Robust Design of Multimachine Power System Stabilizers Using Simulated Annealing

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***Abstract*—Robust design of multimachine Power System Stabilizers (PSS's) using Simulated Annealing (SA) optimization technique is presented in this paper. The proposed approach employs SA to search for optimal parameter settings of a widely used conventional fixed-structure lead-lag PSS (CPSS). The parameters of the proposed simulated annealing based power system stabilizer (SAPSS) are optimized in order to shift the system electromechanical modes at different loading conditions and system configurations simultaneously to the left in the s-plane. Incorporation of SA as a derivative-free optimization technique in PSS design significantly reduces the computational burden. One of the main advantages of the proposed approach is its robustness to the initial parameter settings. In addition, the quality of the optimal solution does not rely on the initial guess. The performance of the proposed SAPSS under different disturbances and loading conditions is investigated for two multimachine power systems. The eigenvalue analysis and the nonlinear simulation results show the effectiveness of the proposed SAPSS's 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.**

***Index Terms*—Dynamic stability, robust PSS, simulated annealing.**

I. 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]–[20]. 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 [5], [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 PSS's are presented to damp out one of the electromechanical modes at a time [7], [8]. 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 PSS's is avoided in [9], [10]. 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, PSS's should provide some degree of robustness to the variations in system parameters, loading conditions, and configurations.

H_∞ optimization techniques [11], [12] 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 [13]. 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) [14]. 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 [15] 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.* [16] 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 [17] 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 [17], [18]. Genetic algorithm based approach to robust CPSS design is presented in [18]. It is shown that the optimal selection of PSS parameters results in a robust performance of CPSS. However, there exist some

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structural problems in the conventional genetic algorithm such as the premature convergence and duplications among strings as evolution is processing [19]. A gradient procedure for optimization of PSS parameters at different operating conditions is presented in [20]. 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, SA based approach to robust PSS design is proposed in this paper.

SA algorithm [21], [22] is a derivative-free promising algorithm for handling the combinatorial optimization problems. It has been theoretically proved that SA algorithm converges to the optimal solution [21]. In addition, the SA algorithm is robust *i.e.* the final solution quality does not strongly depend on the choice of the initial solution. Another strong feature of SA algorithm is that a complicated mathematical model is not required and the problem constraints can be easily incorporated [21].

In this paper, SA algorithm is proposed to robust PSS design. The problem of robust PSS design is formulated as an optimization problem and SA algorithm is employed to solve this 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 PSS's under different disturbances, loading conditions, and system configurations.

II. 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 PSS's, the linearized incremental models around an equilibrium point are usually employed [23]. Therefore, the state equation of a power system with n machines and m stabilizers can be written as:

$$\Delta\dot{X} = A\Delta X + BU \tag{2}$$

where A is $4n \times 4n$ matrix and equals of $\partial f/\partial X$ 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.

B. PSS Structure

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

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

where

T_w is the washout time constant,

U_i is the PSS output signal at the ith machine, and

$\Delta\omega_t$ 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.

C. Objective Function

To increase the system damping, an eigenvalue based objective function J defined below is considered.

$$J = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} (\sigma - 0 - \sigma_{i,j})^2 \tag{4}$$

where np is the number of operating points considered in the design process. Also, σ_{ij} is the real part of the ith eigenvalue of the jth operating point 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. The condition $\sigma_{ij} \geq \sigma_0$ is imposed on J evaluation to consider only the unstable or poorly damped modes which are mainly belonging to the electromechanical ones. The problem constraints are the CPSS parameter bounds. Therefore, the design problem can be formulated as the following optimization problem.

Minimize

$$J \tag{5}$$

Subject to

$$K_i^{\min} \leq K_i \leq K_i^{\max} \tag{6}$$

$$T_{1i}^{\min} \leq T_{1i} \leq t_{1i}^{\max} \tag{7}$$

$$T_{3i}^{\min} \leq T_{3i} \leq T_{3i}^{\max} \tag{8}$$

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

III. Simulated Annealing Algorithm

A. Overview

Simulated annealing is a derivative-free optimization technique that simulates the physical annealing process in the field of combinatorial optimization. Annealing is the physical process of heating up a solid until it melts, followed by slow cooling it down by decreasing the temperature of the environment in steps. At each step, the temperature is maintained constant for a period of time sufficient for the solid to reach thermal equilibrium. At any temperature T, the thermal equilibrium state is characterized by the *Boltzmann distribution*. This distribution gives the probability of the solid being in a state i with energy E_i at temperature T as

$$P_i = k \exp(-E_i/T) \tag{9}$$

where k is a constant.

Metropolis *et al.* [22] proposed a *Monte Carlo* method to simulate the process of reaching thermal equilibrium at a fixed value of the temperature T. In this method, a randomly generated perturbation of the current configuration of the solid is applied so that a trial configuration is obtained. Let E_c and E_t denote the energy level of the current and trial configurations respectively. If $E_t < E_c$, then a lower energy level has been reached, and the trial configuration is accepted and becomes the current configuration. On the other hand, if $E_t \geq E_c$ the trial configuration is accepted as current configuration with probability proportional to exp $(-\Delta E/T)$, $\Delta E = E_t - E_c$. The process continues until the thermal equilibrium is achieved after a large number of perturbations, where the probability of a configuration approaches *Boltzmann distribution*.

By gradually decreasing the temperature T and repeating Metropolis simulation, new lower energy levels become achievable. As T approaches *zero* least energy configurations will have a positive probability of occurring.

B. SA Algorithm

At first, the analogy between a physical annealing process and a combinatorial optimization problem is based on the following [21]:

- Solutions in an optimization problem are equivalent to configurations of a physical system.
- The cost of a solution is equivalent to the energy of a configuration.

In addition, a control parameter C_p is introduced to play the role of the temperature T. The basic elements of SA are briefly stated and defined as follows:—

- ***Current, trial, and best solutions,*** $x_{\text{current}}, x_{\text{trial}}$, and x_{best}: these solutions are sets of the optimized parameter values at any iteration.
- ***Acceptance criterion***: at any iteration, the trial solution can be accepted as the current solution if it meets one of the following criteria; a) $J(x_{\text{trial}}) < J(x_{\text{current}})$; b) $J(x_{\text{trial}}) > J(x_{\text{current}})$ and exp$(-(J(x_{\text{trial}}) - J(x_{\text{current}}))/Cp) \geq$ rand(0, 1). Here, rand(0, 1) is a random number with domain [0, 1] and $J(x_{\text{trial}})$ and $J(x_{\text{current}})$ are the objective function values associated with x_{trial} and x_{current} respectively. Criterion b) indicates that the trial solution is not necessarily rejected if its objective function is not as good as that of the current solution with hoping that a much better solution become reachable.
- ***Acceptance ratio***: at a given value of C_p, an n_1 trial solutions can be randomly generated. Based on the acceptance criterion, an n_2 of these solutions can be accepted. The acceptance ratio is defined as n_2/n_1.
- ***Cooling schedule***: it specifies a set of parameters that governs the convergence of the algorithm. This set includes an initial value of control parameter C_{p0}, a decrement function for decreasing the value of C_p, and a finite number of iterations or transitions at each value of C_p *i.e.* the length of each homogeneous *Markov chain*. The initial value of C_p should be large enough to allow virtually all transitions to be accepted. However, this can be achieved by starting off at a small value of C_{p0} and multiplying it with a constant α larger than 1, *i.e.* $C_{p0} = \alpha C_{p0}$. This process continues until the acceptance ratio is close to 1. This is equivalent to heating up process in physical systems. The decrement function for decreasing the value of C_p is given by $C_p = \mu C_p$ where μ is a constant smaller than but close to 1. Typical values lie between 0.8–0.99 [21].
- ***Equilibrium condition***: it occurs when the current solution does not change for a certain number of iterations at a given value of C_p. It can be achieved by generating a large number of transitions at that value.
- ***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 *Markov chains* since the last change of the best solution is greater than a prespecified number; or, b) the number of *Markov chains* reaches the maximum allowable number.

The general algorithm of SA can be described in steps as follows:

Step 1) Set the initial value of C_{p0} and randomly generate an initial solution x_{initial} and calculate its objective function. Set this solution as the current solution as well as the best solution, *i.e.* $x_{\text{initial}} = x_{\text{current}} = x_{\text{best}}$.

Step 2) Randomly generate an n_1 of trial solutions in the neighborhood of the current solution.

Step 3) Check the acceptance criterion of these trial solutions and calculate the acceptance ratio. If acceptance ratio is close to 1 go to step 4; else set $C_{po} = \alpha C_{p0}$, $\alpha > 1$, and go back to step 2.

Step 4) Set the chain counter $k_{ch} = 0$.

Step 5) Generate a trial solution x_{trial}. If x_{trial} satisfies the acceptance criterion set $x_{\text{current}} = x_{\text{trial}}, J(x_{\text{current}}) = J(x_{\text{trial}})$, and go to step 6; else go to step 6.

Step 6) Check the equilibrium condition. If it is satisfied go to step 7; else go to step 5.

Step 7) Check the stopping criteria. If one of them is satisfied then stop; else set $k_{ch} = k_{ch} + l$ and $C_p = \mu C_p$, $\mu < 1$, and go back to Step 5.

C. Application of SA to Robust PSS Design

In the proposed SAPSS 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 above-described SA algorithm is excited by generating randomly initial values of the CPSS 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

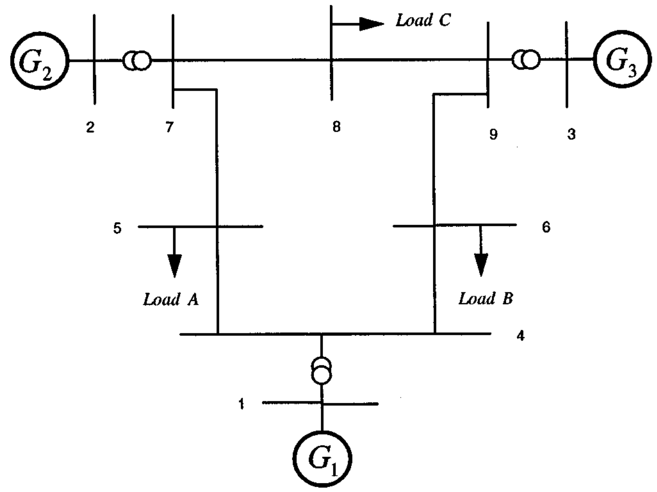

Fig. 1. Three-machine nine-bus power system.

TABLE I
GENERATOR OPERATING CONDITIONS OF EXAMPLE 1

Gen	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 II
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

search if the objective function value reaches *zero, i.e.,* all the dominant eigenvalues are completely shifted to the left of $s = \sigma_0$ line.

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 left of $s = \sigma_0$ line in the s-plane.

IV. EXAMPLE 1: THREE MACHINE POWER SYSTEM

A. 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 [23]. The participation factor method [24] and the sensitivity of PSS effect method [25] were used to identify the optimum locations of PSS's. The results of both methods indicate that G_2 and G_3 are the optimum locations for installing PSS's.

B. PSS Design

To design the proposed SAPSS, four operating cases are considered. The generator operating conditions and the loads at these cases are given in Tables I and II respectively. The system eigenvalues without PSS's are given in Table III. It is clear that the electromechanical modes are poorly damped and some of them are unstable. 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 s, 0.05 s, and 0.05 s respectively. Here σ_0 is chosen to be 3.0. SA algorithm has been applied to search for the optimized parameter settings so as to shift simultaneously the eigenvalues associated with electromechanical modes of the four cases to the left of the line $s = -3.0$ in the s-plane.

TABLE III
EIGENVALUES OF EXAMPLE 1 WITHOUT PSSS

Base Case	Case 1	Case 2	Case 3
-0.01 ±*j* 9.07	-0.02±*j* 8.91	-0.30 ±*j* 8.95	**0.38 ±*j* 8.87**
-0.78 ±*j* 13.86	-0.52 ±*j* 13.83	-0.84 ±*j* 13.72	-0.34 ±*j* 13.69
-10.28 ±*j* 11.95	-10.16 ±*j* 12.15	-10.07 ±*j* 12.97	-10.73 ±*j* 11.68
-10.05 ±*j* 6.78	-10.18 ±*j* 7.09	-9.99 ±*j* 7.38	-10.08 ±*j* 7.20
-11.12, -8.37	-10.01 ±*j* 3.45	-9.66 ±*j* 4.49	-10.12 ±*j* 3.12
-0.09	-0.09	-0.09	-0.09

TABLE IV
THE OPTIMAL VALUES OF THE PROPOSED SAPSS PARAMETERS FOR EXAMPLE 1

Gen#	k	T_1	T_3
G_2	11.008	0.216	0.104
G_3	0.319	0.410	0.233

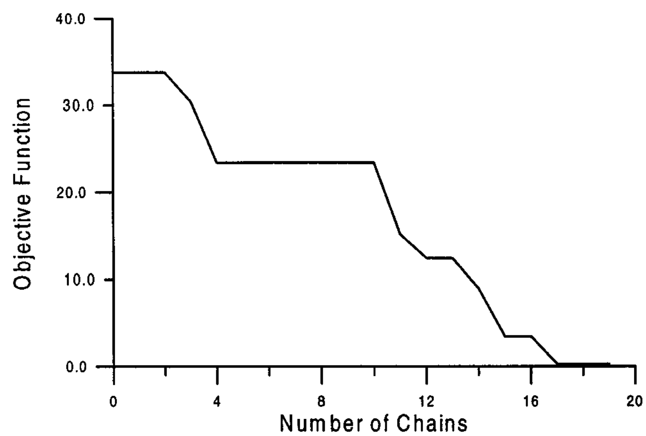

Fig. 2. Objective function variations of example 1.

The final values of the optimized parameters are given in Table IV. The convergence rate of the objective function J with the number of chains is shown in Fig. 2. With the optimal values of the proposed SAPSS's, the system eigenvalues are given in Table V. It is quite clear that the system eigenvalues associated with the electromechanical modes have been successfully shifted to the left of $s = -3$ line with the proposed SAPSS's. This demonstrates that the system damping with the proposed SAPSS's is greatly enhanced.

C. Nonlinear Time-Domain Simulation

To demonstrate the effectiveness of the proposed SAPSS's over a wide range of loading conditions, two different disturbances are considered as follows.

TABLE V
EIGENVALUES OF EXAMPLE 1 WITH THE PROPOSED SAPSSS

Base Case	*Case 1*	*Case 2*	*Case 2*
-3.00 ±*j* 19.32	-3.26 ±*j* 19.42	-3.69 ±*j* 17.80	-3.11 ±*j* 19.13
-4.50 ±*j* 6.81	-3.00 ±*j* 7.11	-3.58 ±*j* 8.09	-3.57 ±*j* 7.33
-6.66 ±*j* 12.28	-5.10 ±*j* 12.93	-6.80 ±*j* 13.23	-7.50 ±*j* 12.08
-4.04 ±*j* 9.98	-5.88 ±*j* 9.96	-4.35 ±*j* 9.20	-3.22 ±*j* 10.24
-10.18 ±*j* 7.40	-10.22 ±*j* 7.68	-10.07 ±*j* 7.66	-10.13 ±*j* 7.63
-36.20, -28.87	-36.27, -29.20	-33.99, -27.53	-36.15, -29.23
-11.80, -7.85	-11.74, -9.19	-12.94, -10.10	-11.91, -9.03
-0.56, -0.20	-0.76, -0.20	-0.42, -0.20	-0.64, -0.20
-0.03	-0.02	-0.04	-0.03

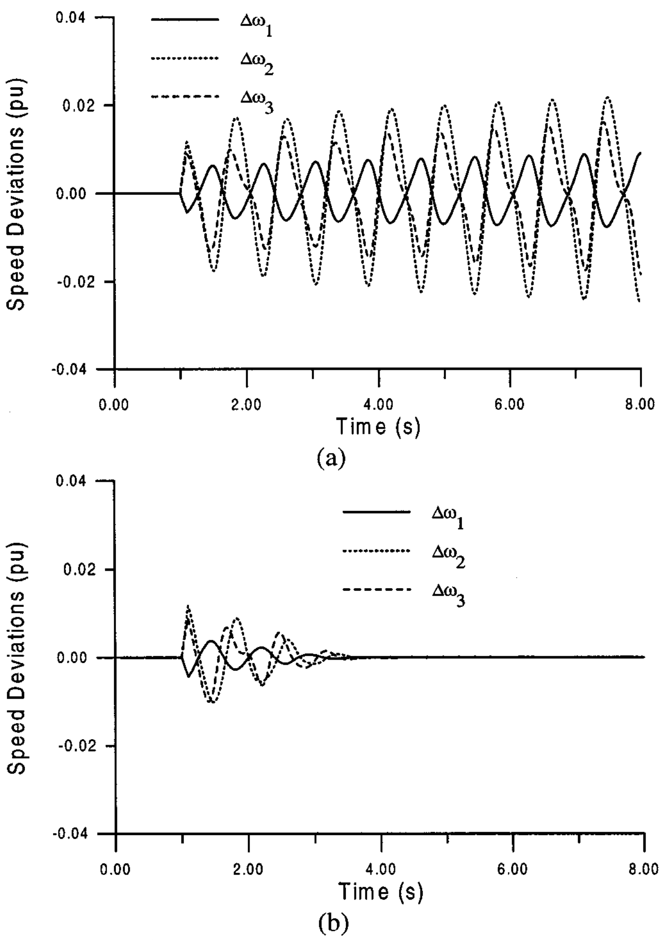

Fig. 3. System response of example 1 with disturbance (a) (a) Without PSS's, (b) With the proposed SAPSSs.

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 1.0 s

The system responses to the considered faults with and without the proposed SAPSS's are shown in Figs. 3 and 4 respectively. It is clear that the proposed SAPSS's provide good damping characteristics to low frequency oscillations and enhance greatly the dynamic stability of power systems.

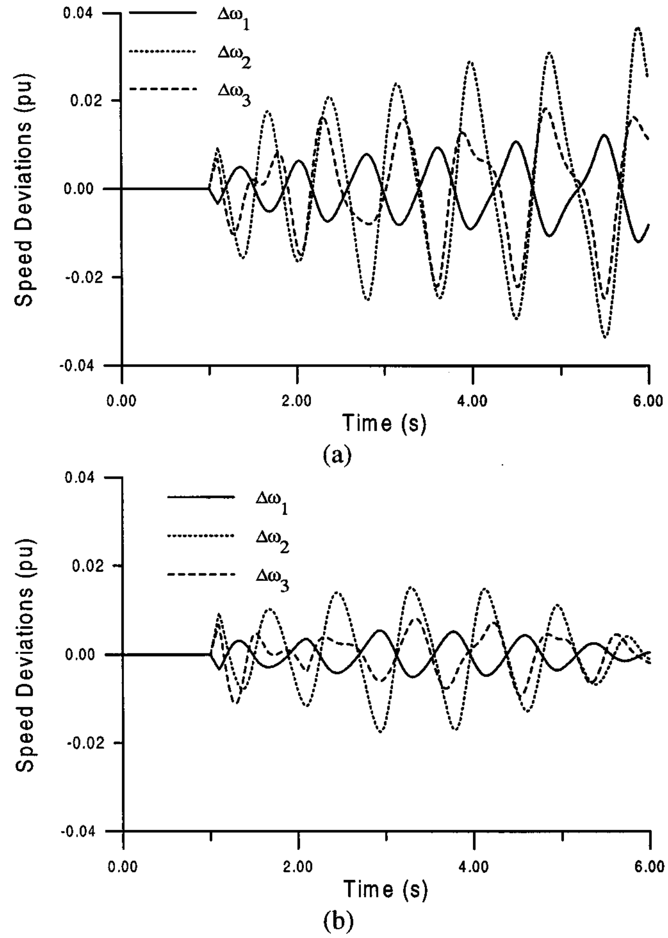

Fig. 4. System response of example 1 with the disturbance (b) (a) Without PSS's (b) With the proposed SAPSSs.

V. EXAMPLE 2: NEW ENGLAND POWER SYSTEM

A. Test System

In this example, the 10-machine 39-bus New England power system shown in Fig. 5 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 [26]. Although, the number and location of PSS's required can be investigated [24], [25], it is assumed that all generators except G_1 are equipped with PSS's for illustration and comparison purposes.

B. PSS Design

To design the proposed SAPSS, 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 hard from the stability point of view [27]. They can be described as

1) Base Case;
2) Case 1; outage of line 21–22;
3) Case 2; outage of line 1–38.
4) Case 3; outage of line 21–22, 25% increase in loads at buses 16 and 21, and 25% increase in generation of G_7.

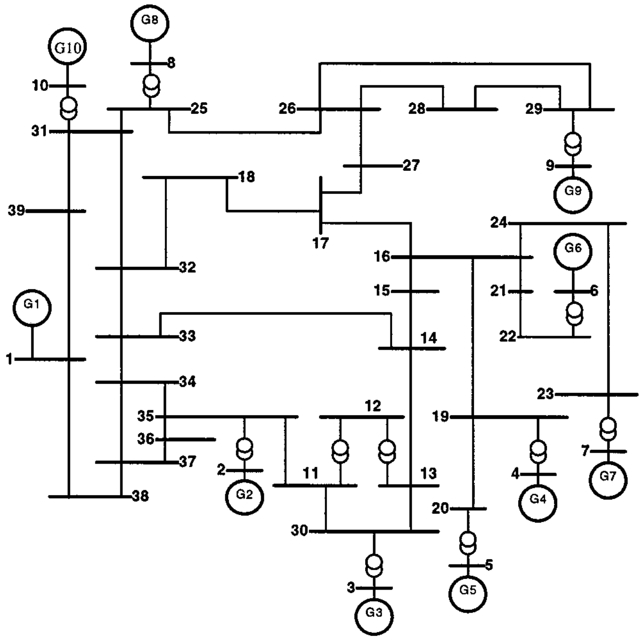

Fig. 5. Single line diagram for New England system.

TABLE VI
EIGENVALUES OF EXAMPLE 2 WITHOUT PSSS

Base Case	*Case 1*	*Case 2*	*Case 3*
0.191 ±j 5.808	**0.195 ±j 5.716**	**0.189 ±j 5.811**	**0.205 ±j 5.638**
0.088 ±j 4.002	**0.121 ±j 3.798**	**0.006 ±j 3.113**	**0.152 ±j 3.714**
-0.028 ±j 9.649	**0.097 ±j 6.006**	**0.001 ±j 6.180**	**0.126 ±j 5.964**
-0.034 ±j 6.415	-0.032 ±j 9.694	-0.028 ±j 9.650	**0.051 ±j 9.648**
-0.056 ±j 7.135	-0.104 ±j 8.015	-0.032 ±j 7.105	-0.098 ±j 8.013
-0.093 ±j 8.117	-0.109 ±j 6.515	-0.091 ±j 8.115	-0.101 ±j 6.512
-0.172 ±j 9.692	-0.168 ±j 9.715	-0.172 ±j 9.693	-0.167 ±j 9.727
-0.220 ±j 8.013	-0.204 ±j 8.058	-0.218 ±j 8.024	-0.202 ±j 8.079
-0.270 ±j 9.341	-0.250 ±j 9,268	-0.269 ±j 9.342	-0.238 ±j 9.296

The electromechanical modes without PSS's for these conditions are given in Table VI. It is clear that these modes are poorly damped and some of them are unstable. In this example, the optimized parameters are K_i, T_{1i}, and T_{3i}, $i = 2, 3, \cdots, 10$, *i.e.*, the number of optimized parameters is 27. T_w, T_2, and T_4 are set to be 5 s, 0.05 s, and 0.05 s respectively. Here σ_0 is chosen to be -1.0. SA algorithm has been applied to search for settings of these parameters so as to shift the eigenvalues of electromechanical modes of the four cases to the left of the line $s = -1.0$ in the s-plane.

The final values of the optimized parameters are given in Table VII. The convergence rate of the objective function J with the number of chains is shown in Fig. 6. With the optimal values of the proposed SAPSS's, the system eigenvalues are given in Table VIII. It is quite clear that that the system eigenvalues associated with the electromechanical modes have been successfully shifted to the left of $s = -1.0$ line with the proposed SAPSS's. This demonstrates that the system damping with the proposed SAPSS's is greatly improved.

TABLE VII
THE OPTIMAL VALUES OF THE PROPOSED SAPSS PARAMETERS FOR EXAMPLE 2

Gen.	*k*	T_1	T_3
G_2	26.963	0.399	0.880
G_3	15.733	0.650	0.826
G_4	26.842	0.425	0.966
G_5	43.727	0.102	0.427
G_6	18.260	0.974	0.393
G_7	2.737	0.460	0.202
G_8	30.278	0.734	0.743
G_9	18.732	0.171	0.337
G_{10}	26.598	0.945	0.871

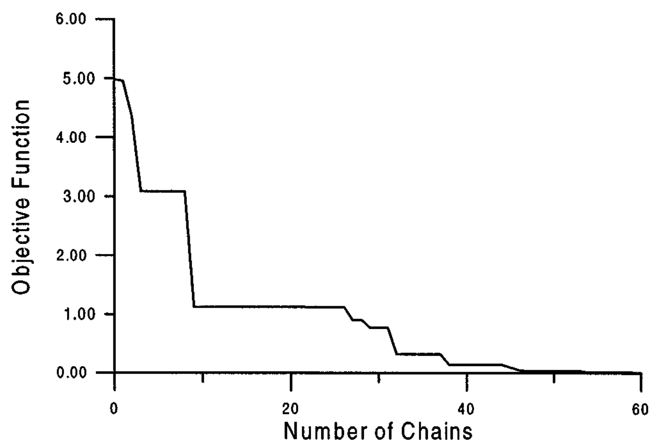

Fig. 6. Objective function variations of example 2.

TABLE VIII
EIGENVALUES OF EXAMPLE 2 WITH THE PROPOSED SAPSSS

Base Case	*Case 1*	*Case 2*	*Case 3*
-1.697 ±j 14.51	-1.705 ±j 14.44	-1.698 ±j 14.51	-1.709 ±j 14.40
-1.321 ±j 11.37	-1.294 ±j 11.36	-1.319 ±j 11.37	-1.279 ±j 11.35
-1.341 ±j 10.33	-1.386 ±j 10.10	-1.338 ±j 10.33	-1.350 ±j 10.11
-1.559 ±j 9.796	-1.481 ±j 9.810	-1.555 ±j 9.794	-1.423 ±j 9.751
-1.071 ±j 9.121	-1.090 ±j 9.071	-1.059 ±j 9.121	-1.071 ±j 9.079
-1.087 ±j 9.050	-1.188 ±j 9.017	-1.076 ±j 9.043	-1.190 ±j 8.998
-1.115 ±j 7.585	-1.282 ±j 6.977	-1.103 ±j 7.370	-1.301 ±j 6.936
-1.931 ±j 5.064	-1.237 ±j 4.420	-1.485 ±j 2.202	-1.157 ±j 4.089
-1.342 ±j 3.483	-1.247 ±j 3.578	-1.003 ±j 2.278	-1.163 ±j 3.723

C. Nonlinear Time-Domain Simulation

To demonstrate the effectiveness of the proposed SAPSS's 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.
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 1.0 s.

The performance of the proposed SAPSS's is compared to that of PSS's with the settings given in [20]. For disturbance (a), the speed deviation of G_9, as the nearest generator to the fault location, is shown in Fig. 7. It is clear that the system response with the proposed SAPSS's is stable while with PSS's of [20] the system is unstable. Additionally, PSS's of [20] fail to

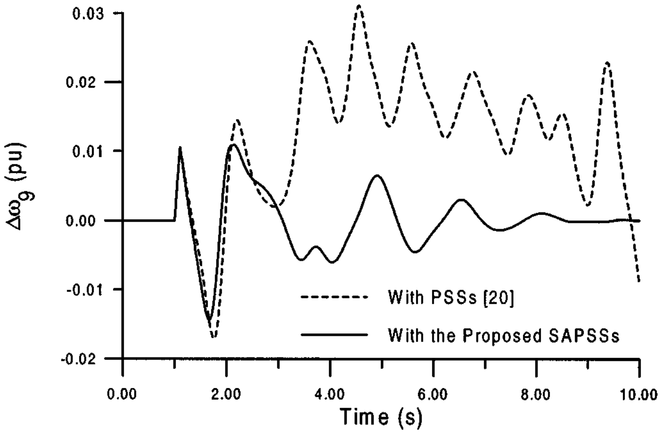

Fig. 7. System response of example 2 with the disturbance (a).

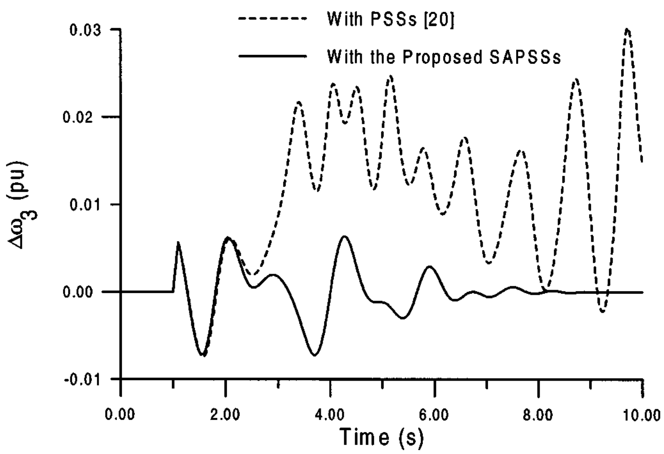

Fig. 8. System response of example 2 with the disturbance (b).

stabilize the system with disturbance b), the proposed SAPSS's provide good damping characteristics and the system is stable under this sever disturbance as shown in Fig. 8. In addition, the proposed PSS's are quite efficient to damp out the local modes as well as the interarea modes of oscillations. This illustrates the superiority of the proposed SAPSS design approach to get optimal or near optimal PSS parameters.

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

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

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

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 IX. It is clear that the values of these indices with the proposed SAPSS's are much smaller. This demonstrates that the settling time and the speed deviations of all units are much reduced by applying the proposed SAPSS's.

TABLE IX
VALUES OF PERFORMANCE INDICES FOR EXAMPLE 2

Fault	PI_1		PI_2	
	PSS [20]	Prop. SAPSS	PSS [20]	Prop. SAPSS
a	**4964**	94.84	**191.8**	9.77
b	**4944**	51.24	**163.6**	7.35

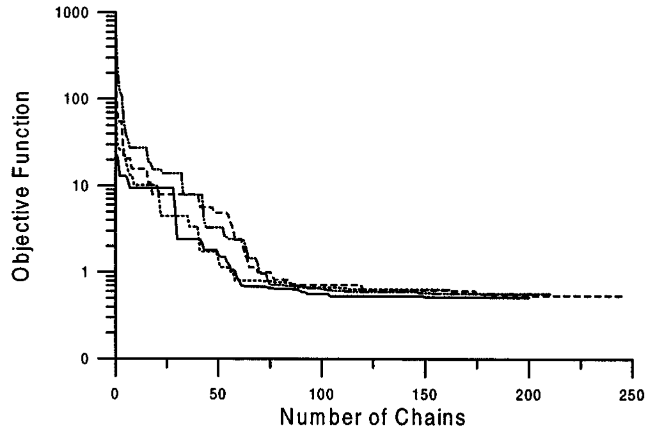

Fig. 9. Objective function values with different initial solutions.

VI. Discussion

Some comments on the proposed approach are now in order:

a) Unlike the methods of [7]–[10], the proposed SA based approach does not rely on the initial solution. Starting anywhere in the search space, SA algorithm ensures the convergence to the optimal solution. Example 2 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. 9. The results emphasize that the proposed approach finally leads to the optimal PSS parameter settings regardless 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 [5]–[10], [18], and [20].

c) To study the effect of the initial parameter settings of the SA algorithm on the optimal solution quality, the problem has been solved several times with different initial values of the control parameter C_p. The results of this study are shown in Fig. 10. It is clear that the proposed approach is robust to its initial parameter settings.

VII. Conclusion

In this study, the simulated annealing algorithm is proposed to the robust PSS design problem. The proposed design approach employs SA 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

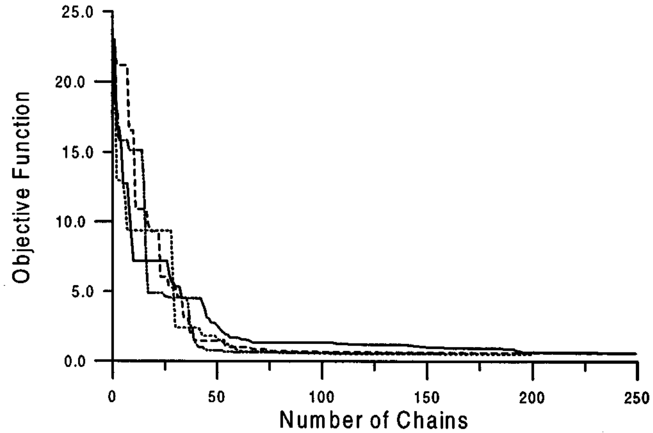

Fig. 10. Objective function values with different initial values of control parameter.

been applied to two different examples of multimachine power systems with different loading conditions and system configurations. The main features of the proposed approach can be summarized as:—

1) 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 optimization methods.
2) The proposed approach is robust to its initial parameter settings.
3) Since eigenvector calculations and sensitivity analysis are not required to evaluate the proposed objective function, heavy computations of the design process are avoided.
4) The eigenvalue analysis reveals the effectiveness of the proposed SAPSS's to damp out local as well as interarea modes of oscillations.
5) The nonlinear time-domain simulation results show that the proposed SAPSS's work effectively over a wide range of loading conditions and system configurations.

REFERENCES

[1] F. P. deMello and C. Concordia, "Concepts of synchronous machine stability as affected by excitation control," *IEEE Trans. PAS*, vol. 88, pp. 316–329, 1969.
[2] D. Xia and G. T. Heydt, "Self-tuning controller for generator excitation control," *IEEE Trans. PAS*, vol. 102, pp. 1877–1885, 1983.
[3] V. Samarasinghe and N. Pahalawaththa, "Damping of multimodal oscillations in power systems using variable structure control techniques," *IEE Proc. Genet. Transm. Distrib.*, vol. 144, no. 3, pp. 323–331, Jan. 1997.
[4] M. A. Abido and Y. L. Abdel-Magid, "Hybridizing rule-based power system stabilizers with genetic algorithms," in *IEEE PES Summer Meeting*, Paper # PE-097-PWRS-0-05-1998.
[5] E. Larsen and D. Swarm, "Applying power system stabilizers," *IEEE Trans. PAS*, vol. 100, no. 6, pp. 3017–3046, 1981.
[6] G. T. Tse and S. K. Tso, "Refinement of conventional PSS design in multimachine system by modal analysis," *IEEE Trans. PWRS*, vol. 8, no. 2, pp. 598–605, 1993.
[7] R. J. Fleming, M. A. Mohan, and K. Parvatism, "Selection of parameters of stabilizers in multimachine power systems," *IEEE Trans. PAS*, vol. 100, no. 5, pp. 2329–2333, 1981.
[8] J. M. Arredondo, "Results of a study on location and tuning of power system stabilizers," *Int. J. Electrical Power & Energy Systems*, vol. 19, no. 8, pp. 563–567, 1997.
[9] C. M. Lim and S. Elangovan, "Design of stabilizers in multimachine power systems," *IEE Proc.*, pt. C, vol. 132, no. 3, pp. 146–153, 1985.
[10] C. L. Chen and Y. Y. Hsu, "Coordinated synthesis of multimachine power system stabilizer using an efficient decentralized modal control (DMC) algorithm," *IEEE Trans. PWRS*, vol. 2, no. 3, pp. 543–551, 1987.
[11] T. C. Yang, "Applying H_∞ optimization method to power system stabilizer design—Parts 1 & 2," *Int. J. Electrical Power & Energy Systems*, vol. 19, no. 1, pp. 29–43, 1997.
[12] R. Asgharian, "A robust H_∞ power system stabilizer with no adverse effect on shaft torsional modes," *IEEE Trans. on Energy Conversion*, vol. 9, no. 3, pp. 475–481, 1994.
[13] M. Vidyasagar and H. Kimura, "Robust controllers for uncertain linear multivariable systems," *Automatica*, vol. 22, no. 1, pp. 85–94, 1986.
[14] H. Kwakernaak, "Robust control and H_∞ optimization-tutorial," *Automatica*, vol. 29, no. 2, pp. 255–273, 1993.
[15] T. C. Yang, "A new decentralised stabilization approach with application to power system stabilizer design," in *IFAC/IFORS/IMACS Symp. Large Scale Systems*, 1995.
[16] P. Kundur, M. Klein, G. J. Rogers, and M. S. Zywno, "Application of power system stabilizers for enhancement of overall system stability," *IEEE Trans. PWRS*, vol. 4, no. 2, pp. 614–626, 1989.
[17] M. J. Gibbard, "Robust design of fixed-parameter power system stabilizers over a wide range of operating conditions," *IEEE Trans. PWRS*, vol. 6, no. 2, pp. 794–800, 1991.
[18] Y. L. Abdel-Magid, M. A. Abido, S. Al-Baiyat, and A. H. Mantawy, "Simultaneous stabilization of multimachine power systems via genetic algorithms," in *IEEE PES*, Paper # 98 SM 322.
[19] J. C. Potts, T. D. Giddens, and S. B. Yadav, "The development and evaluation of an improved genetic algorithm based on migiration and artificial selection," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 24, no. 1, pp. 73–86, 1994.
[20] V. A. Maslennikov and S. M. Ustinov, "The optimization method for coordinated tuning of power system regulators," in *Proc. 12th Power System Computation Conference PSCC*, Dresden, 1996, pp. 70–75.
[21] E. Aarts and J. Korst, *Simulated Annealing and Boltzmann Machines: A Stochastic Approach to Combinatorial Optimization and Neural Computing*: John Wiley & Sons, 1989.
[22] N. Metropolis, A. Rosenbluth, M. Rosenbluth, A. Teller, and E. Teller, "Equation of state calculations by fast computing machines," *Journal of Chemical Physics*, vol. 21, pp. 1087–1092, 1953.
[23] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*. Ames, IA, USA: Iowa State Univ. Press, 1977.
[24] Y. Y. Hsu and C. L. Chen, "Identification of optimum location for stabilizer applications using participation factors," *IEE Proc.*, pt. C, vol. 134, no. 3, pp. 238–244, May 1987.
[25] E. Z. Zhou, O. P. Malik, and G. S. Hope, "Theory and method for selection of power system stabilizer location," *IEEE Trans. on Energy Conversion*, vol. 6, no. 1, pp. 170–176, 1991.
[26] M. A. Pai, *Energy Function Analysis for Power System Stability*: Kluwer Academic Publishers, 1989.
[27] A. Bazanella, A. Fischman, A. Silva, J. Dion, and L. Dugrad, "Coordinated robust controllers in power systems," in *IEEE Stockholm Power Tech Conference*, 1995, pp. 256–261.

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