SIMULTANEOUS STABILIZATION OF MULTIMACHINE POWER SYSTEMS VIA GENETIC ALGORITHMS

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Abstract: *This paper demonstrates the use of genetic algorithms for the simultaneous stabilization of multimachine power systems over a wide range of operating conditions via single-setting power* system stabilizers. The power system operating at various conditions is treated as a finite set of plants. The problem of selecting the parameters of power system stabilizers which simultaneously stabilize this set of plants is converted to a simple optimization problem which is solved by a genetic algorithm with an eigenvalue-based objective function. Two objective functions are presented, *allowing the selection of the stabilizer parameters to shift* some of the closed-loop eigenvalues to the left-hand side of a vertical line in the complex s-plane, or to a wedge-shape sector in the complex s-plane. The effectiveness of the suggested technique in damping local and inter-area modes of oscillations in multimachine power systems is verified through eigenvalue analysis and simulation results.

Keywords: *Dynamic stability, Genetic algorithms, Power system* stability, Simultaneous stabilization.

I. INTRODUCTION

This paper demonstrates the use of genetic algorithms (GA) to select the parameters of power system stabilizers (PSSs) that will simultaneously stabilize a power system operating at various loading conditions.

The application of genetic algorithms has recently attracted the attention of researchers in the field of artificial intelligence. From the literature it is clearly seen that genetic algorithms can provide powerful tools for optimization [1-4]. Genetic algorithms are used as parameter search techniques which utilize the genetic operators to find near optimal solutions. 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.

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The use of high-speed excitation systems has long been recognized as an effective method of increasing stability limits. Static excitation systems appear to offer the practical ultimate in high-speed performance, thereby providing a gain in stability limits. Unfortunately, the high speeds and gains that give them this capability also result in poor system damping under certain loading conditions [5]. To offset this effect and to improve the system damping in general, supplementary stabilizing signals are introduced in the excitation systems through fixed parameters lead/lag power system stabilizers [6-7]. The parameters of the PSS are normally fixed at certain values which are determined under a particular operating condition.

It is important to recognize that machine parameters change with loading, making the dynamic behavior of the machine quite different at different operating points. Since these parameters change in a rather complex manner [8-9], a set of PSS parameters which stabilizes the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in the operating point. This paper considers the problem of simultaneous stabilization of the power system via a single set of PSS parameters. In daily operation of a power system, the operating condition changes as a result of load changes. The power system under various loading conditions could therefore be considered as a finite number of plants. The parameters of a PSS that can simultaneously stabilize this set of plants can be determined off-line using a genetic algorithm and an objective function based on the system eigenvalues. The PSSs designed in this manner will perform well under various loading conditions and stability of the system is guaranteed. By contrast, the conventionally designed PSSs will only perform well at the design loading condition.

In this paper, the parameters of the PSS are determined using GA and eigenvalue-based objective functions. Two objective functions are considered. The use of the first objective function will result in shifting the undamped mechanical modes of oscillation 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 place these modes in a wedge-shape sector in the complex s-plane, thus improving the damping ratio of these modes. The advantage of the eigenvalue-based objective functions is the ability to incorporate certain system specifications such as rise time, maximum overshoot, damping ratio, and steady state error.

It is imperative to realize that simultaneous stabilization is known to be a very difficult problem [10]. No general analytic solution is available. Powerful iterative optimization algorithms are the alternative in the absence of analytic solutions.

Two multimachine power systems are considered in this work. Simulation results and eigenvalue analysis are used throughout the paper to assess the effectiveness of the suggested PSSs tuning technique.

II. GENETIC ALGORITHMS

Genetic algorithms are global search techniques, based on the operations observed in natural selection and genetics [1]. They operate on a population of current approximations- the individuals- initially drawn at random, from which improvement is sought. Individuals are encoded as strings (chromosomes) constructed over some particular alphabet, e.g., the binary alphabet {0,1}, so that chromosomes values are uniquely mapped onto the decision variable domain. Once the decision variable domain representation of the current population is calculated, individual performance is assumed according to the objective function which characterizes the problem to be solved. It is also possible to use the variable parameters directly to represent the chromosomes in the GA solution.

At the reproduction stage, a fitness value is derived from the raw individual performance measure given by the objective function, and used to bias the selection process. Highly fit individuals will have increasing opportunities to pass on genetically important material to successive generations. In this way, the genetic algorithms search from many points in the search space at once and yet continually narrow the focus of the search to the areas of the observed best performance.

The selected individuals are then modified through the application of genetic operators, in order to obtain the next generation. Genetic operators manipulate the characters (genes) that constitute the chromosomes directly, following the assumption that certain genes code, on average, for fitter individuals than other genes. Genetic operators can be divided into three main categories [2], selection, crossover, and mutation.

1. Selection: Selects the fittest individuals in the current population to be used in generating the next population.
2. Crossover: Causes pairs, or larger groups of individuals to exchange genetic information with one another.
3. Mutation: Causes individual genetic representations to be changed according to some probabilistic rule.

Genetic algorithms are more likely to converge to global optima than conventional optimization techniques, since they search from a population of points, and are based on probabilistic transition rules. Conventional optimization techniques are ordinarily based on deterministic hill-climbing methods, which, may find local optima. Genetic algorithms can also tolerate discontinuities and noisy function evaluations.

III. PROBLEM FORMULATION AND RESULTS

In this section, two eigenvalue-based objective functions are considered. These objective functions will place some of the closed-loop eigenvalues in the left-hand side of a vertical line in the complex s-plane, or in a wedge-shape sector in the complex s-plane.

Consider the problem of determining the parameters of a power system stabilizer that relatively stabilize a family of N plants :

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

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

i) <u>Placement of the eigenvalues to the left of a vertical line</u>

Very often, the closed-loop modes are specified to have some degree of relative stability. In this case, the closed-loop eigenvalues are constrained to lie to the left of a vertical line corresponding to a specified damping factor.

A necessary and sufficient condition for the set of plants in eqn. (1) to be simultaneously relatively stabilizable with a single control law is that the eigenvalues of the closed-loop system lie in the left-hand side of a vertical line in the complex s-plane. This condition motivates the following approach for determining the parameters of the PSS.

Select the parameters of the PSS to minimize the following objective function:

$$J_1 = \max\ \{\mathrm{Re}(\lambda_{k,i}) + \beta\}\quad k = 1, 2 \ldots, N;\ i = 1, 2, \ldots, n \tag{2}$$

where $\lambda_{k,i}$ is the i^{th} closed-loop eigenvalue of the k^{th} plant, subject to the constraints that finite bounds are placed on the power system stabilizer parameters. The relative stability is determined by the value of β as shown in Fig. 1.

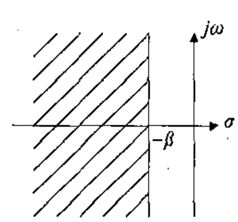

Fig 1. Region in the left-hand side of a vertical line

Plainly, if a solution is found such that $J_1 < 0$, then the resulting gains simultaneously relatively-stabilize the collection of plants. The existence of a solution is verified numerically by minimizing J_1.

ii) *Placement of the eigenvalues in a wedge-shape sector in the left complex s-plane*

In many cases, certain time-domain control system specifications such as maximum overshoot, rise time and steady-state error goals can be realized by placing the closed-loop eigenvalues of the system within a prescribed region in the left-half of the complex s-plane [11]. In order to do this, the objective function of (2) is changed to:

$$J_2 = \max \{ \ \mathrm{Re}(\lambda_{k,i}) + \beta + \frac{1}{\alpha}\left|\mathrm{Im}(\lambda_{k,i})\right| \ \} \quad k = 1, 2 \ldots, N;\ i = 1, 2, \ldots, n \qquad (3)$$

This will place the closed-loop eigenvalues in a wedge-shape sector as shown in Fig. 2.

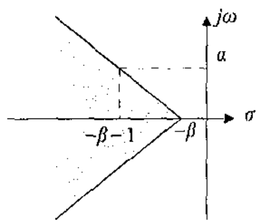

Fig. 2 Wedge-shape sector in the complex s-plane

The minimization of the objective function J_2 will result in a PSS structure that satisfies the time-domain performance specifications as well as relative stability.

It is necessary to mention here that if only particular eigenvalues need to be relocated, then only those eigenvalues should be taken into consideration in the computation of the objective function. This is usually the case in dynamic stability where it is desired to relocate the electromechanical modes of oscillations.

IV. SYSTEM MODEL

In this study, two multimachine power systems are considered. The first system is a nine-bus-three-machine power system [12], and the second system is the 10-machine 39-bus New England power system [13]. Each synchronous machine is described by a nonlinear fourth-order model as given in the Appendix. The supplementary stabilizing signal considered is one proportional to speed. A widely used conventional PSS is considered throughout the study [12]. The transfer function of the i^{th} PSS is :

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

The structure of the PSS considered in (4) has been used by many researchers to assess and compare the results of their work. The first term in (4) is a washout term with a time lag τ_w. The second term is a lead compensation to improve the phase lag through the system. The following numerical values were used in the study:

$\tau_w = 10\,s$; $\tau_2 = \tau_4 = 0.05\,s$.

The remaining parameters, namely, K, τ_1, and τ_3 are assumed to be adjustable parameters. The optimization problem, namely, the selection of these PSS parameters is easily and accurately solved using genetic algorithms. 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 those eigenvalues that need to be shifted. In a typical run of the GA, an initial population is randomly generated . This initial population is referred to as the 0th generation. Each individual in the initial population has an associated objective function value. Using the objective function information, the GA then produces a new population. The application of a genetic algorithm involves repetitively performing two steps:

1. The calculation of the objective function for each of the individuals in the current population. To do this, the system eigenvalues must be computed.
2. The genetic algorithm then produces the next generation of individuals using the selection , crossover and mutation operators.

These two steps are repeated from generation to generation until the population has converged, producing the optimum parameters.

The following GA parameters were used in the search: population size=50; maximum number of generations=100; crossover and mutation probabilities =0.75 and 0.001 respectively.

V. SIMULATION RESULTS

To evaluate the effectiveness of the proposed technique, two multimachine power systems are studied.

A. *Example 1. Nine-bus three-Machine System*

In this part of the study, the nine-bus three-machine power system shown in Fig. 3 is considered. Details of the system data are given in [12].

Without power system stabilizers, the system damping is poor and the system exhibits highly oscillatory response [12]. It is therefore necessary to install one or more PSS to improve the dynamic performance. To identify the optimum locations of PSSs, the participation factor method [14] and the sensitivity of PSS effect method [15] were used. The results indicate that machines G_2 and G_3 are the optimum

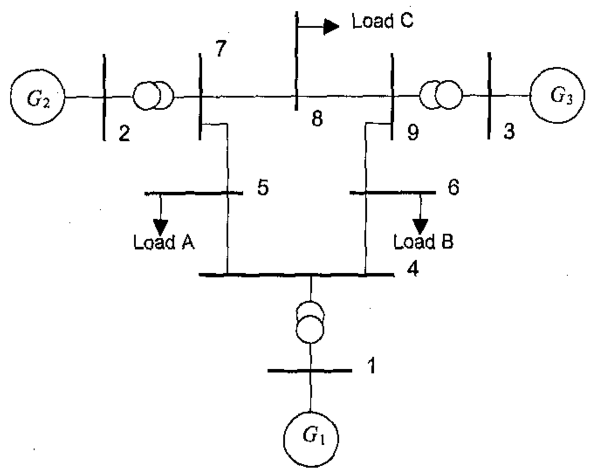

Fig. 3 Three-machine nine-bus power system

locations for installing PSSs to damp out the local modes of oscillations.

The simultaneous stabilization of the system is demonstrated by considering three different loading conditions as given in Table 1. The admittances of the loads in each case are given in Table 2. Only the electromechanical modes are to be shifted. The system eigenvalues without power system stabilizers are summarized in Table 3.

TABLE 1
OPERATING CONDITIONS IN PU [12]

Loading	G_1		G_2		G_3	
	P	Q	P	Q	P	Q
Nominal	0.71	0.28	1.63	0.07	0.85	-0.11
Heavy	2.21	1.09	1.92	0.57	1.28	0.36
Light	0.36	0.17	0.8	-0.11	0.45	-0.2

TABLE 2
ADMITTANCES OF LOADS IN PU

Load	Nominal	Heavy	Light
A	1.261-j 0.504	2.314-j 0.925	0.640-j 0.542
B	0.878-j 0.293	2.032-j 0.677	0.431-j 0.335
C	0.969-j 0.339	1.584-j 0.634	0.472-j 0.236

TABLE 3
SYSTEM EIGENVALUES [NO PSSs]

Nominal Loading	Light Loading	Heavy Loading
-0.7801 ± j13.8623	-0.8449 ± j13.7193	-0.5175 ± j13.8303
-10.2815 ± j 11.9483	-10.0658 ± j 12.9731	-10.1630 ± j 12.1502
-0.0128 ± j 9.0683	-0.3006 ± j 8.9542	-0.0193 ± j 8.9062
-10.0457 ± j 6.7750	-9.9868 ± j 7.3839	-10.1811 ± j 7.0860
-11.1367, -8.3467	-9.6562 ± j 4.4906	-10.0072 ± j 3.4568
-0.09073	-0.0907	-0.0926

Using J_1 as the objective function with $\beta = 2.5$, the optimum values of the PSS parameters for the two PSSs used are given in Table 4. In this work, the selected bounds on the parameters are $(0.01, 20)$ for gains and $(0.06, 0.8)$ for time constants.

TABLE 4
PSS PARAMETERS [EXAMPLE 1, WITH J_1]

PSS on Generator	K	τ_1	τ_3
G_2	8.393	0.08387	0.3465
G_3	0.6548	0.22710	0.3226

The objective function achieved is $J_1 = -0.24$ indicating that the mechanical modes have been shifted to the left of the vertical line $s = -2.5$ in the complex s-plane. The convergence rate of the objective function J_1 is shown in Fig. 4. The eigenvalues with the parameters of the PSSs set as in Table 4 are given in Table 5.

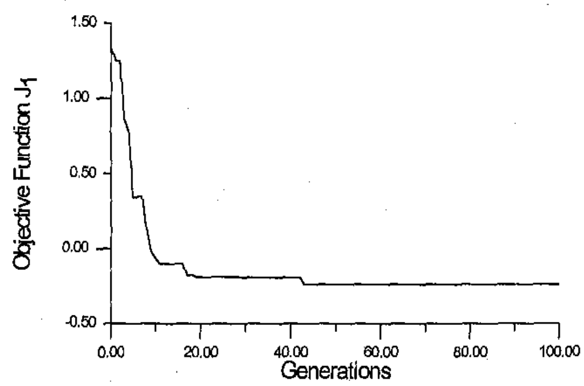

Fig. 4 Variation of the objective function J_1

TABLE 5
SYSTEM EIGENVALUES [WITH PSSs and J_1]

Nominal Loading	Light Loading	Heavy Loading
-35.9954 , -30.4939	-33.8404 , -28.9069	-35.9847, -30.9355
-2.7552 ± j 19.5991	-3.4025 ± j 18.160	-2.9913 ± j 19.6067
-6.5530 ± j 14.3300	-7.0272 ± j 14.5412	-5.9104 ± j 15.0387
-10.000 j ± 7.8590	-10.009 ± j 7.9805	-10.0847 ± j 7.9315
-12.8797 , -8.2145	-13.5140 , -10.2023	-12.8762 , -9.1274
-3.7257 ± j 8.8760	-3.5029 ± j 7.3199	-2.702 ± j 6.7981
-3.9228 ± j 6.1872	-3.61555 ± j 8.8343	-4.5129 ± j 8.8014
-0.3954 , -0.0217	-0.2911 , -0.0302	-0.5474 , -0.0153
-0.1002	-0.1001	-0.1001

The simulation results for all three operating points and following a 6-cycles, three-phase fault disturbance near bus 7 at the end of line 5-7 are shown in Figs. 5 to 7. The system responses for the three loading conditions and with PSS parameter settings as in [12] are also shown for comparison in Figs. 8 to 10. It is clear that an excellent improvement in the damping over a wide range of operating conditions have been achieved with one set of PSS parameters .

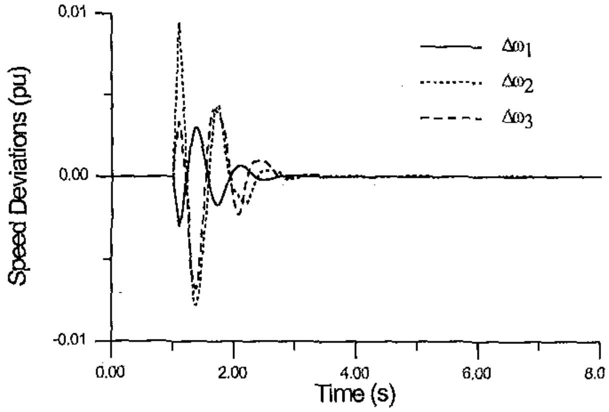

Fig. 5. Response to a three-phase fault [nominal condition with J_1]

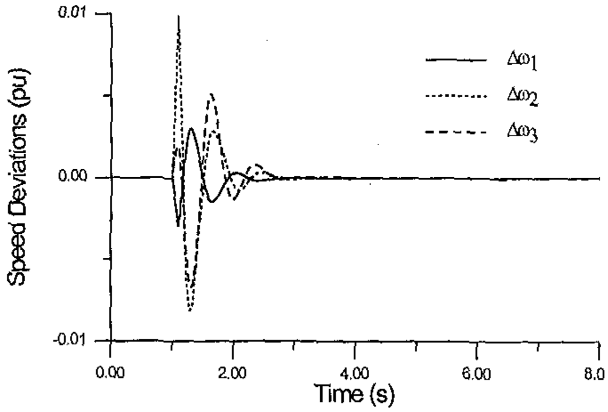

Fig. 6 Response to a three-phase fault [light condition with J_1]

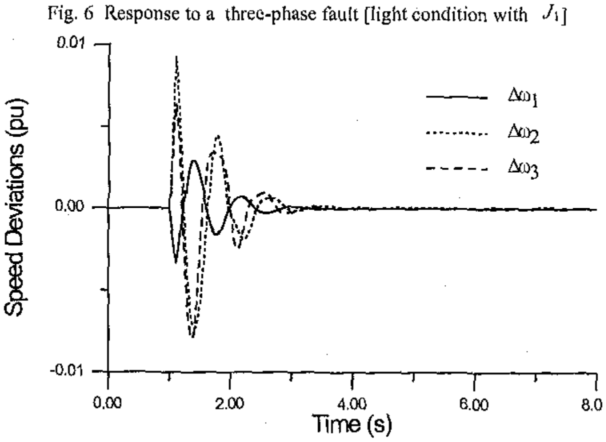

Fig. 7. Response to a three-phase fault [heavy condition with J_1]

The optimum values of the PSS parameters, when the objective function selected is J_2 with $\beta = 0$ and $\alpha = 5$, are listed in Table 6. The objective function achieved is $J_2 = -0.224$ indicating that the mechanical modes have been shifted to the specified wedge-shape sector in the complex s-plane. The convergence rate of the objective function J_2 is shown in Fig. 11. The eigenvalues with the parameters of the PSSs set as in Table 6 are given in Table 7. The simulation results following the same disturbance, are shown in Figs. 12 to 14 for the three operating conditions.

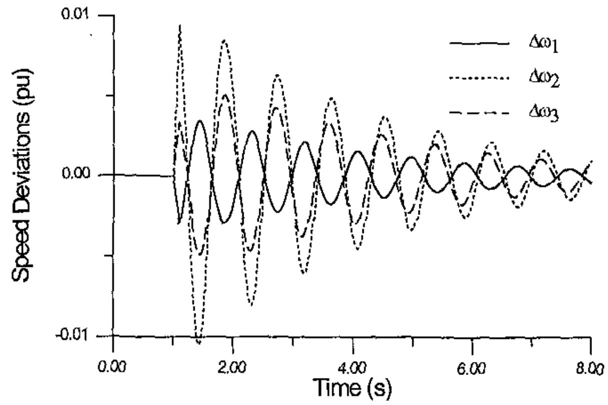

Fig. 8. Response to a three-phase fault for nominal condition [PSS parameters settings as in [12]]

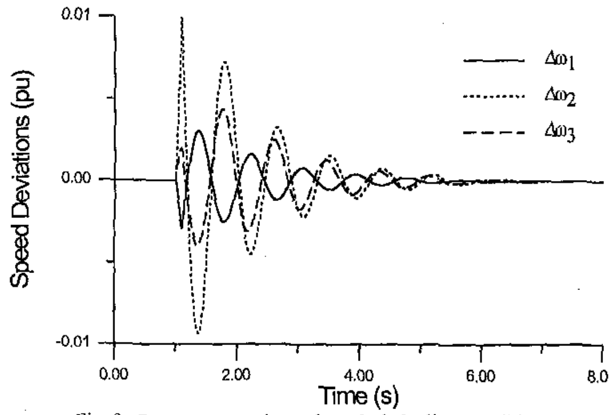

Fig. 9. Response to a three-phase fault for light condition [PSS parameters settings as in [12]]

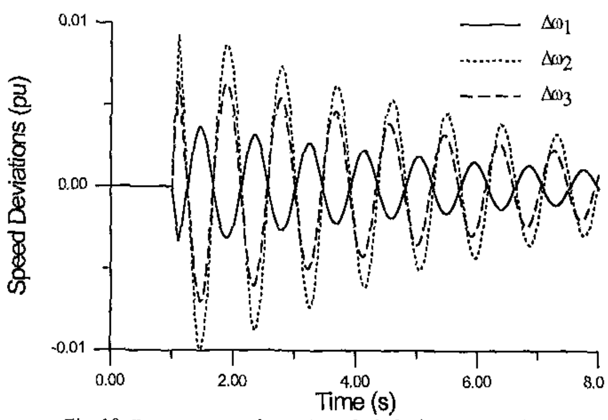

Fig. 10 Response to a three-phase fault for heavy condition [PSS parameters settings as in [12]]

TABLE 6
PSS PARAMETERS [EXAMPLE 1, WITH J_2]

PSS on Generator	K	τ_1	τ_3
G_2	3.879	0.10774	0.4658
G_3	0.65484	0.27484	0.13161

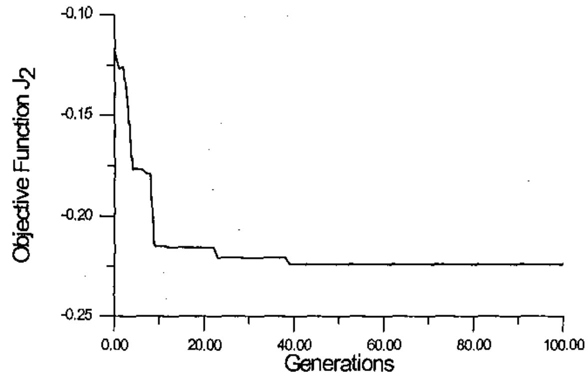

Fig. 11 Variation of the objective function J_2

TABLE 7
SYSTEM EIGENVALUES [WITH PSSs and J_2]

Nominal Loading	Light Loading	Heavy Loading
-35.2173 , -27.3073	-33.1322 , -26.1281	-35.2907 , -27.5627
-4.1585 ± j 17.6982	-5.9152 ± j 15.8150	-4.8990 ± j 17.9458
-4.5413 ± j 13.7243	-3.7950 ± j 14.8584	-3.4021 ± j 14.3960
-2.2267 ± j 7.7304	-1.8385 ± j 7.9569	-1.7245 ± j 7.5016
-12.7454 , -8.7752	-14.2278 , -10.6460	-12.7935 , -10.0088
-8.2758 ± j 8.7492	-7.6262 ± j 9.0049	-1.7245 ± j 7.5016
-9.5810 ± j 6.0801	-9.5806 ± j 7.1991	-9.7736 ± j 7.0548
-0.2702 , -0.03213	-0.2125 , -0.0416	-0.3526 , -0.0243
-0.1001	-0.1001	-0.1001

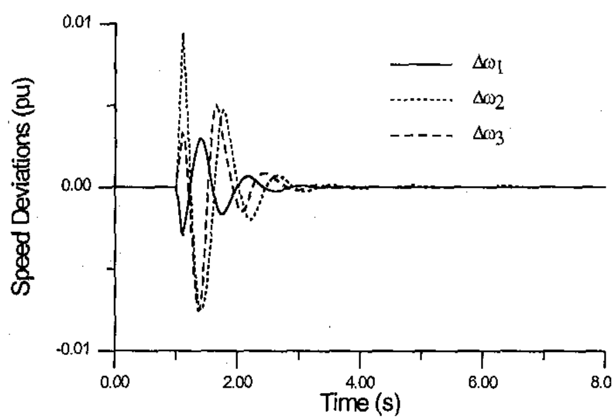

Fig. 12. Response to a three-phase fault [nominal conditions with J_2]

The robustness of the PSS tuned using the suggested technique was further demonstrated by considering its performance at a test operating point characterized by admittances of 2.5-j1.5, 2.3-j0.9, and 2.0-j1.0 for loads A, B, and C respectively, and by (P,Q) = (2.29,1.56), (2.0,0.96), and (1.4,0.68), for generators G_1, G_2, and G_3 respectively. The eigenvalues without and with PSSs set as in Tables 4 and 6, are listed in Table 8. The simulation results following the same disturbance, are shown in Fig. 15.

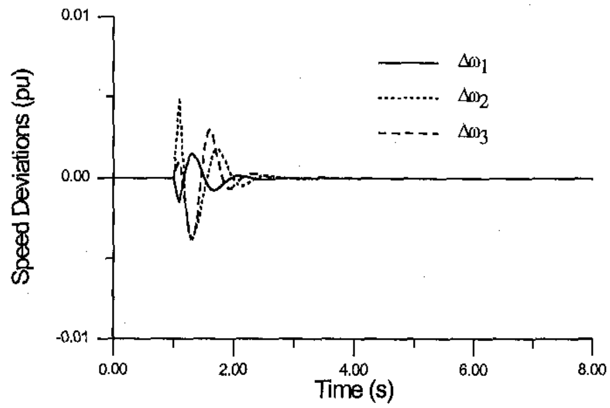

Fig. 13. Response to a three-phase fault [light conditions with J_2]

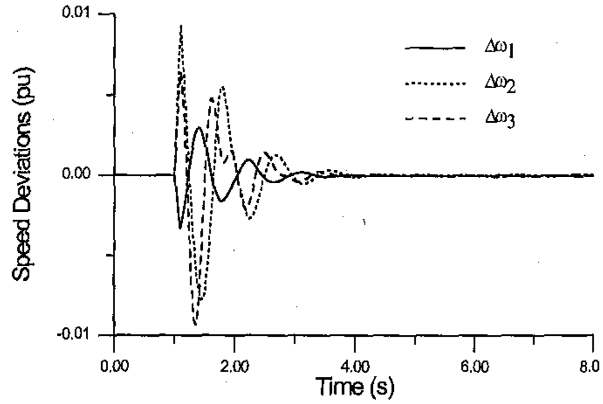

Fig. 14. Response to a three-phase fault [heavy conditions with J_2]

TABLE 8
EIGENVALUES FOR TEST OPERATING POINT

Without PSS	PSS [J_1]	PSS [J_2]
-0.4120 ± j 13.836	-35.6631 , -30.8207	-35.0184 , -27.4429
-0.0117 ± j 8.8111	-3.2211 ± j 19.4048	-2.9196 ± j 14.428
-10.1718 ± j 12.1465	-5.6345 ± j 15.0516	-5.2504 ± j 17.9698
-10.1905 ± j 7.2927	-10.0923 ± j 7.9329	-9.9138 ± j 7.3562
-10.1142 ± j 4.7012	-13.0630 , -9.7765	-13.0685 , -10.7079
-0.09	-4.8718 ± j 9.2984	-8.1230 ± j 8.7728
	-2.2313 ± j 6.8159	-1.4841 ± j 7.4158
	-0.5528 , -0.0150	-0.3495 , -0.02436
	-0.1	-0.1

B. *Example 2. Thirty nine-bus ten-Machine System*

In this part of the study, the 10-machine 39-bus power system shown in Fig. 16 is considered. Details of the system data are given in [13]. Generator G_1 is an equivalent power source representing parts of the U.S.-Canadian interconnection system. This large system was selected to further demonstrate the versatility of the suggested technique.

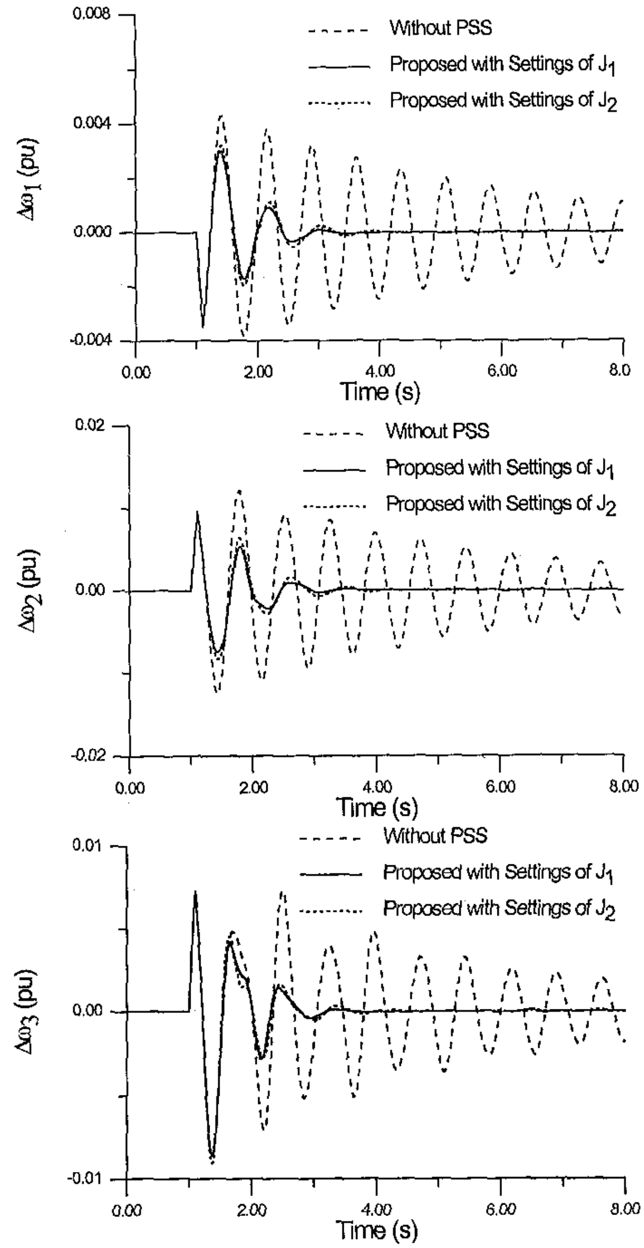

Fig. 15. Response to a three-phase fault [test operating point]

Without power system stabilizers, the system damping is poor and the system exhibits highly oscillatory response [13]. It is therefore necessary to install one or more PSS to improve the dynamic performance. To identify the optimum locations of PSSs, the participation factor method [14] and the sensitivity of PSS effect method [15] were used. The results indicate that machines G_5, G_7 and G_9 are the optimum locations for installing PSSs to damp out the local and inter-area modes of oscillations.

The simultaneous stabilization of the system is demonstrated by considering three different loading conditions labeled as nominal, light and heavy. These loading conditions were obtained by varying the load admittances of the system. The system nine mechanical modes without PSSs, are given in Table 9, for the three operating points considered. Note that the system is unstable for heavy loading

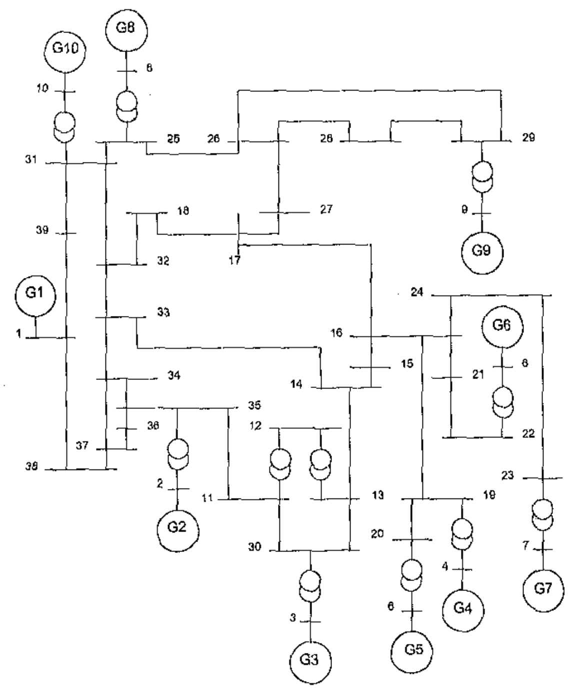

Fig. 16. Single line diagram for the New England System [13].

Using J_1 as the objective function with $\beta = 0.12$, the optimum values of the PSS parameters for the three PSSs used are given in Table 10.

The objective function achieved is $J_1 = -0.0058$ indicating that the mechanical modes have been shifted to the left of the vertical line $s = -0.12$ in the complex s-plane. The system mechanical modes, with the parameters of the PSSs set as in Table 10, are given in Table 11.

TABLE 9

NEW ENGLAND SYSTEM MECHANICAL MODES [NO PSSs]

Nominal Loading	Light Loading	Heavy Loading
-0.1497 ± j 9.7347	-0.1251 ± j 9.7589	-0.0474 ± j 9.9539
-0.0974 ± j 9.7325	-0.1061 ± j 9.7251	-0.1271 ± j 9.9859
-0.1596 ± j 9.3918	-0.1763 ± j 9.3650	-0.1874 ± j 9.6220
-0.1060 ± j 8.2562	-0.0957 ± j 8.2862	-0.1652 ± j 8.2474
-0.1602 ± j 8.0703	-0.1133 ± j 8.0257	-0.0986 ± j 8.0706
-0.1048 ± j 7.3998	-0.1036 ± j 7.4389	-0.0245 ± j 7.2248
-0.1208 ± j 6.7662	-0.1267 ± j 6.8346	-0.1202 ± j 6.5599
-0.0487 ± j 6.2368	-0.0908 ± j 6.3413	**0.0713 ± j 6.0828**
-0.0344 ± j 4.3339	-0.0591 ± j 4.4094	-0.0240 ± j 4.2226

TABLE 10
PSS PARAMETERS [EXAMPLE 2, WITH J_1]

PSS on Generator	K	τ_1	τ_3
G_5	7.1032	0.251	0.4897
G_7	12.262	0.418	0.5374
G_9	17.421	0.0839	0.1794

TABLE 11
NEW ENGLAND SYSTEM MECHANICAL MODES [WITH J_1]

Nominal Loading	Light Loading	Heavy Loading
-0.1505 ± j 9.7339	-0.1258 ± j 9.7589	-0.1273 ± j 9.9851
-0.3829 ± j 9.2979	-0.3976 ± j 9.2673	-0.5969 ± j 9.5426
-0.2355 ± j 8.4489	-0.2091 ± j 8.4601	-0.2765 ± j 8.3930
-0.4461 ± j 8.0569	-0.4363 ± j 8.0780	-0.1763 ± j 8.2518
-0.1701 ± j 8.0748	-0.1265 ± j 8.0321	-0.4260 ± j 8.1458
-0.3664 ± j 7.3302	-0.3469 ± j 7.3190	-0.4919 ± j 7.1658
-0.8253 ± j 5.7902	-0.8090 ± j 6.0256	-0.5352 ± j 6.1122
-2.1609 ± j 5.1353	-2.3512 ± j 5.5410	-1.5505 ± j 4.9521
-0.4535 ± j 3.7823	-0.4111 ± j 4.0102	-0.4692 ± j 3.4604

The dynamic responses of the system to a 6-cycles three-phase fault near bus 29 at the end of line 26-29 are shown in Figs. 17 to 19, for the three loading conditions.
For comparison purposes, the system responses for the same conditions and with PSS parameter settings as suggested in [13] are shown in Figs. 20 to 22. It is quite evident that an excellent improvement in the damping over a wide range of operating conditions has been achieved with one set of PSS parameters.

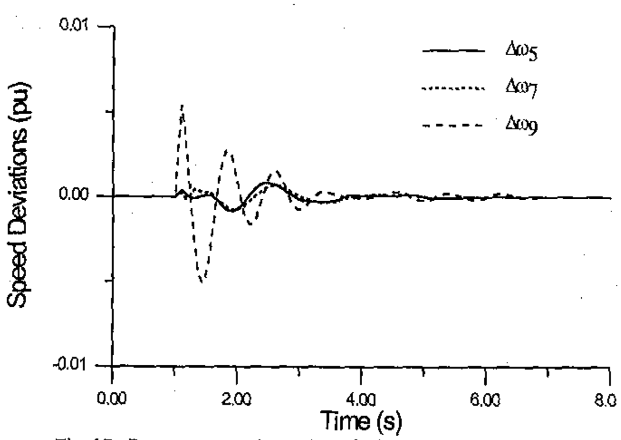

Fig. 17. Response to a three-phase fault for nominal condition [New England system with J_1]

The optimum values of the PSS parameters, when the objective function selected is J_2 with $\beta = 0$ and $\alpha = 77$, are listed in Table 12. The achieved J_2 is -0.013.
The system mechanical modes, with the parameters of the PSSs set as in Table 12, are given in Table 13.

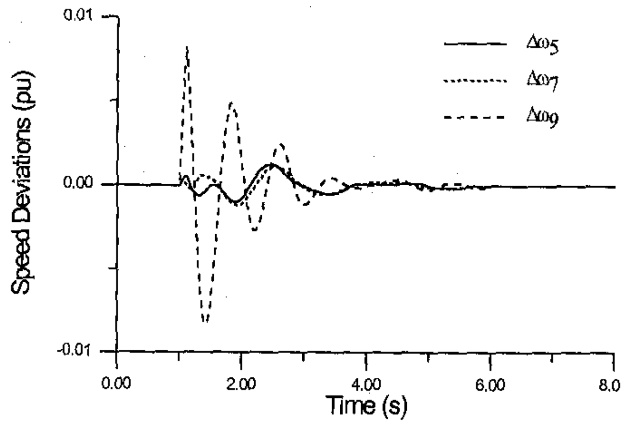

Fig. 18. Response to a three-phase fault for light condition [New England system with J_1]

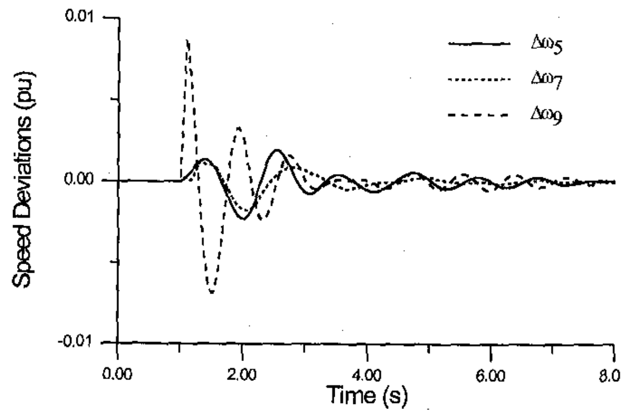

Fig. 19. Response to a three-phase fault for heavy condition [New England system with J_1]

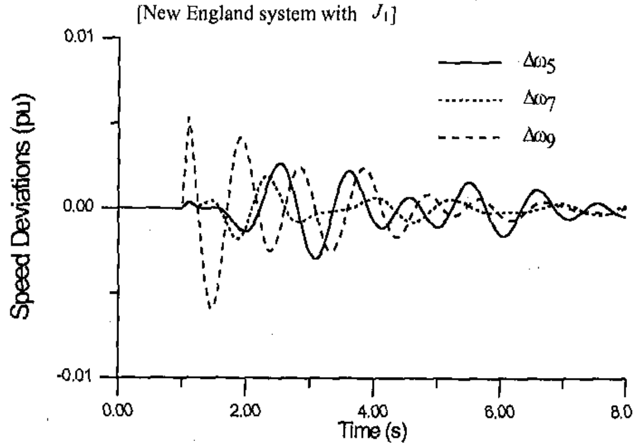

Fig. 20. Response to a three-phase fault for nominal condition [New England system: PSSs setting as in [13]]

The dynamic responses of the system to the same type of disturbance are shown in Figs. 23 to 25, for the three loading conditions considered.
It is worth noting that, in general, for a system consisting of m machines, each equipped with a PSS of the type described in this paper, the system order will be $4m$, the number of parameter to be optimized by the GA will be $3m$, and the

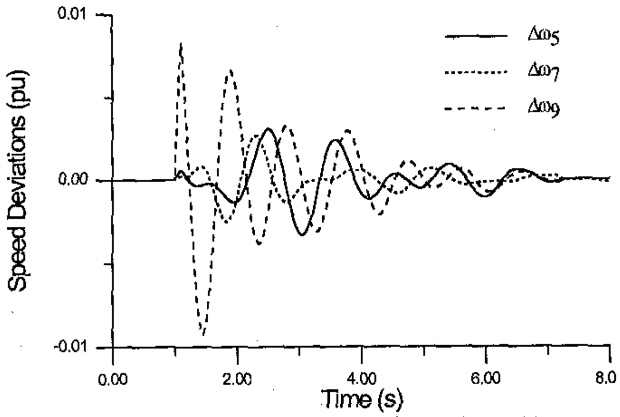

Fig. 21. Response to a three-phase fault for light condition [New England system: PSSs setting as in [13]]

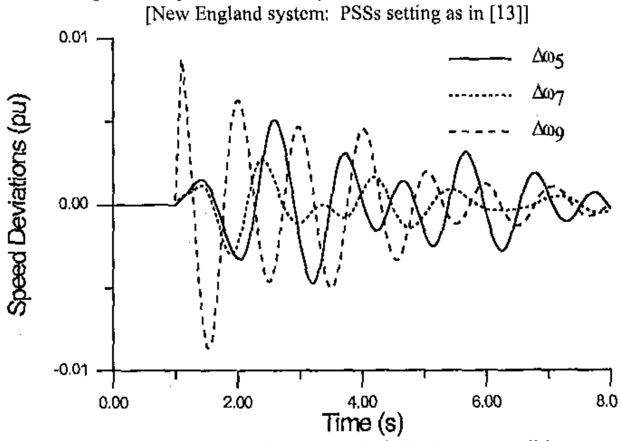

Fig. 22. Response to a three-phase fault for heavy condition [New England system: PSSs setting as in [13]]

TABLE 12
PSS PARAMETERS [EXAMPLE 2, WITH J_2]

PSS on Generator	K	τ_1	τ_3
G_5	9.6826	0.7284	0.7523
G_7	9.6826	0.2987	0.3226
G_9	20.00	0.1316	0.06

TABLE 13
NEW ENGLAND SYSTEM MECHANICAL MODES [WITH J_2]

Nominal Loading	Light Loading	Heavy Loading
-0.1505 ± j 9.7342	-0.1257 ± j 9.7591	-0.1275 ± j 9.9853
-0.2105 ± j 9.1586	-0.2172 ± j 9.1238	-0.2915 ± j 9.2310
-0.1616 ± j 8.4558	-0.1590 ± j 8.4568	-0.1628 ± j 8.2783
-0.4218 ± j 7.9190	-0.1235 ± j 8.0287	-0.2134 ± j 8.2517
-0.1691 ± j 8.0731	-0.5212 ± j 7.9030	-0.5792 ± j 8.0788
-0.2456 ± j 7.2810	-1.4988 ± j 7.0178	-0.3056 ± j 7.1172
-1.522 0± j 6.3114	-0.2306 ± j 7.2694	-0.8478 ± j 6.1657
-0.5730 ± j 4.7553	-0.4556 ± j 4.7771	-0.9705 ± j 4.8363
-0.5514 ± j 2.7146	-0.6273 ± j 2.7882	-0.3622 ± j 2.7631

number of mechanical modes to be shifted will be $m-1$. If N operating points are considered for simultaneous stabilization, the GA will tune the $3m$ PSS parameters such that the $N(m-1)$ modes are relocated as specified.

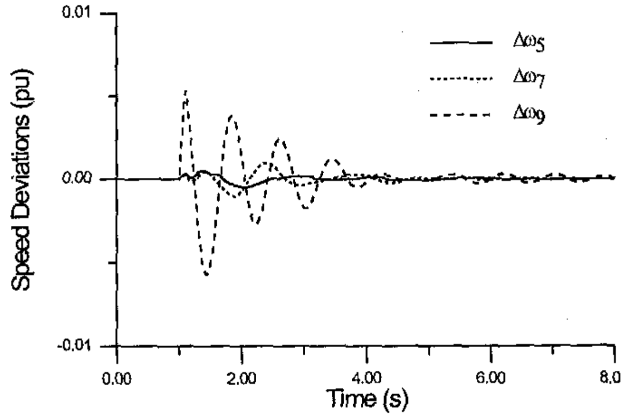

Fig. 23. Response to a three-phase fault for nominal condition [New England system with J_2]

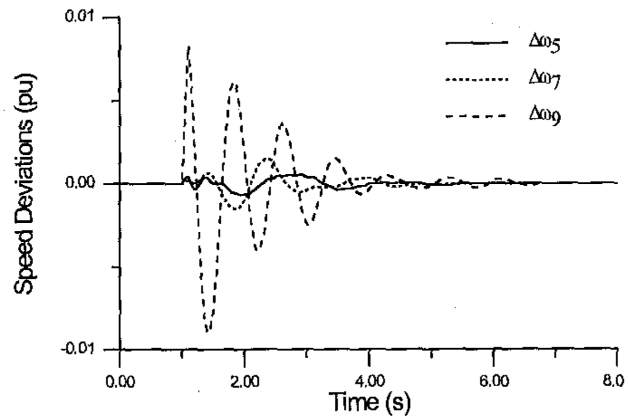

Fig. 24. Response to a three-phase fault for light condition [New England system with J_2]

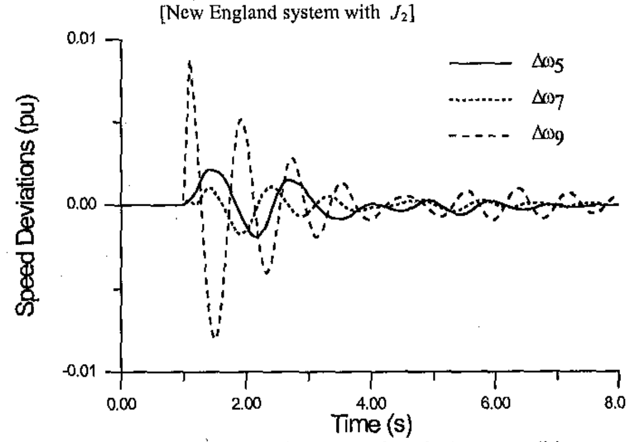

Fig. 25. Response to a three-phase fault for heavy condition [New England system with J_2]

VI. CONCLUSIONS

The simultaneous stabilization of a power system over a wide range of operating conditions via a single-setting power system stabilizer using genetic algorithms is investigated in this paper. The power system operating at various loading is treated as a finite set of plants. The problem of selecting a single set of power system stabilizer parameters, which simultaneously stabilizes this set of plants is converted to a simple optimization problem which is solved by a genetic algorithm and an eigenvalue-based objective function. Two objective functions are presented, allowing the selection of the stabilizer parameters to shift all or some of the system eigenvalues to the left-hand side of a vertical line in the complex s-plane, or to a wedge-shape sector in the complex s-plane. The effectiveness of the suggested technique in enhancing the dynamic stability of multimachine power systems is verified through eigenvalue analysis and simulation results. It is shown that it is possible to select a single set of PSS parameters to ensure the stabilization of the system over a wide loading range.

VII. ACKNOWLEDGMENTS

The authors acknowledge the support and encouragement of King Fahd University of Petroleum and Minerals .

VIII. REFERENCES

[1] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning,* Reading, MA: Addison-Wesley Publishing Company Inc., 1989.

[2] P. J. Fleming and C. M. Fonseca, "Genetic algorithms in control systems engineering", Research Report No. 470, Dept. of Automatic control and Systems Engineering, University of Sheffield, Sheffield, UK., March 1993.

[3] J. J. Grefenstette, "Optimization of control parameters for genetics algorithms," *IEEE Transactions on Systems, Man and Cybernetics*, vol. SMC-16, no. 1, January/ February 1986, pp. 122-128.

[4] L. Davis, *Handbook of Genetic Algorithms*, New York, Van Nostrand Reinhold, 1991.

[5] P.L. Dandeno, A.N. Karas, K.R. McClymont, and W. Watson, "Effect of high-speed rectifier excitation systems on generator stability limits," *IEEE Trans.*, vol. PAS-87, 1968, pp. 190-196.

[6] F. P. de Mello, L.N. Hannett, and J. M. Undrill, "Practical approach to supplementary stabilizing from accelerating power," *IEEE Trans.*, vol. PAS-97, 1978, pp. 1515-1522.

[7] E. V. Larsen and D. A. Swann, "Applying power system stabilizers," *IEEE Trans.*, vol. PAS-100, no. 6, 1981, pp. 3017-3046.

[8] F. P. de Mello and C. Concordia, "Concepts of Synchronous machine stability as affected by excitation," *IEEE Trans.*, vol. PAS-88, 1969, pp. 316-327.

[9] M. K. El-Sherbini and D. M. Mehta, "Dynamic Systems stability - investigation of the effect of different loadings and excitation systems," *IEEE Trans.*,vol. PAS-92, 1973, pp. 1538-1546.

[10] M. D. Vidyasagar, *Control System Synthesis : A factorization Approach*, Cambridge, MA, MIT Press, 1985.

[11] Y. L. Abdel-Magid, M. Bettayeb, and S. Selim, "Power System Output Feedback Stabilizer Design via Genetic Algorithms," *Proceedings of the 2nd IEE/IEEE International Conference on Genetic Algorithms in Engineering Systems: Innovations and Applications, GALESIA'97*, Glasgow, United Kingdom, 2-4 September 1997, pp. 56-62.

[12] P. M. Anderson and A. A. Fouad, *Power System control and stability*, Iowa, Iowa State Univ. Press, 1977.

[13] T. Hiyama and T. Sameshima, "Fuzzy logic control scheme for on-line stabilization of multimachine power system," *Fuzzy Sets and Systems*, vol. 39, 1991, pp. 181-194.

[14] Y. Y. Hsu and C. L. Chen, "Identification of optimum location for stabilizer applications using participation factors," *IEE Proceedings, Pt. C*, vol. 134, no.3, May 1987, pp. 238-244.

[15] E. Z. Zhou, O. P. Malik, and G. S. Hope, "Theory and method for selection of power system stabilizer location," *IEE Trans. on Energy Conversion*, vol. 6, no. 1, 1991, pp. 170-176.

IX. APPENDIX

Machine Model

$$\dot{\delta}_i = \omega_b(\omega_i - 1) \tag{A.1}$$

$$\dot{\omega}_i = \frac{T_{mi} - T_{ei} - D_i(\omega_i - 1)}{M_i} \tag{A.2}$$

$$\dot{E}'_{qi} = \frac{E_{fdi} - (x_{di} - x'_{di})\, i_{di} - E'_{qi}}{T'_{doi}} \tag{A.3}$$

$$\dot{E}_{fdi} = \frac{K_{ai}(V_{refi} - V_i + U_i) - E_{fdi}}{T_{ai}} \tag{A.4}$$

$$T_{ei} = E'_{qi}\, i_{qi} - (x'_{qi} - x'_{di})\, i_{di}\, i_{qi} \tag{A.5}$$

X. BIOGRAPHIES

Y. L. Abdel-Magid (M' 74, SM' 87) received the B. Sc. (Honors) from Cairo University, Egypt, in 1969 and the M. Sc. and the Ph. D. degrees from the University of Manitoba, Winnipeg, Canada, in 1972 and 1976 respectively, all in Electrical Engineering. From 1976 to 1979, he was with Manitoba Hydro as a Telecontrol engineer. During the 1990-1991 academic year, he was a visiting scholar at Stanford University, Palo Alto, CA, USA. His research interests include power system control and operation, adaptive and robust control of power systems, and applications of AI techniques in power systems.

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DISCUSSION

Glauco N. Taranto, Djalma M. Falcão and A. L. B. do Bomfim (COPPE/Federal University of Rio de Janeiro): The authors are to be commended for an interesting paper on the simultaneous tuning of multiple power system stabilizers using Genetic Algorithms. Their viewpoint lines up with our previous work reported in [A], [B] and [C], thus corroborating the utilization of GAs in the tuning of damping controllers.

As indicated by the authors, the objective function is evaluated using only those eigenvalues that need to be shifted. Two questions arise from this statement:

- How the authors track the modes that need to be shifted, during the GA execution?
- It is known that for high-gain PSSs, an exciter mode outside the electromechanical frequency bandwidth may become poorly damped. If, in such a case, only the electromechanical modes are being accounted for in the objective function, the final tuned control parameters may be unacceptable. Could the authors comment on this point?

Based on our experience with the New England system, it is quite impossible to enhance the system overall damping up to reasonable values considering PSSs only at the Generators 5, 7 and 9, as confirmed by the authors' results. Damping enhancement is constrained by low-damped multivariable zeros, as shown in Figure 1. Those zeros are obtained from the matrix transfer function with the inputs being the reference voltages at the voltage regulator summing junction of Generators 5, 7 and 9 and the outputs being the rotor speed of these generators, respectively. Even though the operating condition presented in Figure 1 does not exactly correspond to any of the operating conditions considered in the paper it suffices to support our viewpoint.

By the time of this writing, we have not heard from the IEEE Power System Analysis, Computing, and Economics Committee, a position with respect to the reviewing process of our paper [D] also submitted in December 1997. In [D], besides a large-scale system application, we have also applied the GA-based tuning approach formulated in [A], to the New England system. Simultaneous tuning of nine PSSs (PSS on Generator 1 was not considered) in fourteen operating conditions was performed. For this case the nine-input nine-output transfer function matrix has the pole-zero map shown in Figure 2. One can note the absence of low-damped zeros at the bandwidth of interest. The point we want to stress, is that although GA being a powerful optimization tool, in this case used for tuning fixed-control structures, cannot be blindly used. We promote the idea of combining GA with analytical techniques.

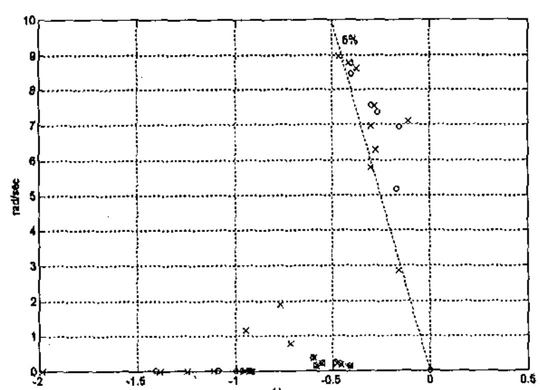

Figure 1 – Multivariable Pole-Zero Map (3 input – 3 output transfer matrix)

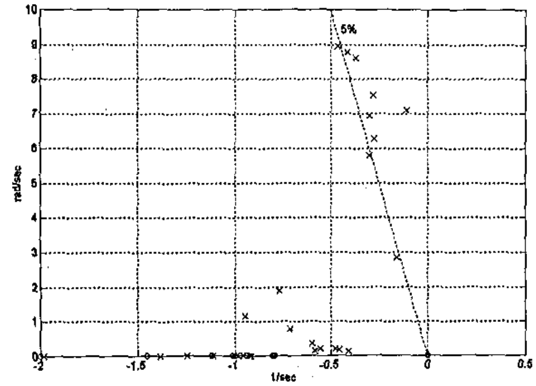

Figure 2 – Multivariable Pole-Zero Map (9 input – 9 output transfer matrix)

Very few details are given in the paper as far as the GA process itself is concerned. Have the authors used a standard GA? Details could be given for:

1. What is the performance of the GA approach in a number of trials? Are the examples given from one single run, or for an average of runs with different initial populations?
2. What was the stopping criteria used?
3. What were the CPU time spent to run both examples? In which piece of hardware?

[A] G. N. Taranto & D. M. Falcão, "A Genetic-Based Control Design for Damping Power System Inter-Area Oscillations," *Proceedings of the 35th IEEE Conference on Decision and Control*, Kobe, Japan, December 1996.

[B] A. L. B. do Bomfim, G. N. Taranto & D. M. Falcão, "Tuning of Power System Damping Controllers Using Genetic Algorithms," *Proceedings of the International Conf. on Intelligent System Application to Power Systems (ISAP)*, Seoul, South Korea, July 1997.

[C] G. N. Taranto & D. M. Falcão, "Robust Decentralized Control Design using Genetic Algorithms in Power System Damping Control," *IEE Proceedings on. Generation, Trans-mission and Distribution*, Vol. 145, No. 1, pp. 1-6, January 1998.

[D] A. L. B. do Bomfim, G. N. Taranto & D. M. Falcão, "Simultaneous Tuning of Power System Damping Controllers Using Genetic Algorithms," submitted to the IEEE T-PWRS in December 1997.

Abdel-Magid, Y.L., Abido M.A., Al-Baiyat S. and Mantawy A.H.: The authors express their appreciation to Dr. Glauco N. Taranto, Djalma M. Falcao and A. L. B. do Bomfim for their valuable comments. We would like to clarify the questions raised by the discussers in the same order as the discussion:

1. The modes that need to be shifted were tracked using the participation factors method as explained in reference 14 of the paper.
2. The exciter modes outside the electromechanical frequency bandwidth that may become poorly damped at high-gain PSSs may be taken into consideration by incorporating them in the formulation of the objective

function calculation. In this manner, the damping of these modes will be also improved.

3. The placement of the stabilizers on generators 5, 7 and 9 was determined using the participation factors method explained in references 14 and 15 of the paper, to enhance the poorly-damped modes as shown in Table 9. This agrees with the results obtained in reference 13 of the paper. It is clear that the improvement in the damping of the electromechanical modes, with this choice of stabilizers, is not the same for all modes. In fact, the improvement is small for some of the modes. It is imperative to realize that some factors such as system topology, system parameters, machine constants, PSSs structures, and operating conditions could affect the results and the conclusions reached. However, we agree with the discussers that, in general, analytical methods can be combined with powerful AI techniques such as GA, if needed.

4. The results given in the paper were obtained following several runs with different population sizes, crossover and mutation probabilities. The GA parameters are given in the paper. The stopping criterion was the maximum number of generation or the achievement of an acceptable value for the objective function. Figures 4 and 11 of the paper show the performance of the GA for Example 1. The simulations, using Fortran, were made on a Pentium-66 PC. A typical CPU time of 25 seconds/generation was observed for Example 2.