Optimal Multiobjective Design of Robust Power System Stabilizers Using Genetic Algorithms

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***Abstract*—Optimal multiobjective design of robust multimachine power system stabilizers (PSSs) using genetic algorithms is presented in this paper. A conventional speed-based lead-lag PSS is used in this work. The multimachine power system operating at various loading conditions and system configurations is treated as a finite set of plants. The stabilizers are tuned to simultaneously shift the lightly damped and undamped electromechanical modes of all plants to a prescribed zone in the s-plane. A multiobjective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of the lightly damped electromechanical modes. The problem of robustly selecting the parameters of the power system stabilizers is converted to an optimization problem which is solved by a genetic algorithm with the eigenvalue-based multiobjective function. The effectiveness of the suggested technique in damping local and interarea modes of oscillations in multimachine power systems, over a wide range of loading conditions and system configurations, is confirmed through eigenvalue analysis and nonlinear simulation results.**

***Index Terms*—Dynamic stability, genetic algorithms, multiple objective optimization, robustness, simultaneous stabilization.**

I. Introduction

THE EMPLOYMENT of power system stabilizers for improving the dynamic stability of power systems has received increasing interest during the past two decades [1]–[19]. Presently, the conventional lead-lag power system stabilizer is widely used by power system utilities. Recently, several approaches based on modern control theory have been applied to the PSS design problem. These include optimal, adaptive, variable structure, and intelligent control [2]–[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 online 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] and [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.

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 cannot treat situations where a nominal stable system becomes unstable after being perturbed [12]. Moreover, the pole-zero cancellation phenomenon associated with this approach produces closed loop poles whose damping is directly dependent on the open loop system (nominal system) [13]. On the other hand, the order of the H_∞-based 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 online 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. A gradient procedure for optimization of PSS parameters at different operating conditions is presented in [17]. 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.

A genetic algorithm (GA)-based approach [20]–[23] to robust PSS design, in which several operating conditions and system configurations are simultaneously considered in the design process, is presented in [18] and [19]. The advantage of the GA technique is that it is independent of the complexity of the performance index considered. It suffices to specify the objective function and to place finite bounds on the optimized parameters. In [19], the robust PSS design was formulated as a single objective function problem, and not all PSS parameters were considered adjustable.

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However, in practice, one is typically confronted with multiple objective functions [24], [25] and these objective functions are generally of diverse natures. In this paper, the problem of robust PSS design is formulated as a multiobjective optimization problem and GA is employed to solve this problem. Moreover, unlike [19], all PSS parameters were considered adjustable, and more severe disturbances were used to assess the potential of the multiobjective approach. Robustness is achieved by considering several operating conditions and system configurations simultaneously. The multiobjective problem is concocted to optimize a composite set of two eigenvalue-based objective functions comprising the desired damping factor, and the desired damping ratio of the lightly damped and undamped electromechanical modes. The use of the first objective function will result in PSSs that shift the lightly damped and undamped electromechanical modes to the left-hand side of a vertical line in the complex s-plane; hence, improving the damping factor. The use of the second objective function will yield PSSs' settings that place these modes in a wedge-shape sector in the complex s-plane, thus improving the damping ratio of these modes. Consequently, the use of the multiobjective function will therefore guarantee that the relative stability, and the time domain specifications are concurrently secured.

The proposed design approach has been applied to a multimachine power system. 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.

II. Problem Statement

A. Power System Model

Consider the problem of determining the parameters of a power system stabilizer that relatively stabilize a family of N plants simultaneously (representing the power system operating at various conditions)

$$\dot{X}(t) = A_k X(t) + B_k U(t); \qquad k = 1, 2, \ldots, N \quad (1)$$

where $X(t) \in R^n$ is the state vector and $U(t) \in R^m$ is the supplementary stabilizing signals.

In this study, $X = [\delta, \omega, E'_q, E_{fd}]$, where δ and ω are the rotor angle and speed, respectively, and E'_q and E_{fd} are the internal voltage, and the field voltage, respectively.

B. PSS Structure

A widely used speed-based conventional PSS is considered throughout the study. The transfer function of the ith PSS is

$$U_i(s) = K_i \frac{sT_{wi}}{1 + sT_{wi}} \left[\frac{(1 + sT_{1i})(1 + sT_{3i})}{(1 + sT_{2i})(1 + sT_{4i})}\right] \Delta\omega_i(s). \quad (2)$$

The first term in (2) is a washout term with a time lag T_w. The second term is a lead compensation to improve the phase lag through the system. The parameters T_w is assumed fixed in the study.

The remaining parameters, namely, K_i, T_{1i}, T_{2i}, T_{3i}, and T_{4i} are assumed to be adjustable parameters. The optimization problem, namely, the selection of these PSS parameters, is solved using GAs. For a given operating point, the multimachine power system is linearized around the operating point, the eigenvalues of the closed-loop system are computed, and the objective function is evaluated using only the unstable and lightly damped eigenvalues that need to be shifted.

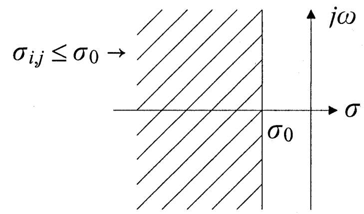

Fig. 1. Region in the left-side of the s-plane where $\sigma_{i,j} \leq \sigma_0$.

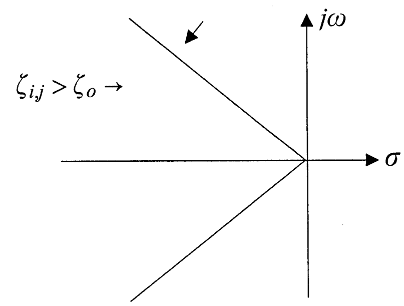

Fig. 2. A wedge-shape sector in the s-plane where $\zeta_{i,j} \geq \zeta_0$.

C. Objective Functions

1) To have some degree of relative stability. The parameters of the PSS may be selected to minimize the following objective function:

$$J_1 = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 \quad (3)$$

where np is the number of operating points considered in the design process, and $\sigma_{i,j}$ is the real part of the ith eigenvalue of the jth operating point, subject to the constraints that finite bounds are placed on the power system stabilizer parameters. The relative stability is determined by the value of σ_0. This will place the closed-loop eigenvalues in a sector in which $\sigma_{i,j} \leq \sigma_0$ as shown in Fig. 1.

2) To limit the maximum overshoot, the parameters of the PSS may be selected to minimize the following objective function:

$$J_2 = \sum_{j=1}^{np} \sum_{\zeta_{i,j} \leq \zeta_0} \{\zeta_0 - \zeta_{i,j}\}^2 \quad (4)$$

where $\zeta_{i,j}$ is the damping ratio of the ith eigenvalue of the jth operating point. This will place the closed-loop eigenvalues in a wedge-shape sector in which $\zeta_{i,j} \geq \zeta_0$ as shown in Fig. 2.

3) The single objective problems described may be converted to a multiple objective problem by assigning

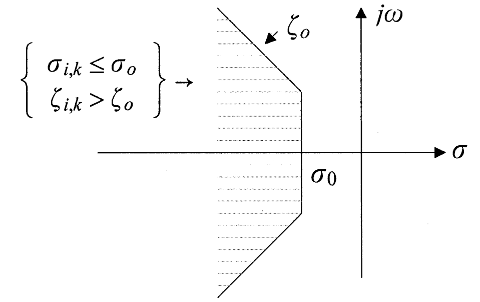

Fig. 3. A D-shape sector in the s-plane where $\zeta_{i,\,j} \ge \zeta_0$ and $\sigma_{i,\,k} \le \sigma_o$.

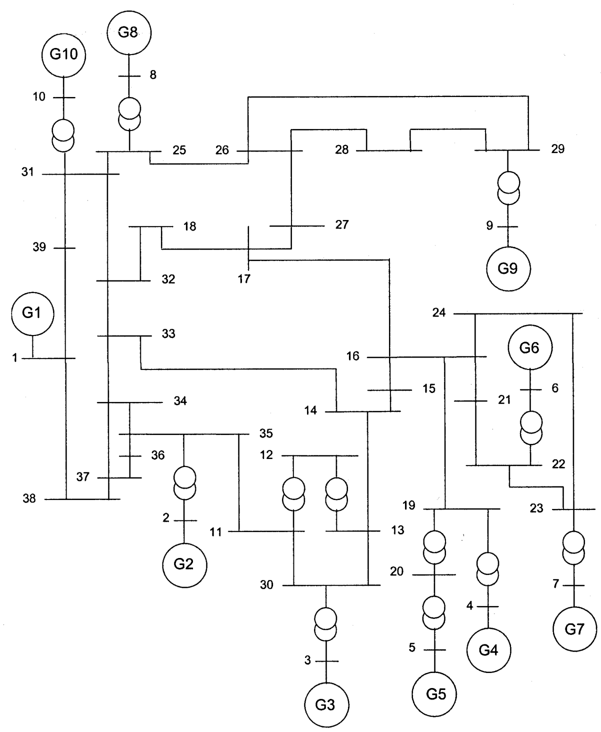

Fig. 4. Single line diagram for the New England System.

distinct weights to each objective. In this case, the conditions $\sigma_{i,\,j} \le \sigma_0$ and $\zeta_{i,\,j} \ge \zeta_0$ are imposed simultaneously. The parameters of the PSS may be selected to minimize the following objective function:

$$J = J_1 + aJ_2 = \sum_{j=1}^{np} \sum_{\sigma_{i,\,j} \ge \sigma_0} [\sigma_0 - \sigma_{i,\,j}]^2 + a \sum_{j=1}^{np} \sum_{\zeta_{i,\,j} \le \zeta_0} [\zeta_0 - \zeta_{i,\,j}]^2. \quad (5)$$

This will place the system closed-loop eigenvalues in the D-shape sector characterized by $\sigma_{i,\,j} \le \sigma_0$ and $\zeta_{i,\,j} \ge \zeta_0$ as shown in Fig. 3.

It is necessary to mention here that only the unstable or lightly damped electromechanical modes of oscillations are relocated.

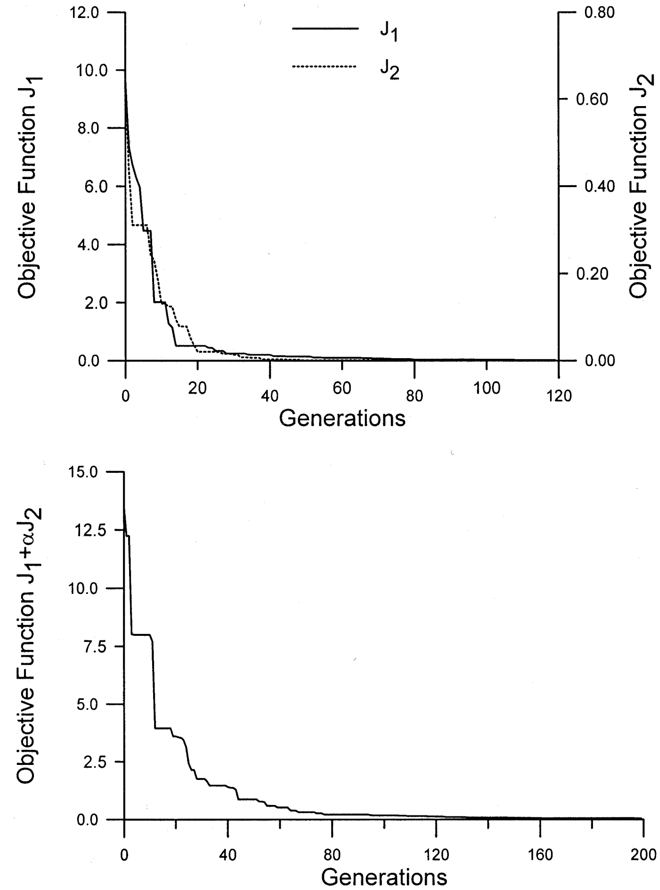

Fig. 5. Variations of the objective functions J_1, J_2, and J (for $a = 10$).

The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS parameter bounds:

$$\text{Minimize } J \text{ subject to} \quad \begin{cases} K_{i,\,min} \le K_i \le K_{i,\,\max} \\ T_{1i,\,\min} \le T_{1i} \le T_{1i,\,\max} \\ T_{2i,\,\min} \le T_{2i} \le T_{2i,\,\max} \\ T_{3i,\,\min} \le T_{3i} \le T_{3i,\,\max} \\ T_{4i,\,\min} \le T_{4i} \le T_{4i,\,\max}. \end{cases} \quad (6)$$

The proposed approach employs GA (Appendix) to solve this optimization problem and search for optimal or near optimal set of PSS parameters $\{K_i, T_{1i}, T_{2i}, T_{3i}, T_{4i};\, i = 1, 2, 3 \cdots m\}$, where m is the number of machines.

III. Results and Discussions

A. Test System

In this study, the ten-machine 39-bus New England power system shown in Fig. 4 is considered [26]. Generator G_1 is an equivalent power source representing parts of the U.S.-Canadian interconnection system. it is assumed here that all generators except G_1 are equipped with PSSs.

B. PSS Design

To design the proposed PSSs, three different operating conditions that represent the system under severe loading conditions

TABLE I
EIGENVALUES AND DAMPING RATIOS OF ELECTROMECHANICAL MODES WITH AND WITHOUT PSSs

	Base Case	Case 1	Case 2	Case 3
Without PSSs	0.191 ±j 5.808, -0.033	0.195 ±j 5.716, -0.034	0.189 ±j 5.811, -0.033	0.205 ±j 5.638, -0.036
	0.088 ±j 4.002, -0.022	0.121 ±j 3.798, -0.032	0.006 ±j 3.113, -0.002	0.152 ±j 3.714, -0.041
	-0.028 ±j 9.649, 0.003	0.097 ±j 6.006, -0.016	0.001 ±j 6.180, -0.0002	0.126 ±j 5.964, -0.021
	-0.034 ±j 6.415, 0.005	-0.032 ±j 9.694, 0.003	-0.028 ±j 9.650, 0.003	0.051 ±j 9.648, -0.005
	-0.056 ±j 7.135, 0.008	-0.104 ±j 8.015, 0.013	-0.032 ±j 7.105, 0.005	-0.098 ±j 8.013, 0.012
	-0.093 ±j 8.117, 0.011	-0.109 ±j 6.515, 0.017	-0.091 ±j 8.115, 0.011	-0.101 ±j 6.512, 0.016
	-0.172 ±j 9.692, 0.018	-0.168 ±j 9.715, 0.017	-0.172 ±j 9.693, 0.018	-0.167 ±j 9.727, 0.017
	-0.220 ±j 8.013, 0.027	-0.204 ±j 8.058, 0.025	-0.218 ±j 8.024, 0.027	-0.202 ±j 8.079, 0.025
	-0.270 ±j 9.341, 0.029	-0.250 ±j 9.268, 0.027	-0.269 ±j 9.342, 0.029	-0.238 ±j 9.296, 0.026
With PSSs [J_1 settings]	**-1.198** ±j 12.649, 0.094	**-1.256** ±j 12.157, 0.103	**-1.195** ±j 12.648, 0.094	**-1.198** ±j 12.025, 0.100
	-1.276 ±j 11.825, 0.107	**-1.243** ±j 11.799, 0.105	**-1.276** ±j 11.824, 0.107	**-1.227** ±j 11.777, 0.104
	-1.080 ±j 10.782, 0.100	**-1.057** ±j 10.784, 0.098	**-1.077** ±j 10.780, 0.099	**-1.046** ±j 10.787, 0.096
	-1.554 ±j 9.717, 0.158	**-1.230** ±j 9.653, 0.126	**-1.556** ±j 9.715, 0.158	**-1.210** ±j 9.647, 0.124
	-1.250 ±j 9.676, 0.128	**-1.529** ±j 9.452, 0.160	**-1.221** ±j 9.667, 0.125	**-1.509** ±j 9.416, 0.158
	-1.045 ±j 8.867, 0.117	**-1.029** ±j 8.737, 0.117	**-1.039** ±j 8.871, 0.116	**-1.018** ±j 8.726, 0.116
	-1.089 ±j 8.167, 0.132	**-1.129** ±j 7.638, 0.146	**-1.152** ±j 8.014, 0.142	**-1.100** ±j 7.566, 0.144
	-1.304 ±j 6.400, 0.200	**-1.134** ±j 5.903, 0.189	**-1.135** ±j 6.213, 0.180	**-1.058** ±j 5.755, 0.180
	-1.136 ±j 4.043, 0.270	**-1.088** ±j 3.667, 0.284	**-1.029** ±j 2.294, 0.409	**-1.025** ±j 3.464, 0.284
With PSSs [J_2 settings]	-2.887 ±j 12.498, **0.225**	-3.068 ±j 12.561, **0.237**	-2.883 ±j 12.504, **0.225**	-3.115 ±j 12.582, **0.240**
	-3.543 ±j 11.319, **0.299**	-3.471 ±j 11.228, **0.295**	-3.512 ±j 11.268, **0.298**	-3.433 ±j 11.183, **0.294**
	-2.894 ±j 10.996, **0.255**	-2.788 ±j 10.961, **0.247**	-2.883 ±j 10.992, **0.254**	-2.747 ±j 10.965, **0.243**
	-2.688 ±j 9.943, **0.261**	-2.588 ±j 9.847, **0.254**	-2.673 ±j 9.939, **0.260**	-2.494 ±j 9.805, **0.246**
	-2.236 ±j 9.445, **0.230**	-2.357 ±j 9.457, **0.242**	-2.154 ±j 9.489, **0.221**	-2.337 ±j 9.439, **0.240**
	-3.319 ±j 8.575, **0.361**	-3.405 ±j 8.184, **0.384**	-3.549 ±j 7.972, **0.407**	-3.395 ±j 8.147, **0.385**
	-1.720 ±j 6.112, **0.271**	-1.120 ±j 5.293, **0.207**	-1.793 ±j 6.046, **0.284**	-1.052 ±j 5.145, **0.200**
	-1.312 ±j 3.605, **0.342**	-1.375 ±j 3.437, **0.372**	-2.225 ±j 3.480, **0.539**	-1.435 ±j 3.397, **0.389**
	-1.034 ±j 2.990, **0.328**	-0.815 ±j 3.108, **0.254**	-0.491 ±j 2.336, **0.206**	-0.697 ±j 3.124, **0.218**
With PSSs [J settings]	**-3.281** ±j 14.606, **0.219**	**-3.272** ±j 14.494, **0.220**	**-3.282** ±j 14.608, **0.219**	**-3.268** ±j 14.429, **0.221**
	-2.739 ±j 13.119, **0.204**	**-2.613** ±j 12.395, **0.206**	**-2.738** ±j 13.116, **0.204**	**-2.508** ±j 12.217, **0.201**
	-2.632 ±j 11.242, **0.228**	**-2.648** ±j 11.083, **0.232**	**-2.625** ±j 11.245, **0.227**	**-2.594** ±j 11.024, **0.229**
	-2.421 ±j 10.141, **0.232**	**-2.302** ±j 10.226, **0.220**	**-2.414** ±j 10.145, **0.232**	**-2.275** ±j 10.253, **0.217**
	-1.911 ±j 8.964, **0.209**	**-1.885** ±j 8.915, **0.207**	**-1.898** ±j 8.971, **0.207**	**-1.852** ±j 8.909, **0.204**
	-1.801 ±j 8.735, **0.202**	**-1.787** ±j 8.595, **0.204**	**-1.787** ±j 8.741, **0.200**	**-1.771** ±j 8.588, **0.202**
	-1.586 ±j 7.639, **0.203**	**-1.540** ±j 7.044, **0.214**	**-1.588** ±j 7.536, **0.206**	**-1.506** ±j 6.985, **0.211**
	-1.451 ±j 6.231, **0.227**	**-1.260** ±j 5.778, **0.213**	**-1.316** ±j 6.028, **0.213**	**-1.176** ±j 5.646, **0.204**
	-1.075 ±j 3.913, **0.265**	**-1.037** ±j 3.643, **0.274**	**-1.005** ±j 2.133, **0.426**	**-1.004** ±j 3.487, **0.277**

and critical line outages in addition to the base case are considered. These conditions are extremely harsh from the stability viewpoint [27]. 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 I. It is clear that these modes are poorly damped and some of them are unstable. There are 45 parameters to be optimized, namely K_i, T_{1i}, T_{2i}, T_{3i}, and T_{4i}, $i = 2, 3, \ldots, 10$. The time constant T_w is set to be 5 s [17].

In this study, σ_0 and ζ_0 are chosen to be -1.0 and 0.20, respectively. Several values for the weight a were tested; it was found that the effect of varying a on the final goals is minimal. The results presented here are for $a = 10$.

The convergence rate of the single objective functions J_1 and J_2, and the multiobjective function $J = J_1 + aJ_2$ are shown in Fig. 5.

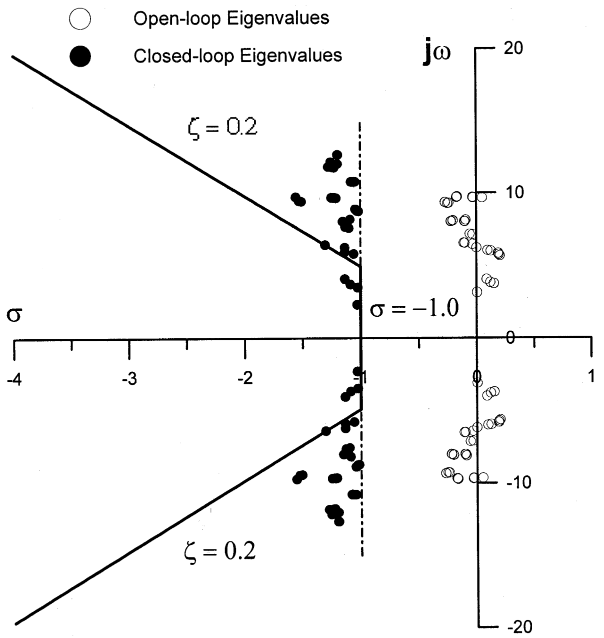

Fig. 6. Eigenvalues associated with electromechanical modes (J_1).

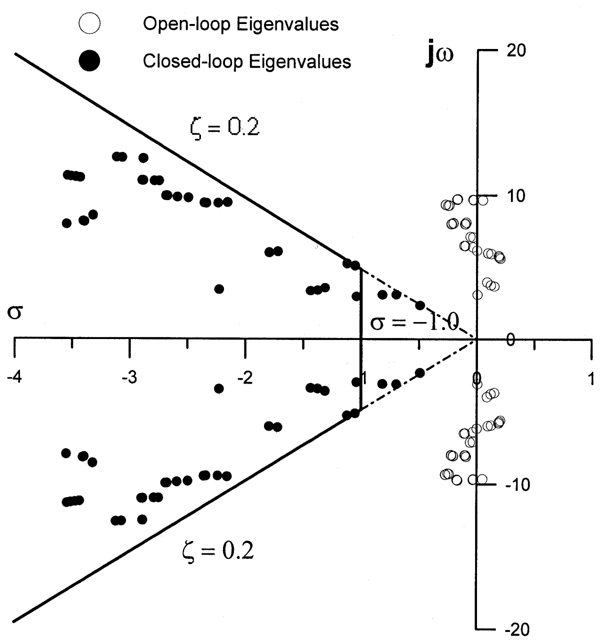

Fig. 7. Eigenvalues associated with electromechanical modes (J_2).

The final value of the objective function J_1 is $J_1 = 0$, indicating that all of the electromechanical modes have been shifted to the left of the vertical line $\sigma_0 = -1.0$. The final value of the objective function J_2 is $J_2 = 0$, indicating that all of the electromechanical modes have been shifted to the specified wedge-shape sector in the s-plane. The final value of the objective function is $J = J_1 + aJ_2$ is $J = 0$, indicating that all of the electromechanical modes have been shifted to the specified D-shape sector in the s-plane. The system electromechanical modes, for the base case and the three operating conditions (cases 1–3), without and with the PSSs tuned using J_1, J_2, and J are listed in Table I. They are also portrayed in the complex s-plane as shown in Figs. 6–8.

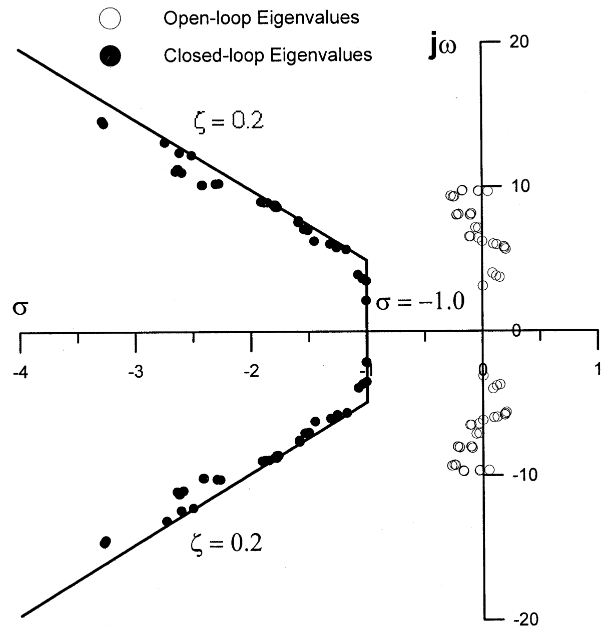

Fig. 8. Eigenvalues associated with electromechanical modes [$J = J_1 + 10J_2$].

TABLE II
OPTIMAL PSSs PARAMETERS

Gen	K	T_1	T_2	T_3	T_4
	Objective Function J_1				
G_2	39.2777	0.7111	0.0359	0.2747	0.0695
G_3	42.6168	1.127	0.0476	0.3596	0.0561
G_4	20.1555	0.774	0.0287	0.6302	0.0685
G_5	34.5081	0.1737	0.0617	0.2445	0.0714
G_6	40.8901	1.1186	0.0847	1.0241	0.0448
G_7	3.675	0.171	0.0491	0.2165	0.0362
G_8	25.5179	0.383	0.0223	1.1799	0.0695
G_9	5.0028	0.2708	0.0579	0.255	0.0161
G_{10}	19.5941	1.3031	0.027	0.9439	0.0536
	Objective Function J_2				
	K	T_1	T_2	T_3	T_4
G_2	38.9357	0.8276	0.0247	0.7307	0.0555
G_3	31.7945	0.9154	0.0383	0.8157	0.0397
G_4	34.2916	0.7733	0.0248	1.1095	0.0479
G_5	10.2385	0.1612	0.0953	1.1954	0.0466
G_6	35.6744	0.5857	0.0113	0.8186	0.0414
G_7	3.6945	0.2656	0.0255	0.3279	0.0739
G_8	22.0294	0.809	0.0228	1.0641	0.0354
G_9	5.0927	0.5636	0.0729	0.1998	0.0288
G_{10}	26.6298	1.0674	0.0421	1.2356	0.0271
	Objective Function J				
	K	T_1	T_2	T_3	T_4
G_2	48.8622	0.3686	0.0137	0.445	0.0159
G_3	28.6638	0.7259	0.0252	0.6528	0.037
G_4	42.938	0.7016	0.0426	0.5638	0.0403
G_5	49.4392	0.1211	0.0619	0.3043	0.0228
G_6	48.4517	0.6944	0.0156	1.4158	0.0793
G_7	1.2414	0.3564	0.0275	0.5639	0.1211
G_8	26.9913	0.8148	0.0164	0.7331	0.0177
G_9	5.7991	0.2522	0.0494	0.2892	0.0285
G_{10}	20.5553	1.2483	0.0371	1.1991	0.0305

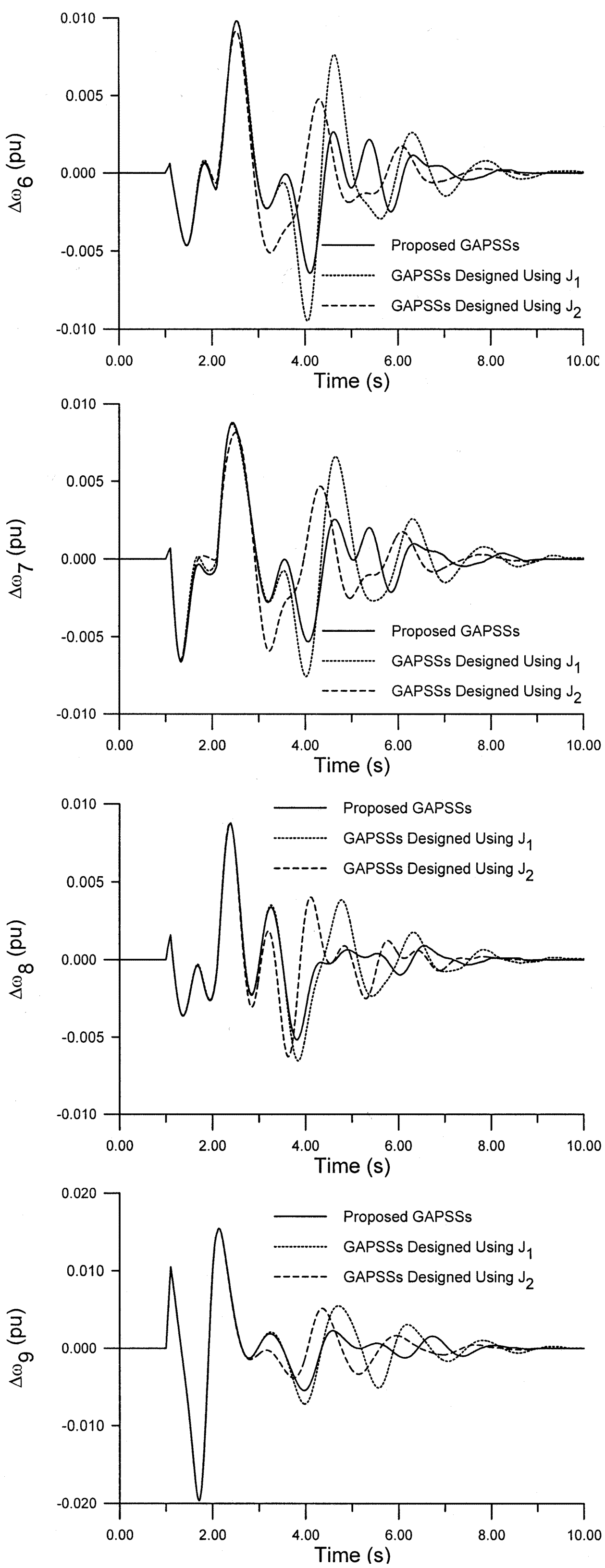

Fig. 9. Speed deviations (nonlinear system).

It can be readily seen from Table I and Figs. 6–8 that, for all objective functions considered, none of the system eigenvalues associated with the electromechanical modes lie outside the relevant prescribed area. Note that the parameter settings associated with J_1 are not able to shift the electromechanical modes in the region specified by $\zeta \geq 0.2$. The parameter settings associated with J_2 are not able to shift the electromechanical modes in the region specified by $\sigma \leq -1$. However, the parameter settings associated with the multiobjective function J achieved both goals, namely $\zeta \geq 0.2$ and $\sigma \leq -1$. This clearly indicates that the single objective approach is not able to shift all electromechanical modes to the prescribed D-shape sector.

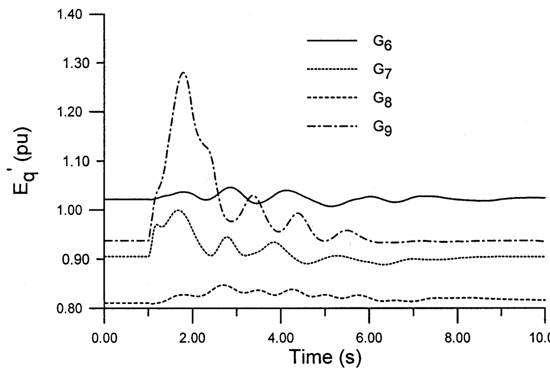

Fig. 10. Internal voltage variations (nonlinear system).

This fact indicates that the closed-loop plant performance is consistent with the design requirements in spite of changes in the operating conditions, and system configurations. Moreover, it is also clear that the system damping with the proposed J-tuned PSSs is greatly improved.

The final values of the optimized parameters with both single objective functions J_1 and J_2, and the multiobjective function J are given in Table II.

C. Nonlinear Time-Domain Simulation

To demonstrate the effectiveness of the PSSs tuned using the proposed multiobjective function over a wide range of operating conditions, the following disturbance is considered for nonlinear time simulations.

- A six-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 1.0 s.

The performance of the PSSs when the multiobjective function J is used in the design is compared to that of the PSSs designed using the single objective functions J_1 or J_2. The speed deviations of generators G_6, G_7, G_8, and G_9 are shown in Fig. 9. It is clear that the system response with the PSSs tuned using the multiobjective function J settles faster, and provides superior damping in comparison with the case when either of J_1 or J_2 are used. This indicates that the time domain specifications were simultaneously met. For completeness, the internal voltage of the same generators, when the multiobjective function J is used, are shown in Fig. 10.

IV. Conclusions

In this study, optimal multiobjective design of robust multimachine power system stabilizers (PSSs) using GAs is proposed. A conventional speed-based lead-lag PSS is used in

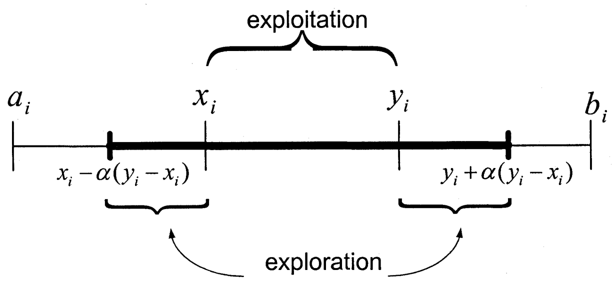

Fig. 11. Blend crossover operator (BLX-a).

this work. The multimachine power system operating at various loading conditions, and system configurations is treated as a finite set of plants. The stabilizers are tuned to simultaneously shift the lightly damped electromechanical modes of all plants to a prescribed zone in the s-plane. A multiobjective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of the lightly damped electromechanical modes. The problem of robustly selecting the parameters of the power system stabilizers is converted to an optimization problem which is solved by a GA with the eigenvalue-based multiobjective function.

The eigenvalue analysis confirms that the closed-loop plant performance is consistent with the design requirements in spite of changes in the operating conditions, and reveals the superiority of the PSSs tuned using the multiobjective function in damping local and 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.

APPENDIX
GENETIC ALGORITHMS

Due to difficulties of binary representation when dealing with continuous search space with large dimension, the proposed approach has been implemented using real-coded genetic algorithm (RCGA) [28]. A decision variable x_i is represented by a real number within its lower limit a_i and upper limit b_i (i.e., $x_i \in [a_i,\, b_i]$). The RCGA crossover and mutation operators are described as follows.

Crossover: A blend crossover operator (BLX-a) has been employed in this study. This operator starts by choosing randomly a number from the interval $[x_i - a(y_i - x_i),\, y_i + a(y_i - x_i)]$, where x_i and y_i are the ith parameter values of the parent solutions and $x_i < y_i$. To ensure the balance between exploitation and exploration of the search space, $a = 0.5$ is selected. This operator is depicted in Fig. 11.

Mutation: The nonuniform mutation operator has been employed in this study. In this operator, the new value of x_i' the parameter x_i after mutation at generation t is given as

$$x_i' = \begin{cases} x_i + \Delta(t,\, b_i - x_i) & \tau = 0 \\ x_i - \Delta(t,\, x_i - a_i) & \tau = 1 \end{cases} \tag{A.1}$$

$$\Delta(t,\, y) = y\left(1 - r^{(1-(t/g_{\max}))^{\beta}}\right) \tag{A.2}$$

where τ is a binary random number, r is a random number $r \in \{0,\, 1\}$, $g_{\max}$ is the maximum number of generations, and β is a positive constant chosen arbitrarily. In this study, $\beta = 5$ was selected. This operator gives a value $\in [a_i,\, b_i]$ such that the probability of returning a value $x_i \in [a_i,\, b_i]$ such that the probability of returning a value close to x_i increases as the algorithm advances. This makes uniform search in the initial stages where t is small and very locally at the later stages.

RCGA has been applied to search for optimal settings of the optimized parameters of the proposed PSSs. In our implementation, the crossover and mutation probabilities of 0.9 and 0.01, respectively, are found to be quite satisfactory. The number of individuals in each generation is selected to be 100. In addition, the search will terminate if the best solution does not change for more than 50 generations or the number of generations reaches 500.

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