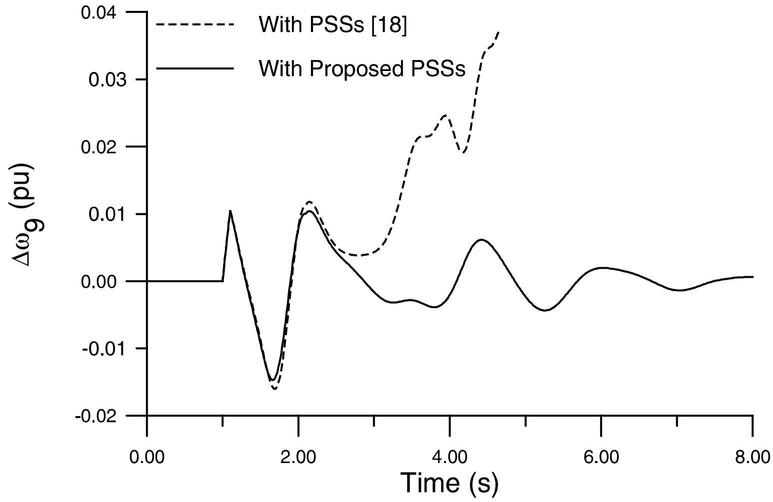

Fig. 11. System responses of example 2 with the case 2.

Table 9
Values of performance indices for example 2

Fault of	PI_1		PI_2	
	PSS [18]	Proposed PSS	PSS [18]	Proposed PSS
Base	2.4277	0.9929	1.0491	0.7151
Case 1	3.3486	0.8947	1.0858	0.6989
Case 2	35713.6	38.7466	1118.6	5.8645

This demonstrates that the settling time and the speed deviations of all units are much reduced by applying the proposed PSSs.

6. Discussion

Some comments on the proposed approach are now in order:

(a) Unlike the methods of Refs. [13–16], the proposed TS based approach does not rely on the initial solution. Starting anywhere in the search space, 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. 12. The results emphasize that the proposed TS based approach finally leads to the optimal solution regardless of the initial one.

(b) Based on the above conclusion, the proposed approach can be used to improve the solution quality of other methods described in Refs. [7–16].

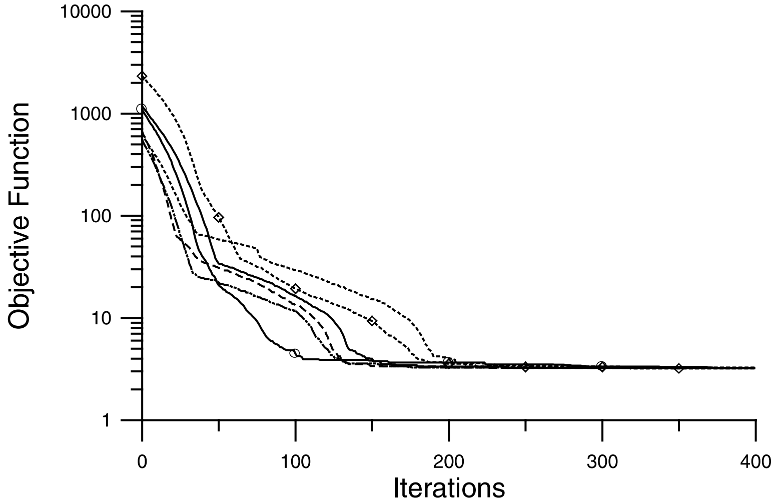

Fig. 12. Objective function values of example 1 with different initializations.

7. Conclusions

In this study, the TS algorithm is proposed to the PSS design problem. The proposed approach has been applied to two different examples of multimachine power systems with different loading conditions and system configurations. The results show the potential of TS algorithm for optimal settings of PSS parameters. It is also shown that the solution quality of the proposed approach is independent of the initialization step. Therefore, the proposed approach can be used to improve the quality of the solutions of other classical optimization methods. The eigenvalue analysis reveals the effectiveness of the proposed PSSs to damp out local as well as interarea modes of oscillations. The nonlinear time simulation results show that the proposed PSSs can work effectively over a wide range of loading conditions and system configurations.

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