

Coordinated Synthesis of PSS Parameters in Multi-Machine Power Systems Using the Method of Inequalities Applied to Genetic Algorithms

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Abstract—A new method has been proposed based on the method of inequalities for the coordinated synthesis of Power System Stabilizer (PSS) parameters in multi-machine power systems in order to enhance overall system small signal stability. Since the coordination and control of PSS's is a Pareto-optimization problem, a comprehensive list of design objectives has been presented in terms of a set of inequalities. To solve these inequalities, Genetic Algorithms have been applied to determine the PSS parameters.

Index Terms—Power System Stabilizers, Small Signal Stability, Method of Inequality, Genetic Algorithms.

I. INTRODUCTION

WITH the interconnection of large electric power systems, low frequency oscillations have become the main problem for power system small signal stability. They restrict the steady-state power transfer limits, which therefore affects operational system economics and security. Considerable effort has been placed on the application of Power System Stabilizers (PSS's) to damp low frequency oscillations and thereby improve the small signal stability of power systems [1]–[3]. To date, PSS's have proved to be very effective and economical tools and therefore have been widely used by utilities.

With the wide application of PSS's, there exists the possibility of adverse interactions, especially in multi-machine, multi-modal power systems. In recent years, the coordination and control of PSS's in order to improve the dynamic performance of a multi-machine system has received great attention.[4]–[17]. Feedback control is the principal method adopted in power systems because stabilization objectives can be easily met. Feedback control generally can be divided into state feedback control and output feedback control.

Optimal control has been applied by Yu [4], which implies a trade-off between performance and the cost of control. However, optimal control involves considerable trial and error in choosing the weight matrix until satisfactory performance is achieved. Pole-placement control has been adopted by Chow [5] and Yu [6], which places the eigenvalues far from the imaginary axis making the speed of response very fast. But this method involves pole-zero cancellation, which is only effective for one

operating condition. Once the operating conditions change, the oscillations may reappear. Both optimal control and pole assignment are state feedback control methods that require all of the state variables to be measured and acquired. Since not all of the state variables are available, a state observer usually needs to be designed, thereby making the control system more complex and restricting its configuration. Consequently, the controllers designed by state feedback methods are impractical in large interconnected power systems.

Decentralized output feedback control, termed as modulation control, has been recognized as a practical method and adopted by utilities. According to the strategies used for the coordinated synthesis of PSS parameters, they can be divided into two categories: sequential setting algorithms and simultaneous setting algorithms. Sequential eigenvalue assignment algorithms which select the PSS parameters in multimachine systems have been proposed by Fleming [7] and Abdalla [8]. The main disadvantage of this method is that the sequential addition of stabilizers will disturb the previously assigned eigenvalues. For the simultaneous setting of the PSS parameters, numerical optimization techniques are generally used to find optimum solutions. Optimization methods currently adopted by most researchers are based on gradient methods or linear programming. [9]–[13] select the parameters of PSS's by the use of gradient-based iterative methods, which may encounter difficulties with regard to the search direction and finally may fail to find solutions. In addition, the solution is heavily dependent on the initial value and might easily converge to a local minimum. Linear programming has been applied by [14]–[17] to tune the parameters, which formulates the variation of the relevant eigenvalues as a linear function of the controller parameter increment based on modal analysis. The linear estimation of the eigenvalue variation is only valid within a small range of the parameter space. Therefore, the initial value of the control parameters has a decisive effect on the final solution. Moreover, the valid parameter space is very difficult to forecast because the computation of the eigenvalues is highly nonlinear. To date, researchers have only considered the electro-mechanical oscillation modes related to the generator swing equations. However, the arbitrary setting of the pole locations for the electro-mechanical oscillation modes may cause new poorly damped or unstable oscillation modes, termed as control modes, because of the interactions between the PSS's and the other components as well as the interactions amongst the PSS's. Following a small disturbance, these modes would eventually dominate the dynamic performance of the system.

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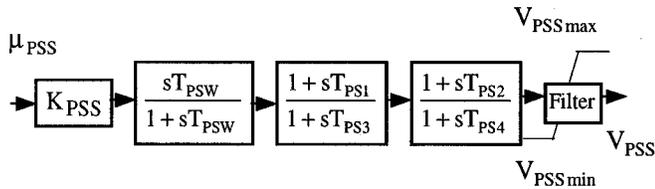


Fig. 1. The structure of a Power System Stabilizer.

It has been shown in this paper that the coordination and control of PSS's is a pareto-optimization problem. Consequently, it is impossible to improve one performance index without worsening the others. There exists a very large set of Pareto-optimal solutions and therefore the use of optimization methods for choosing the "best" solution is time consuming. Therefore, a comprehensive list of design objectives have been proposed in this paper, which are directly expressed in terms of a set of inequalities. The satisfaction of the design criteria means that the design objectives have been achieved and a satisfactory design has been obtained. The original algorithms to solve the inequalities include Moving Boundaries Process (MBP) and Nelder Mead Dynamic Minimax (NMDM). As emphasized in the research performed by Whidborne [18], these methods may fail to find the feasible solutions. In recent years, there has been widespread interest from the control community in applying Genetic Algorithms (GA's) to solve design problems in control system engineering [19]–[20]. Compared with the traditional methods, the parallel nature of GA's aids in exploring a set of feasible solutions, which provides the designer with a large amount of information about the possible design schemes.

II. POWER SYSTEM MODEL AND MODAL ANALYSIS

A. Power System Model

The linear state space representation of a power system containing PSS's applied to generators can be expressed as:

$$\begin{aligned} \frac{d\Delta X}{dt} &= A\Delta X + B\Delta\mu \\ \Delta Y &= C\Delta X \end{aligned} \quad (1)$$

where

- ΔX is a vector of state variables deviations;
- $\Delta\mu$ is a vector of PSS output deviations;
- ΔY is a vector of PSS input deviations.

The typical structure of a PSS consists of a gain, a washout unit, phase compensation units and an output limiter plus a filter unit, which is shown in the Fig. 1 [2]. The washout unit is used to avoid steady changes of the input signal modifying the terminal voltage. From the viewpoint of interarea mode oscillations, the washout time constant is set at 10s to reduce phase lead at the frequency range of the interarea modes and therefore to minimize the adverse interactions with the interarea modes. To provide pure damping, the PSS should have appropriate phase-lead characteristics to compensate the phase-lag between the generator exciter input and the electrical output torque. Two lead-lag blocks are used in this paper although the number and characteristics of phase compensation units could be modified according

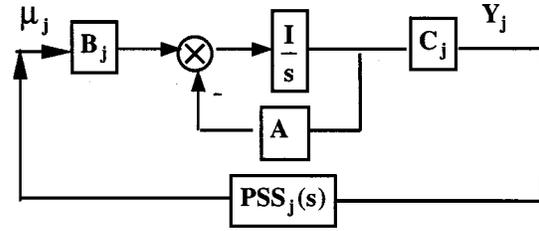


Fig. 2. State-space representation with the j^{th} PSS.

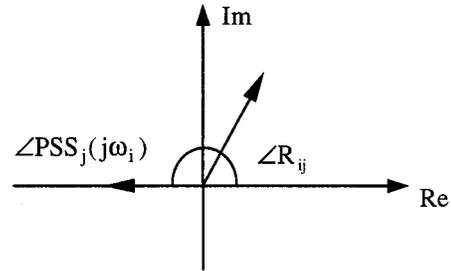


Fig. 3. The relationship between residue phase and phase compensation of the j^{th} PSS to damp the i^{th} natural mode.

to the design requirements. The PSS gain should be set to a value, which results in satisfactory damping without compromising the stability of the other modes and the system transient stability margin. The parameters of the gain and time constants of the phase compensation units therefore need to be determined such that the system has sufficient damping. The output limits are imposed to restrict the level of generator output voltage fluctuations during transient conditions.

B. Modal Analysis

Suppose only one PSS, signified as the j^{th} PSS, is designed to damp the i^{th} oscillation mode, the state space representation related to the j^{th} PSS is shown in Fig. 2.

The modal controllability and modal observability indicates the capability of the j^{th} PSS to control and observe the i^{th} natural modes, which can be expressed as $CO_{ij} = LV_{ij} * B_j$ and $OB_{ij} = C_j * RV_{ij}$ respectively. Suppose that the j^{th} PSS has a transfer function $PSS_j(s) = K_{PSSj} H_{PSSj}(s)$, the sensitivity of the i^{th} eigenvalue, λ_i to the gain of supplementary damping controller K_{PSSj} can be derived as:

$$\frac{\partial \lambda_i}{\partial K_{PSSj}} = R_{ij} \left. \frac{\partial PSS_j(s)}{\partial K_{PSSj}} \right|_{s=\lambda_i}, \quad (2)$$

where R_{ij} the residue associated with the i^{th} natural mode and the j^{th} PSS, which can be expressed as $R_{ij} = CO_{ij} * OB_{ij}$. Thus the residue R_{ij} indicates the capability of the j PSS, which is placed at a specific position and uses a specific input signal, to affect the i^{th} natural mode. As shown in Fig. 3, in order to provide pure damping, it is desirable to move the vector R_{ij} to be in line with negative real axis [3]. It is preferable to slightly under-compensate the phase $\Delta PSS_j(j\omega_i)$, which means that both positive synchronizing torque and damping torque are achieved [2].

III. INTERACTION ANALYSIS AND DESIGN OBJECTIVES

A. Interaction Analysis

1) *Interaction Analysis Related to the Electro-Mechanical Oscillation Modes:* Since the electro-mechanical oscillation modes involve the generator swing equations, their number is one less than the number of generators. When a PSS is inserted into the system, it will affect all of the electro-mechanical oscillation modes through its own control matrix B_j . Based on modal analysis, the magnitude of the residue $R_{k,j}$ ($k = 1, 2, \dots, n_{gen} - 1$) indicates the capability of the j^{th} PSS to affect these modes, and the phase diagram of the residue $R_{k,j}$ ($k = 1, 2, \dots, n_{gen} - 1$) gives the phase characteristics of the j^{th} PSS. Since multiple electro-mechanical oscillation modes exist in the system, it is possible that the phase difference between two electro-mechanical oscillation modes can be approximately 180° , which means that the action of damping one electro-mechanical oscillation mode would simultaneously weaken the damping of another one. The extent of this negative damping effect depends upon the magnitude of the residue corresponding to that mode. This indicates that the design objectives are in conflict and the solution is therefore Pareto-optimal. Since every PSS will definitely affect all electro-mechanical oscillation modes to some extent, the interactions should be considered when several PSS's are inserted into the system. All the PSS's should be coordinated to provide sufficient damping for all the electro-mechanical oscillation modes because the damping effect on each mode is the cumulative effect of the contributions of each PSS.

Additionally, in order to ensure transient stability margins, the frequency excursion of every electro-mechanical oscillation mode should be limited within a narrow range. Since the residue phase characteristics of a PSS is different for different modes, the PSS designed to provide pure damping on one mode will affect the frequency of the other modes. When several PSS's are inserted into the system, they should therefore be coordinated to ensure that the frequency deviation of each electro-mechanical oscillation mode is within a narrow range.

2) *Interaction Analysis Related to the Original Natural Modes:* A similar approach to that described in (i) can be used to investigate the damping effect of the PSS's on the natural modes. The total number of natural modes of the system including all of the dynamic devices is equal to the number of state variables, which is much larger than the number of the electro-mechanical modes. It should be noted that the contribution of the PSS's to the natural modes could be positive or negative. Consequently, after the PSS's are introduced into the system, old natural oscillation modes may be excited due to the interactions between the PSS's and other components, which is a factor that limits the damping ability of the PSS's. All PSS's should be coordinated and controlled to minimize the detrimental effect on other natural modes so that these modes have sufficient stability margin for different operating conditions.

3) *Interaction Analysis Related to the New Modes:* According to the structure of the PSS shown in Fig. 1, it can be seen that the PSS's will add new modes into the power system. These modes may become poorly damped

oscillation modes due to the interactions amongst the PSS's as well as the interactions between the PSS's and other dynamic components, thereby limiting the damping ability of the PSS's. More importantly, the interactions related with these modes cannot be predicted due to the uncertainty of the PSS parameters. All of the PSS's should be coordinated to ensure that these modes are well damped and have sufficient small signal stability margins.

B. Control Design Objectives

Based upon the above interaction analysis, an eigenvalue control scheme is proposed to meet the design objectives for the coordination of the PSS's. The eigenvalue control strategy aims at increasing the damping ratio of the electro-mechanical oscillation modes without worsening the transient stability margins or causing the other modes to become unstable.

The comprehensive control design objectives are summarized as follows:

- (i) The damping ratio of the electro-mechanical oscillation modes is set above the minimum acceptable damping ratio, ζ_{madr} , which ensures that these modes have sufficient damping and considerable stability margin.

$$\zeta_k \geq \zeta_{madr} \quad (k = 1, 2, \dots, n_{gen} - 1). \quad (3)$$

- (ii) Frequency excursions of the electro-mechanical oscillation modes should be limited within a narrow range, which ensures that the system transient stability margins will not be adversely affected. This requirement can be represented as:

$$(1 - \gamma_{\min})\omega_k \leq \omega_k + \text{Im}(\Delta\lambda_k) \leq (1 + \gamma_{\max})\omega_k \quad (k = 1, 2, \dots, n_{gen} - 1). \quad (4)$$

- (iii) Except for the electro-mechanical modes, all other modes, including the original natural modes and the new modes, should be placed in the left half s plane. In particular, the damping ratio of the control modes caused by interactions between the PSS's and other automatic controllers or the interactions amongst the PSS's should be above the minimum marginal damping ratio, ζ_{mmdr} . This ensures that these modes will not become the dominant poorly damped modes and have sufficient stability margin for different operating conditions.

$$\zeta_i \geq \zeta_{mmdr} \quad (i = 1, 2, \dots, n; n \neq k). \quad (5)$$

In Fig. 4, the control objectives are depicted in the complex s -plane.

IV. APPLICATION OF GENETIC ALGORITHMS TO DETERMINE THE PARAMETERS

Genetic Algorithms are heuristic search algorithms based on the mechanics of natural selection, genetics and evolution. [21]–[22]. The main procedure of applying GA's to search the optimum parameters of the PSS's include:

1) *Encoding:* The first step in applying GA's to the selection of PSS parameters is Encoding, which maps the parameters of the PSS's into a fixed-length string.

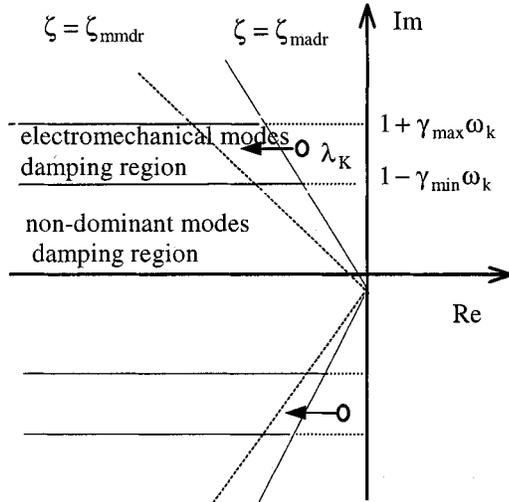


Fig. 4. Coordination and control objectives of PSSs.

2) *Fitness Computation*: According to the comprehensive design objectives as mentioned above, the procedures of fitness computation are described in Fig. 5.

3) *New Population Production*: New populations are created using three operators: Reproduction, Crossover and Mutation. Reproduction is a process in which individual strings are copied according to their fitness value. Reproduction directs the search toward the best existing individuals but does not create any new individuals. The main operator working on the parents is Crossover, which happens for a selected pair with a crossover probability P_c . Multi-point crossover has been applied to solve combinations of features encoded on chromosomes. Although Reproduction and Crossover produce many new strings, they do not introduce any new information into the population. As a source of new bits, mutation is introduced and is applied with a low probability P_m .

4) *Stopping Criterion*: If all of the objectives are met, the generation cycles will terminate. Otherwise, go to step (ii) and compute the fitness for each population.

5) *Decoding*: This process converts binary alphabets into digital numbers, which gives meaning to the strings, after which the PSS parameters are finally determined.

The whole procedure of applying GA's to determine the parameters of PSS's is summarized as:

- (i) Initialize population using random selection method.
- (ii) For each individual string, compute its fitness value as shown in Fig. 5.
- (iii) Check whether the objectives are met. If yes, go to step (v), otherwise, continue to step (iv)
- (iv) Produce new population using reproduction, crossover and mutation, then go back to step (ii)
- (v) Determine the parameters using the decoding process

V. EVALUATION

The coordinated synthesis of the PSS parameters using Genetic Algorithms has been evaluated using the New England Test System, which contains 10 single-unit equivalent generators, 39 busbars and 34 transmission lines. In this representation,

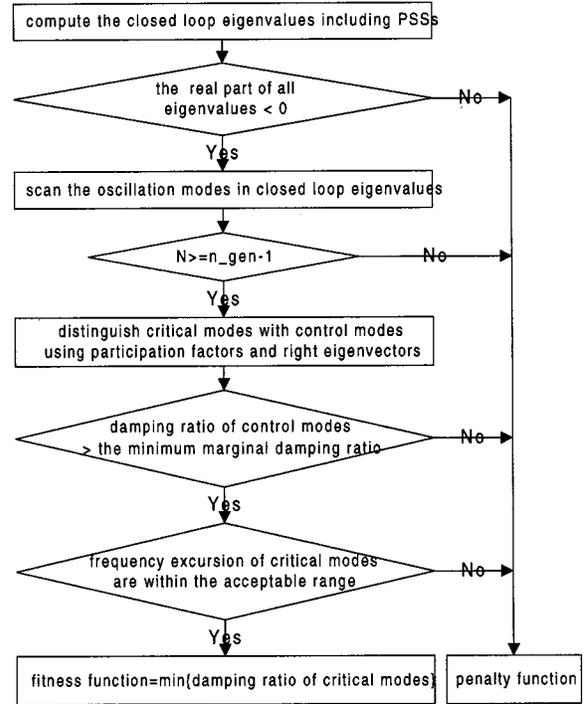


Fig. 5. Flow chart of fitness computation.

TABLE I
ELECTRO-MECHANICAL OSCILLATION MODES OF NEW ENGLAND TEST SYSTEM COMPARED WITH AESOPS RESULTS

critical Modes Eigenvalues	AESOPS Results	Frequency Hz	Damping Ratio
$-0.368 \pm j8.755$	$-0.37 \pm j8.74$	1.39	0.0420
$-0.403 \pm j8.675$	$-0.40 \pm j8.67$	1.38	0.0464
$-0.314 \pm j8.477$	$-0.31 \pm j8.48$	1.35	0.0370
$-0.275 \pm j7.459$	$-0.28 \pm j7.45$	1.19	0.0368
$-0.001 \pm j6.965$	$0 \pm j6.96$	1.11	-0.0002
$-0.249 \pm j6.997$	$-0.25 \pm j6.99$	1.11	0.0356
$-0.251 \pm j6.357$	$-0.25 \pm j6.35$	1.01	0.0394
$-0.260 \pm j5.996$	$-0.26 \pm j5.99$	0.95	0.0433
$-0.280 \pm j3.849$	$-0.28 \pm j3.84$	0.61	0.0725

the generator at busbar 39 is an equivalent of the USA-Canada interconnected system and its dynamic behavior approaches that of an infinite bus due to its own low impedance and high inertia characteristics.

There are nine electro-mechanical oscillation modes associated with the swing equations of the ten generators, which are compared to the results calculated by AESoPS [23] as shown in Table I.

To make the results comparable with the research of Pagola *et al.* [15], all of the generators except generator 39 have been equipped with PSS's. The residue phasor diagram of each PSS gives the comprehensive description of the PSS affecting all of the electro-mechanical modes. Fig. 6 shows that the PSS located in generator 30 has a great effect on mode 5 and mode 9. The action of damping on mode 5 and mode 9 would simultaneously weaken the damping on mode 6 since the phase difference is

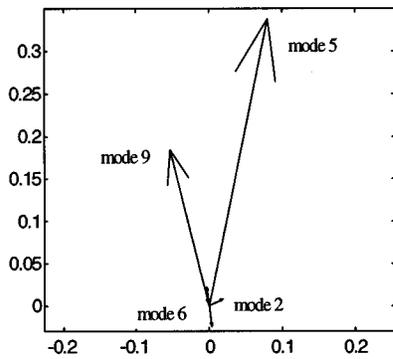


Fig. 6. Residue phasor diagram of PSS in generator 30.

TABLE II
ELECTRO-MECHANICAL OSCILLATION MODE COMPARISON BETWEEN WITHOUT PSS'S AND WITH PSS'S

Without PSS Eigenvalue	With PSS Eigenvalue	Frequency Hz	Damping Ratio
$-0.368 \pm j8.755$	$-1.712 \pm j9.011$	1.43	0.187
$-0.403 \pm j8.675$	$-1.593 \pm j9.163$	1.45	0.171
$-0.314 \pm j8.477$	$-1.120 \pm j8.671$	1.38	0.128
$-0.275 \pm j7.459$	$-1.160 \pm j7.465$	1.19	0.154
$-0.001 \pm j6.965$	$-0.939 \pm j6.998$	1.11	0.133
$-0.249 \pm j6.997$	$-1.924 \pm j7.258$	1.15	0.256
$-0.251 \pm j6.357$	$-1.177 \pm j6.294$	1.00	0.184
$-0.260 \pm j5.995$	$-1.414 \pm j5.657$	0.90	0.242
$-0.280 \pm j3.849$	$-0.834 \pm j3.385$	0.54	0.239

nearly 180°, which implies that the design objectives are in conflict so that the improvement of one performance would worsen the others. Therefore, the coordination synthesis of PSS's is a Pareto-optimal problem.

After undertaking the coordinated synthesis of the PSS's using GA's, all of the electro-mechanical oscillation modes including the interarea mode have been well damped and have considerable stability margins as shown in Table II.

Table III shows the control modes caused by the interactions between the PSS's and the other dynamic devices as well as amongst the PSS's. It can be observed that these modes have been well damped and have sufficient stability margins. The reason causing these control modes can be easily deduced by analyzing the participation factors which are also presented in Table III.

The starting values of the stabilizer parameters are randomly created within the specific range defined in step (i)—Initialization. In order to compare the results with those of the Linear Programming methods published in [15], the time constants are set such that $T_1 = T_2$ and $T_3 = T_4$. The final values of the PSS parameters are listed in Table IV.

The results based on Genetic Algorithms and Linear Programming are compared in Table V. The table also includes the minimum damping ratio for each method at its foot. It should be noted that one of main disadvantages of Pagola's method is that it is not possible to simultaneously tune the time constants and gains of the PSS's. Additionally, the published paper did not include details of the final PSS parameters.

TABLE III
CONTROL MODES IN THE CLOSED LOOP SYSTEM

No	With PSS	Damping Ratio	Main participating variables
1	$-16.7434 \pm j6.1129$	0.9394	$V_{Ex1} V_{pss2} V_{pss3} E_q$ related with Generator 32
2	$-10.3181 \pm j8.4724$	0.7728	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 30
3	$-12.5127 \pm j5.8397$	0.9062	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 33
4	$-10.0982 \pm j7.5397$	0.8013	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 38
5	$-9.9015 \pm j4.8868$	0.7309	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 37
6	$-7.8252 \pm j7.3072$	0.8967	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 35
7	$-7.5090 \pm j7.1201$	0.7256	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 34
8	$-6.7385 \pm j6.1239$	0.7400	$V_{pss2} V_{pss3} V_{Ex1} E_q$ related with Generator 31
9	$-6.2919 \pm j1.1983$	0.9823	$V_{pss2} V_{pss3} V_{Ex1}$ related with Generator 36
10	$-4.1301 \pm j1.2646$	0.9562	$E_{fd} V_{Ex2} E_q V_{tg1} V_{tg2} V_{pss2} V_{pss3}$ related with Gen36
11	$-4.3560 \pm j0.6849$	0.9879	$V_{tg2} V_{pss2} V_{pss3}$ related with Generator 34
12	$-1.3071 \pm j1.8715$	0.5726	$E_q V_{Ex2} E_{fd}$ related with Generator 38
13	$-1.0211 \pm j0.8220$	0.7790	E_q and E_{fd} related with Gen36 Gen38 and Gen35
14	$-0.3131 \pm j0.7230$	0.3974	E_q and V_{Ex2} related with Generator 30

TABLE IV
PARAMETERS OF PSS'S DETERMINED BY USING GA'S

Location	Gain of PSSs	Time constant $T_1=T_2$	Time constant $T_3=T_4$
Gen 30	0.262	0.415	0.060
Gen 31	0.220	0.329	0.099
Gen 32	0.094	0.241	0.039
Gen 33	0.086	0.277	0.056
Gen 34	0.098	0.343	0.115
Gen 35	0.248	0.398	0.088
Gen 36	0.150	0.178	0.128
Gen 37	0.198	0.339	0.084
Gen 38	0.072	0.297	0.077

It can be observed from Table V that, after using linear programming to optimize the PSS gains, the damping of electro-mechanical mode 6 is insufficient and the frequency excursion of the electro-mechanical mode 8 is large. Linear programming related to the PSS time constants converges to a local minimum, in which all of the electro-mechanical oscillation modes do not have sufficient stability margins. As a result, more efficient results can be obtained by using GA's to solve this inequality problem.

VI. CONCLUSIONS

In this paper, an investigation has been carried out into the coordinated synthesis of PSS's in a multi-machine system in order to enhance overall system small signal stability. Since the objective functions are nonlinear and nonconvex, optimization methods therefore often converge to a local minimum. More

TABLE V
EIGENVALUE COMPARISON BETWEEN CONVENTIONAL METHODS AND
GENETIC ALGORITHMS

No.	Genetic Algorithms	Linear Programming of Gains	Linear Programming of Time Constants
1	$-1.712 \pm j9.011$	$-0.99 \pm j8.80$	$-0.83 \pm j8.88$
2	$-1.593 \pm j9.163$	$-0.84 \pm j9.03$	$-0.53 \pm j8.86$
3	$-1.120 \pm j8.671$	$-1.34 \pm j8.48$	$-0.50 \pm j8.74$
4	$-1.160 \pm j7.465$	$-1.06 \pm j7.41$	$-0.57 \pm j7.69$
5	$-0.939 \pm j6.998$	$-1.05 \pm j7.53$	$-0.52 \pm j7.11$
6	$-1.924 \pm j7.257$	$-0.40 \pm j6.90$	$-0.55 \pm j7.30$
7	$-1.177 \pm j6.294$	$-0.92 \pm j6.44$	$-0.49 \pm j6.53$
8	$-1.414 \pm j5.657$	$-2.49 \pm j4.17$	$-0.50 \pm j6.07$
9	$-0.834 \pm j3.385$	$-0.91 \pm j3.91$	$-0.54 \pm j3.89$
ξ_{\min}	0.133	0.058	0.057

importantly, this paper shows that the coordination and control of PSS's is a Pareto-optimal problem, which implies that there exists a set of Pareto-optimal solutions and searching the "global" optimum based on optimization methods is time consuming. The method of inequalities is proposed in this paper to overcome the disadvantages of optimization methods, which is aimed at achieving satisfactory performance rather than optimal performance. A comprehensive eigenvalue control scheme has been presented to damp the electro-mechanical oscillation modes without causing unstable control modes and worsening system transient stability. Genetic Algorithms provide a computational procedure for determining the PSS's parameters simultaneously in order to solve the set of inequalities. This research has shown that, compared with traditional optimization methods, this scheme is more generic, less problem specific and more efficient solutions are therefore easy to obtain.

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