Robust Design of Electrical Power-Based Stabilizers Using Tabu Search

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Abstract: Robust design of multimachine Power System Stabilizers (PSSs) using Tabu Search (TS) optimization technique is presented in this paper. The proposed approach employs TS for optimal parameter settings of a widely used conventional fixed-structure lead-lag PSS (CPSS) that employs electrical power as input. The parameters of the proposed stabilizers 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 optimization technique in PSS design significantly reduces the computational burden. The performance of the proposed PSSs under different disturbances and loading conditions is investigated for a multimachine power system. 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 and enhance greatly the system stability over a wide range of loading conditions and system configurations.

Keywords: Robust PSS, tabu search, dynamic stability.

1. INTRODUCTION

In the past two decades, the utilization of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention [1-18]. Nowadays, the conventional power system stabilizer (CPSS) is widely used by power system utilities. Recently, several approaches based on modern control theory have been applied to PSS design problem. These include optimal, adaptive, variable structure, and intelligent control [2-4]. 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 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 [8-9]. Unfortunately, the proposed techniques are iterative and require heavy computation burden due to system reduction procedure. In addition, the initialization 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 recognize that machine parameters change with loading making the machine behavior quite different at different operating conditions. Since these parameters change in a rather complex manner, a set of CPSS parameters which stabilizes 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_∞ optimization techniques [10-11] have been applied to robust PSS design problem. However, the importance and difficulties in the selection of weighting functions of H_∞ optimization problem have been reported. In addition, the additive and/or multiplicative uncertainty representation can not 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 stabilizer is as high as that of the plant. This gives rise to complex structure of such stabilizers 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 provide satisfactory damping performance over a wide range of system loading conditions. The robustness 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 CPSS, several operating conditions and system configurations are simultaneously considered in CPSS design process [16-17]. A genetic 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 CPSS. However, there exist some structural problems in the conventional genetic algorithm such as the premature convergence and duplications among strings as evolution is processing. A gradient procedure for optimization of PSS parameters at different operating conditions is presented in [18]. Unfortunately, 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. Therefore, TS based approach to robust PSS design is proposed in this paper.

In the last few years, tabu search algorithm [19-22] appeared as another promising heuristic algorithm for handling the combinatorial optimization problems. 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 global optimal solution with probability one [22].

In this paper, the problem of robust PSS design is formulated as an optimization problem and 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

A. Power System Model

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

$$\dot{X} = A\,X + B\,U \tag{2}$$

where A is $4n\times4n$ 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. X is $4n\times1$ state vector while U is $m\times1$ input vector.

B. PSS Structure

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

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

where T_w is the washout time constant, U_i is the PSS output signal at the i^{th} machine, and r_i is the PSS input signal.

Several PSS input signals have been utilized such as speed, electrical power, and accelerating power [6,23]. Although the speed has been the most widely used signal, speed-based PSSs may contribute to negative damping of shaft torsional modes and a torsional filter has to be used. This filter, however, produces some phase lag in the control loop [23]. In this study, the electrical power ΔP_t will be utilized as the PSS input signal. It is worth mentioning that the electrical power signal can be easily derived and implemented. 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 the parameters to be determined.

C. Objective Function

To increase the system damping, the two eigenvalue-based objective functions defined below are considered.

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

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

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 i^{th} eigenvalue of the j^{th} 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 $\zeta = \zeta_0$ line in the s-plane. This insures a good time-domain response in terms of overshoots and settling time. The conditions $\sigma_{i,j} \ge \sigma_0$ and $\zeta_{i,j} \le \zeta_0$ 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. The design problem can be formulated as the following optimization problem:

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

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 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 SEACH ALGORITHM

A. Overview

Tabu search 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 [20-22]. 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 [20]. Generally, TS is characterized by its ability to avoid entrapment in local optimal solution and prevent cycling by using flexible memory of search history.

B. TS Algorithm

The basic elements of TS are briefly 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. The tabu list size plays a great role in the search of 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 centered at 7 seems to be quite effective [22]. 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):*** 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. Different forms of aspiration criteria are used in the literature [19-22]. 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 aspiration criterion is to add some flexibility in the tabu search by directing it towards the attractive moves.
- ***Stopping Criteria:*** 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 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_{trial}^i as the i^{th} 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 objective function value associated with it.

Step 3: Set i=1. If $J(x_{\text{trial}}^i) > J(x_{\text{best}})$ go to Step 4, else set $x_{\text{best}} = x_{\text{trial}}^i$ 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 $x_{\text{current}} = x_{\text{trial}}^i$, and go to Step 7. If it is in 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 $x_{\text{current}} = x_{\text{trial}}^i$, 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 stopping criteria. If one of them is satisfied then stop, else set $k=k+1$ and go back to Step 2.

C. 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 initialization step, the system model is linearized at each operating point. The described TS algorithm is excited by generating randomly initial values of the optimized 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 *s*-plane.

4. RESULTS AND DISCUSSIONS

A. Test System

In this study, the 10-machine 39-bus New England power system shown in Fig. 1 is considered. Generator G_1 is an equivalent power source representing parts of the U.S.-Canadian interconnection system. Details of the system data are given in [24]. Although, the number and location of PSSs required can be investigated, it is assumed here that all generators except G_1 are equipped with PSSs for illustration and comparison purposes.

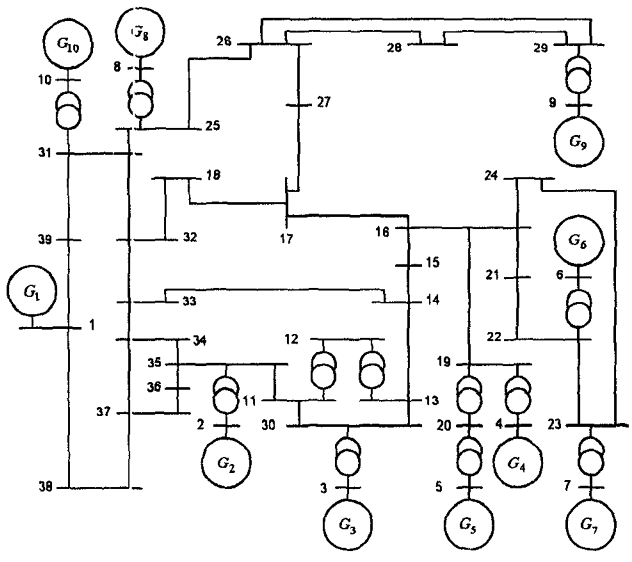

Fig. 1: Single line diagram for New England system

B. PSS Design

To design the proposed PSSs, 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 from the stability viewpoint [25]. They can be described as

Case 1; outage of line 21-22;
Case 2; outage of line 1-38;
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 all conditions are given in Table 1. It is clear that these modes are poorly damped and some of them are unstable. The optimized parameters are K_i, T_{1i}, and T_{3i}, i=2,3,...,10, that results in 27 optimized parameters. T_w, T_2, and T_4 are set to be 5s [18], 0.15s, and 0.15s respectively.

In this case, σ_0 and ζ_0 are chosen to be -1.0 and 0.15 respectively. The final values of the optimized parameters with both objective functions are given in Table 1. The convergence rate 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 Table 1. It is quite clear that the system eigenvalues associated with the electromechanical modes have been shifted to the left of *s*-plane with the proposed PSSs. This demonstrates that the system damping with the proposed PSSs is greatly improved.

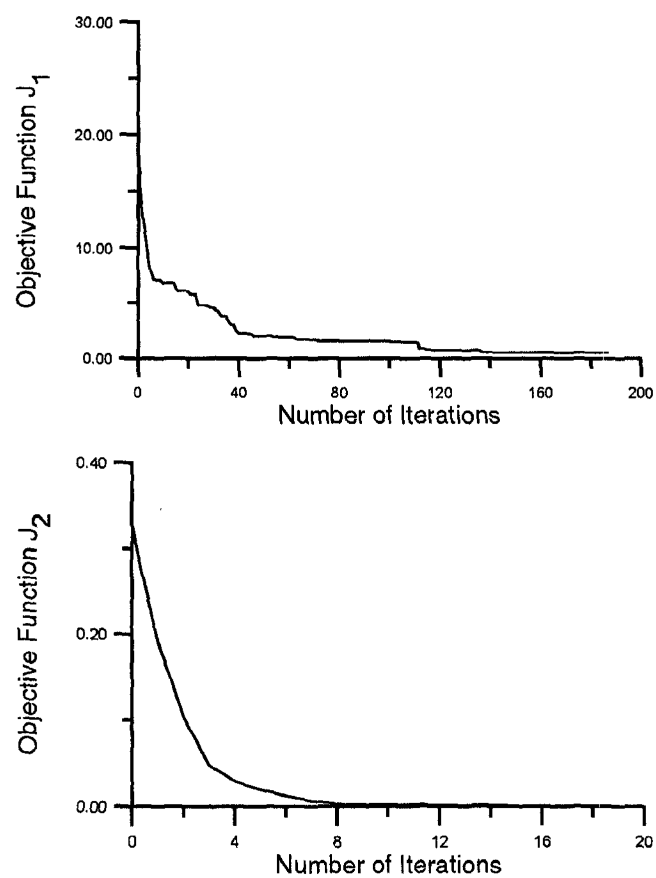

Fig. 2: Objective function variations

C. 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.

Table 1: Eigenvalues and damping ratios with and without PSSs

	Base Case	Case 1	Case 2	Case 3
Without PSSs	**0.191 ±j 5.81, -*0.033***	**0.195 ±j 5.72, -*0.034***	**0.189 ±j 5.81, -*0.033***	**0.205 ±j 5.64, -*0.036***
	0.088 ±j 4.00, -*0.022*	**0.121 ±j 3.80, -*0.032***	**0.006 ±j 3.11, -*0.002***	**0.152 ±j 3.71, -*0.041***
	-0.028 ±j 9.65, *0.003*	**0.097 ±j 6.01, -*0.016***	**0.001 ±j 6.18, -*0.0002***	**0.126 ±j 5.96, -*0.021***
	-0.034 ±j 6.42, *0.005*	-0.032 ±j 9.70, *0.003*	-0.028 ±j 9.65, *0.003*	**0.051 ±j 9.65, -*0.005***
	-0.056 ±j 7.14, *0.008*	-0.104 ±j 8.02, *0.013*	-0.032 ±j 7.11, *0.005*	-0.098 ±j 8.01, *0.012*
	-0.093 ±j 8.12, *0.011*	-0.109 ±j 6.52, *0.017*	-0.091 ±j 8.12, *0.011*	-0.101 ±j 6.51, *0.016*
	-0.172 ±j 9.69, *0.018*	-0.168 ±j 9.72, *0.017*	-0.172 ±j 9.69, *0.018*	-0.167 ±j 9.73, *0.017*
	-0.220 ±j 8.01, *0.027*	-0.204 ±j 8.06, *0.025*	-0.218 ±j 8.02, *0.027*	-0.202 ±j 8.08, *0.025*
	-0.270 ±j 9.34, *0.029*	-0.250 ±j 9.27, *0.027*	-0.269 ±j 9.34, *0.029*	-0.238 ±j 9.30, *0.026*
With Proposed PSSs (J_1 settings)	-2.972 ±j 10.54, *0.271*	-2.923 ±j 10.47, *0.269*	-2.952 ±j 10.48, *0.271*	-2.894 ±j 10.43, *0.267*
	-1.241 ±j 10.46, *0.118*	-0.908 ±j 10.38, *0.087*	-1.237 ±j 10.46, *0.117*	-0.787 ±j 10.30, *0.076*
	-1.266 ±j 9.35, *0.134*	-1.302 ±j 9.39, *0.137*	-1.397 ±j 9.19, *0.150*	-1.300 ±j 9.39, *0.137*
	-2.197 ±j 6.42, *0.263*	-1.916 ±j 8.24, *0.226*	-2.178 ±j 8.19, *0.257*	-1.899 ±j 8.27, *0.224*
	-0.983 ±j 7.96, *0.123*	-1.668 ±j 6.30, *0.256*	-0.989 ±j 8.02, *0.122*	-1.593 ±j 6.19, *0.249*
	-0.977 ±j 6.40, *0.151*	-0.658 ±j 6.10, *0.107*	-0.873 ±j 6.39, *0.135*	-0.653 ±j 5.95, *0.109*
	-1.307 ±j 3.75, *0.329*	-1.303 ±j 3.63, *0.338*	-1.836 ±j 3.58, *0.457*	-1.325 ±j 3.58, *0.347*
	-1.154 ±j 2.74, *0.389*	-1.026 ±j 2.81, *0.343*	-1.742 ±j 2.07, *0.645*	-0.950 ±j 2.85, *0.316*
	-1.587 ±j 2.21, *0.584*	-1.690 ±j 2.20, *0.610*	-0.519 ±j 2.19, *0.230*	-1.745 ±j 2.18, *0.625*
With Proposed PSSs (J_2 settings)	-2.287 ±j 12.37, *0.182*	-2.382 ±j 11.11, *0.210*	-2.278 ±j 12.39, *0.181*	-2.378 ±j 10.99, *0.212*
	-3.495 ±j 9.91, *0.333*	-3.453 ±j 9.92, *0.329*	-3.472 ±j 9.93, *0.330*	-3.427 ±j 9.92, *0.327*
	-2.468 ±j 9.58, *0.249*	-2.471 ±j 9.56, *0.250*	-2.465 ±j 9.59, *0.249*	-2.472 ±j 9.55, *0.251*
	-2.195 ±j 3.21, *0.565*	-2.224 ±j 3.23, *0.568*	-2.206 ±j 3.22, *0.566*	-2.238 ±j 3.24, *0.569*
	-1.910 ±j 2.93, *0.545*	-1.925 ±j 2.95, *0.547*	-1.929 ±j 2.91, *0.553*	-1.932 ±j 2.96, *0.547*
	-0.484 ±j 3.00, *0.159*	-0.466 ±j 3.02, *0.153*	-0.293 ±j 1.93, *0.151*	-0.462 ±j 3.01, *0.152*
	-1.268 ±j 2.63, *0.435*	-1.310 ±j 2.68, *0.439*	-1.269 ±j 2.69, *0.427*	-1.318 ±j 2.70, *0.438*
	-0.618 ±j 1.91, *0.308*	-0.544 ±j 1.88, *0.278*	-0.756 ±j 2.33, *0.308*	-0.563 ±j 1.87, *0.288*
	-0.440 ±j 1.43, *0.294*	-0.418 ±j 1.48, *0.273*	-0.421 ±j 1.41, *0.287*	-0.376 ±j 1.46, *0.249*

(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.

(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 speed-based PSSs with the settings given in [18] where the stabilizers were designed using gradient methods at the same conditions considered in this study. For disturbance (a), the speed deviations of G_3 and G_9 are shown in Fig. 3. 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 stabilize the system with disturbance (b), the proposed PSSs provide good damping characteristics and the system is stable under this sever disturbance as shown in Fig. 4. In addition, the proposed PSSs are quite efficient in damping out the electromechanical modes. This illustrates the superiority of the proposed design approach to get near optimal PSS parameters. The simulation results also show that the performance of the proposed PSSs with J_2 settings is better compared to those with J_1 settings in the sense that the response overshoots and the settling time is significantly reduced.

5. CONCLUSIONS

In this study, the tabu search algorithm is proposed to the robust PSS design problem. The proposed design approach employs TS to search for optimal settings of CPSS parameters. The proposed objective function places simultaneously the electromechanical mode eigenvalues of different operating conditions in prescribed region of *s*-plane. The proposed approach has been applied to a multimachine power system with different loading conditions and system configurations. The eigenvalue analysis reveals the effectiveness of the proposed electrical power-based PSSs to damp out local as well as interarea modes of oscillations. The nonlinear time-domain simulation results show that the proposed PSSs work effectively over a wide range of loading conditions and system configurations.

Table 2: The optimal values of the proposed PSS parameters

Gen	Objective Function J_1			Objective Function J_2		
	k	T_1	T_3	k	T_1	T_3
G_2	1.1133	0.0991	0.3800	2.0630	0.4888	0.1758
G_3	0.4821	0.2283	0.8755	2.5369	0.7719	0.5577
G_4	4.5767	0.2421	0.6128	0.3800	0.6034	0.6912
G_5	0.1261	0.0600	0.2033	0.2228	0.1239	0.1476
G_6	0.6905	0.4908	0.2301	2.0775	0.1400	0.5263
G_7	0.0001	0.1251	0.5628	1.2356	0.0600	0.2435
G_8	1.7365	0.5261	0.8523	0.4889	0.6568	0.8183
G_9	0.0283	0.1869	0.0860	0.1290	0.2331	0.0600
G_{10}	0.5363	1.0000	0.4710	1.9475	0.4245	0.4736

6. ACKNOWLEDGEMENT

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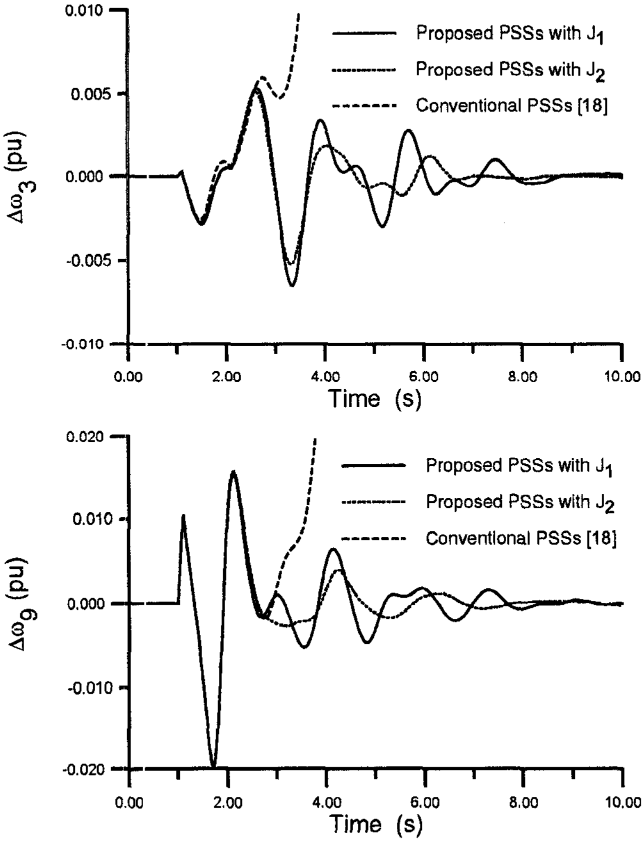

Fig. 3: System response with the disturbance (a)

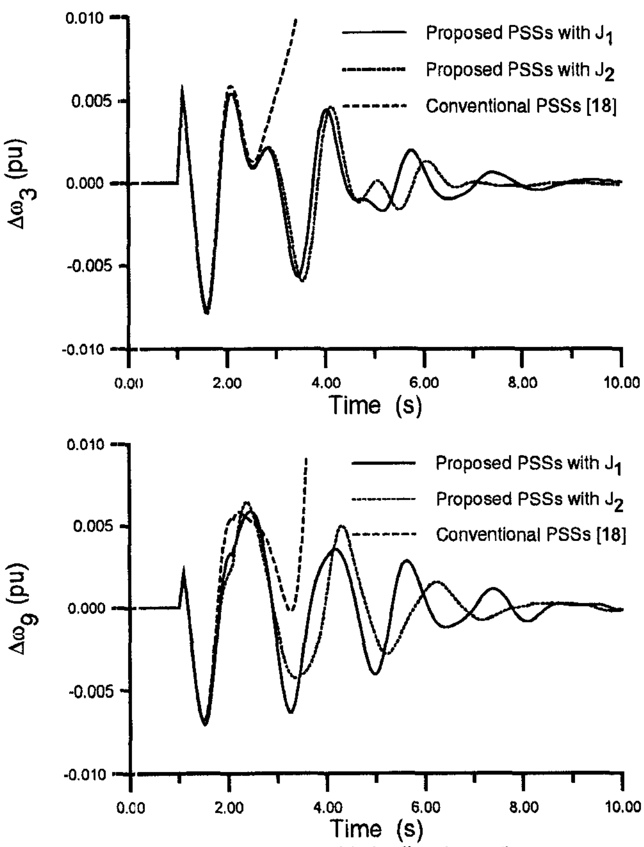

Fig. 4: System response with the disturbance (b)

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