International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.1, Issue1, pp-229-235 ISSN: 2249-6645

SIMULTANEOUS TUNING OF POWER SYSTEM STABILIZER PARAMETERS FOR MULTIMACHINE SYSTEM

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ABSTRACT*: Optimal multiobjective design of robust multimachine power system stabilizers (PSSs) using genetic algorithms is presented in this thesis. A conventional speed-based lead-lag PSS is used. 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 - *Small signal stability, genetic algorithms, multiple objective optimization, robustness, simultaneous stabilization.*

1. INTRODUCTION

In multi-machine power systems with several poorly damped modes of oscillations, several power system stabilizers (PSS) need to be on-line and optimally tuned. With present-day large-scale systems comprising many interconnected machines, the problem of PSS tuning is not a straight-forward exercise, and in some cases can become relatively too complex to resolve. The problem of PSS tuning is further complicated by the fact that operating conditions in a power system are continuously varying. Therefore tuning the PSS such that, it would provide a satisfactory performance over the entire range of variations is a rather exhaustive exercise.
Research has been directed towards the design of adaptive (self-tuning), variable structure and other control strategies that provide robust tuning. However, implementation of such PSS requires continuous on-line calculation of an identified model using parameter estimation and evaluation of the control strategy. In recent years, research has been directed towards the application of advanced numerical computation methods such as neural networks and genetic algorithms (GA) to PSS tuning.

This paper presents the design of a GA based PSS that uses a eigen value based parameter optimization criterion to determine the *fitness function* of an individual within a population of possible solutions. Genetic algorithms are global search techniques and provide a powerful tool for optimization problems by miming the mechanisms of natural selection and genetics. These operate on a population of potential solutions applying the principle of survival of the fittest to produce better and better approximations to a solution. In each generation, a new set of approximations is created by the process of selecting the individuals according to their level of fitness in the problem domain and breeding them together using operators borrowed from natural genetics [1]. Thus, the population of solutions is successively improved with respect to the search objective, by replacing least fit individuals with new ones (offset of individuals from the previous generation), better suited to the environment, just as in natural evolution. The performance (*fitness*) of each individual in the problem domain is assessed through an objective function that ultimately establishes the basis for the biased selection process. Higher the individuals fitness is, higher is its chance to pass on genetic information to successive generations. The selected individuals are then modified through the application of *genetic operators*, in order to obtain the next generation. Thus GA based optimization of PSS parameters is more likely to converge to the global optima than a conventional optimization, since they search from a population of possible solutions, and are based on probabilistic transition rules. Moreover, by tuning the PSS simultaneously, the eigenvalue drift problem is eliminated. In the recent literature, application of genetic algorithm to tune the parameters of PSS has been reported [1], [2], [7]. A GA based optimization method has been used in [2] to tune the parameters of a rule-based PSS. This way, the advantages of the rule-based PSS such as its robustness, less computational burden and ease of realization are maintained. Introduction of GA helps obtain an optimal tuning for all PSS parameters simultaneously, which thereby takes care of interactions between different PSS. In [2] simultaneous tuning for all the PSS in the system using a GA based approach has been developed. The GA seeks to shift all eigenvalues of the system within a region in the stable domain.

2. APPLICATION OF GENETIC ALGORITHM TO PSS DESIGN

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 functions 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. A genetic algorithm (GA)-based approach to robust PSS design, in which several operating conditions and system configurations are simultaneously considered in the design process, is presented. 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. Initially, the robust PSS design was formulated as a single objective function problem, and not all PSS parameters were considered adjustable. However, in practice, one is typically confronted with multiple objective functions and these objective functions are generally of diverse natures. In this thesis, the problem of robust PSS design is formulated as a multiobjective optimization problem and GA is employed to solve this problem. Moreover, unlike [2], 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.

3. CONTROLLER TUNING:

The problem of selecting the parameters of the controllers that would assure maximum damping performance over the considered set of operating points is solved via a GAs optimization procedure with an eigenvalue based performance index.

A. MODEL AND CONTROL STRUCTURE

Equations 1 describe a linear model of power system extracted around a certain operating point.

$$\dot{x} = Ax + Bu \qquad (1)$$
$$y = Cx + Du$$

The controller is a lead-lag type described by:

$$V(s) = K(s)y(s) \qquad (2)$$

where $K(s)$ is the transfer function of the controller, $y(s)$ is the measurement signal and $V(s)$ is the output signal from the controller which will provide additional damping by moving modes to the left. Equation 2 can be expressed in the statespace form as:

$$\dot{x}_k = A_k x_k + B_k y \qquad (3)$$
$$u = C_k x_k + D_k y$$

where x_k is the state vector of the controller. Combining Equations 1 and 3 with Equations 1 and 2 a closed loop system given in Equation 4 is obtained.

$$\dot{x}_{cl} = A_{cl} x_{cl} \qquad (4)$$

Let $\lambda_i = \sigma_i \pm j\omega_i$ be the *i*-th eigenvalue (mode) of the closed loop matrix. Then, the damping coefficient (ζ) of the i-th eigenvalue is defined by

$$\zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \qquad (5)$$

The structure of PSS is given below.

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

B. OBJECTIVE FUNCTION

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

$$J_1 = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \ge \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 \qquad (6)$$

where *np* is the number of operating points considered in the design process, and $\sigma_{i,j}$ is the real part of the *i*-th eigenvalue of the *j*-th operating point. The relative stability is determined by the value of σ_0.

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 region bounded by minimum of the damping coefficients in the left-half of the complex s-plane. In order to do this, the objective function of (7) is changed to:

$$J_2 = \sum_{j=1}^{np} \sum_{\zeta_{i,j} \le \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \qquad (7)$$

where $\zeta_{i,j} \le \zeta_0$ is the damping ratio of the *i*-th eigenvalue of the *j*-th operating point. This will place the closed-loop eigenvalues in a wedge-shape sector in which $\zeta_{i,j} \ge \zeta_0$ as shown in Fig. 4.2

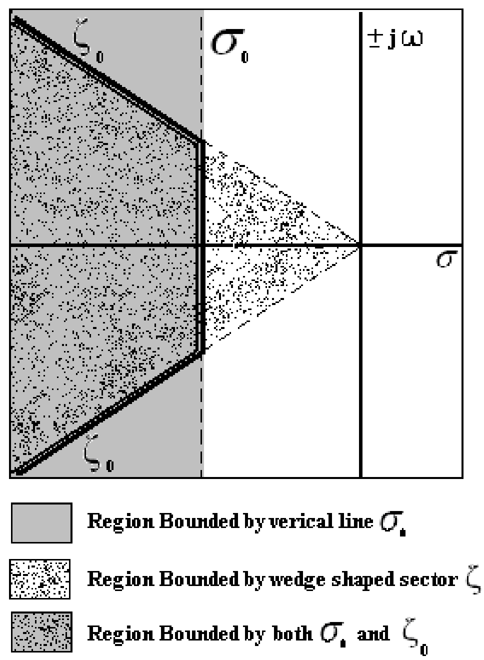


Fig.1 Interested region of pole locations in s-plane

These single objective problems may be converted to a multiple objective problem by assigning 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:

$$J = J_1 + aJ_2 \quad (8)$$

$$J = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 + a \sum_{j=1}^{np} \sum_{\zeta_{i,j} \leq \zeta_0} [\zeta_0 - \zeta_{i,j}]^2$$

This will place the system closed-loop eigenvalues in the D-shape sector as shown in Fig.4.3. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS parameter bounds:

Minimize J subject to

$$\begin{Bmatrix} K_{i,\min} \leq K_i \leq K_{i,\max} \\ T_{1i,\min} \leq T_{1i} \leq T_{1i,\max} \\ T_{2i,\min} \leq T_{2i} \leq T_{2i,\max} \\ T_{3i,\min} \leq T_{3i} \leq T_{3i,\max} \\ T_{4i,\min} \leq T_{4i} \leq T_{4i,\max} \end{Bmatrix} \quad (9)$$

The minimization of the objective function *J* 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 he 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. The proposed approach employs GA to solve this optimization problem and search for optimal or near optimal set of PSS parameters, $K_i, T_{1i}, T_{2i}, T_{3i}, T_{4i}$ for *i* =1 to *m*, where *m* is the number of machines.

C. CONTROL PARATMETERS AND GA PARAMETERS

A two stage lead/lag compensator structure was chosen for the PSS. Hence all the five parameters (K, T_1, T_2, T_3 and T_4) are taken as control parameters. Gain K is bounded between 0.5 and 150 and all Time constants are bounded between 0.01 and 1.5 seconds. These parameter-bounds were defined on the basis of conventional control design for nominal operating condition. In GA implementation, the crossover and mutation probabilities of 0.95 and 0.033, respectively, are found to be quite satisfactory. The number of individuals in each generation is selected to be 200. In addition, the search will terminate if the best solution does not change for more than 50 generations or the number of generations reaches 100 for single objective function and 200 for multi-objective function respectively.

4. TEST SYSTEM AND PSS DESIGN

The one-line diagram of the test system is given in Fig. 2. This two-area power system, which as a benchmark system for inter-area oscillations studies consist of two generators in each area, connected via a 220 km tie line. All generators are equipped with simple exciters and have the same parameters. Damping control is provided at all four generators.

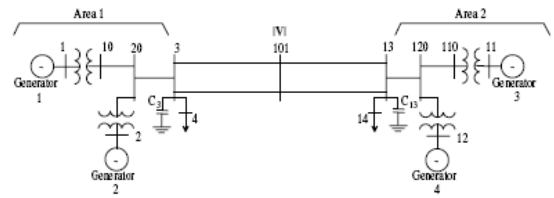


Fig 2. Two Area 4 Machine Power System

To design the proposed PSSs, two different operating conditions that represent the system under severe loading conditions and critical line outages in addition to the base case are considered. These conditions are extremely harsh from the stability viewpoint [6]. Two system configurations, which is heavily loaded with 400 MW of power flowing from area 1 to area 2, were analyzed:

- Operating Condition 1 — System with two lines between bus 3 and 101
- Operating Condition 2 — System with a single line between bus 3 and 101

There are 30 parameters to be optimized, namely $K_i, T_{1i}, T_{2i}, T_{3i}, T_{4i} \quad i = 1,2,3$. The time constant T_w is set to be 5 s [7]. In this study, σ_0 and ζ_0 are chosen to be 1.0 and 0.20, respectively.

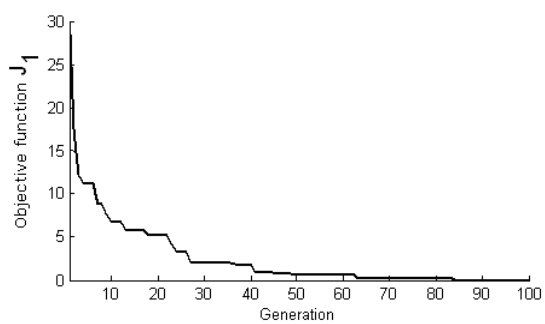


Fig. 3 Convergence for objective function J_1

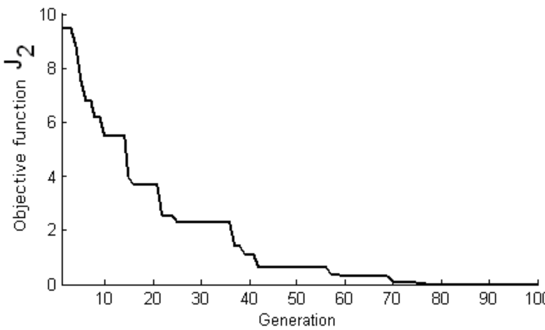


Fig. 4 Convergence for objective function J_2

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 and, and the multiobjective function are shown in Fig. 4, 5 and 6. The final value of the objective functions J_1 and J_2 is 0, indicating that all of the electromechanical modes have been shifted to the left of the vertical line σ_0 = -1 and ζ_0=0.2 respectively. The final value of the objective function $J= J_1+aJ_2$ is J=0, indicating that all of the electromechanical modes have been shifted to the specified D-shape sector in the s-plane.

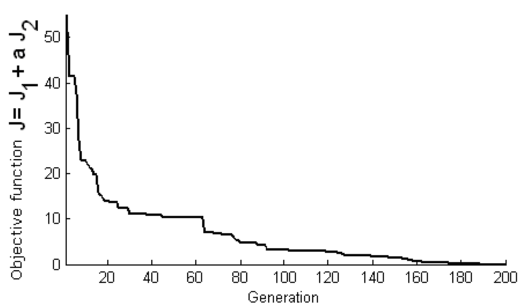


Fig. 5 Convergence for objective function J

Table I Tuned PSS parameters for Objective function J_1 , J_2 and J.

Obj	Gen	K	T_1	T_2	T_3	T_4
J_1	G1	39.2777	0.7111	0.0359	0.274	0.0695
	G2	42.6168	1.127	0.0476	0.359	0.0561
	G3	20.1555	0.774	0.0287	0.630	0.0685
	G4	34.5081	0.1737	0.0617	0.2445	0.0714
J_2	G1	38.9357	0.8276	0.0247	0.7307	0.0555
	G2	31.7945	0.9154	0.0383	0.8157	0.0397
	G3	34.2916	0.7733	0.0248	1..095	0.0479
	G4	10.2385	0.1612	0.0953	1.1954	0.0466
J	G1	48.8622	0.3686	0.0137	0.445	0.0159
	G2	28.6638	0.7259	0.0252	0.6528	0.037
	G3	42.938	0.7016	0.0426	0.5638	0.0403
	G4	49.4392	0.1211	0.0619	0.3043	0.0228

5. SMALL SIGNAL AND LARGE SIGNAL TESTS

Small-signal analysis provides a mean to compare the damping of the different system modes.

Table II. Eigenvalues and Damping ratios of electromechanical modes with and without PSSs

	Case K2L			Case K1L		
	σ	$\pm j\omega$	ζ	σ	$\pm j\omega$	ζ
With out PSSs	0.191	5.808	-0.03	0.195	5.716	-0.03
	0.088	4.002	-0.02	0.121	3.798	-0.03
	-0.028	9.649	0.003	0.097	6.006	-0.01
With PSSs J_1	-1.198	12.649	0.094	-1.26	12.157	0.103
	-1.276	11.827	0.107	-1.24	11.799	0.105
	-1.080	10.782	0.100	-1.05	10.784	0.098
With PSSs J_2	-2.887	12.496	0.225	-3.06	12.561	0.237
	-3.543	11.319	0.299	-3.47	11.228	0.295
	-2.894	10.996	0.255	-2.78	10.961	0.247
With PSSs J	-3.281	14.606	0.219	-3.27	14.494	0.220
	-2.739	13.119	0.204	-2.61	12.395	0.206
	-2.632	11.242	0.228	-2.64	11.083	0.232

To better understand the results, we have completed the small signal analysis of the tuned PSS was performed on the system for both single tie-line (K1L) and on two tie-lines (K2L) configurations. The system electromechanical modes, for the base case and the two operating conditions (cases K1L–K2L), without and with the PSSs tuned using J_1 , J_2 and J are listed in Table II.

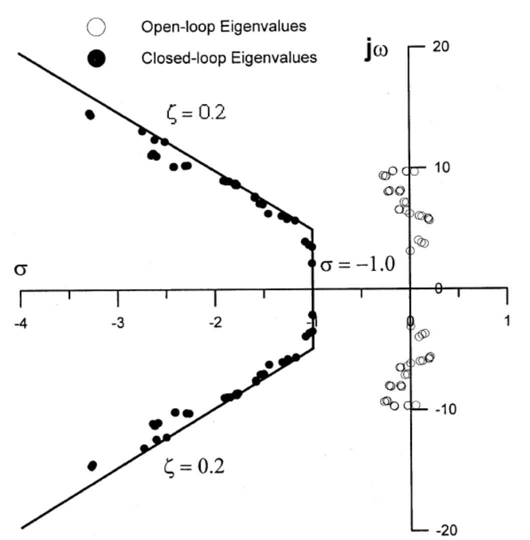


Fig. 6 Eigenvalues associated with modes of ***J***

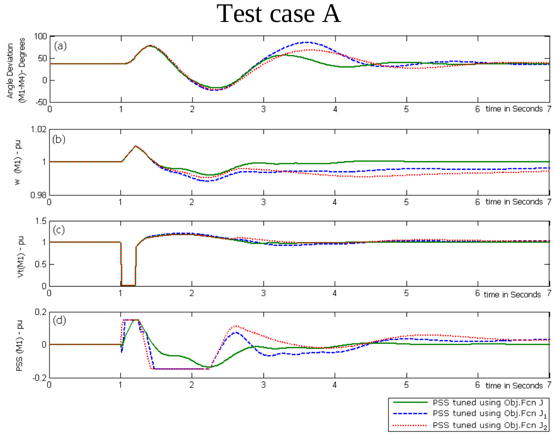
In assessing PSS, small-signal performance is not enough. Good performance during large perturbations and good robustness with respect to changing operating conditions are other criteria of an equal importance. To demonstrate the effectiveness of the PSSs tuned using the proposed multiobjective function over a wide range of operating conditions, the following disturbance is considered for nonlinear time simulations.

Table III. Test Cases for Large Signal Assessment

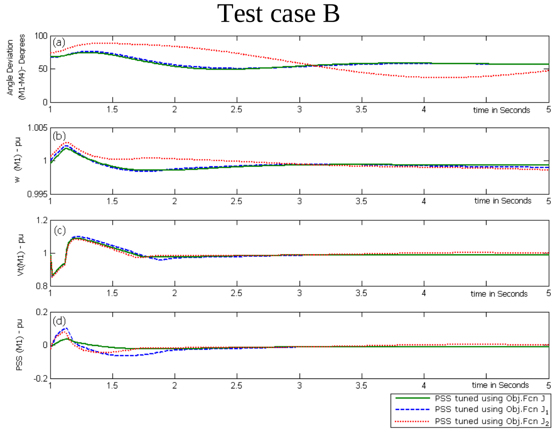
TEST CASE NAME	SYSTEM CONFIGURATION	CONTINGENCY DESCRIPTION
A	**K2L SYSTEM**	**5 cycle, three phase fault at bus 101 with the outage of 230 KV line.**
B	**K2L SYSTEM**	**5 cycle, three phase fault at bus 1 with no equipment outage.**
C	**K1L SYSTEM**	**3 cycle, single phase fault at bus 120 without outage.**

It is clear that the system response from Fig.7 that, 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 is used. This indicates that the time domain specifications were simultaneously met.

Test case A



Test case B



Test case C

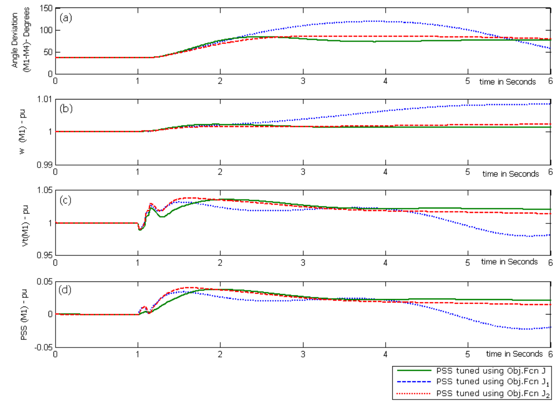


Fig. 7 Responses for Test case A, B and C respectively.

(a) Angular Deviation (δ_{14}) between (M1-M4) in Degrees

(b) Speed (ω_1) of M1 in pu.

(c) Terminal voltage (V_t) of M1 in pu

(d) PSS output for M1 in pu.

7. CONCLUSION

In this thesis, optimal multiobjective design of robust multimachine power system stabilizers (PSSs) using GAs is proposed. 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 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 and non linear time-domain simulations, 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 inter-area modes of oscillations.

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