Design of Multi-Machine Power System Stabilizers using Gravitational Search Algorithm

M. Ramakrishna, G. Naresh

Abstract: Power system stabilizers (PSS) are used to generate supplementary control signals for the excitation system to damp electromechanical oscillations. This paper presents an approach based on the law of gravity and mass interactions called Gravitational Search Algorithm (GSA) fortuning the parameters of PSSs in a multi-machine power system.These stabilizers are tuned simultaneously to shift the lightly damped and undammed electromechanical modes of all plants to a prescribed zone in the s-plane. A multi objective 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 performance of the proposed PSS under different disturbances, loading conditions, and system configurations is investigated on New England 10-machine, 39-bus power system. Non-linear time domain simulation results are presented under wide range of operating conditions and disturbances at different locations to show the effectiveness of the proposed GSA based PSS and their ability to provide efficient damping of low frequency oscillations.

Keywords: Power System Stabilizer, Electromechanical Oscillations, Gravitational Search Algorithm, Multi-machine Power System.

I. INTRODUCTION

Damping of low frequency electromechanical oscillations is considered to be one of the most interesting and challenging tasks in power industry for the secure operation of the power system. These oscillations are often observed when large power systems are connected with weak tie-lines and also due to fast acting exciters with high gain Automatic voltage regulators (AVR). Over the past three decades, Power System Stabilizer (PSS), which acts as a supplementary modulation controller in the excitation systems has been the conventional means to curb with this problem. The PSS feedback suitable phase compensated signals derived from the power, speed and frequency of the operating generator either alone or in various combinations as input signals so as to generate an additional rotor torque to damp out the low frequency oscillations. The gain and the required phase lead/lag of the stabilizer are tuned by using appropriate mathematical models, supplemented by a good understanding of the system operation. The principles of operation of this controller are based on the concepts of damping and synchronizing torques within the generator. A comprehensive analysis of these torques have been dealt with by deMello and Concordia in their landmark paper in 1969 [1]. These controllers have been known to work quite well in the field and are extremely simple to implement. However,

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The tuning of these compensators continues to be a formidable task especially in large multi-machine systems with multiple oscillatory modes. Larsen and Swann, in their three part paper [2], describe in detail the general tuning procedure which employs Gradient procedure for optimization of PSS parameters.

The main drawback of the above controllers is their inherent lack of robustness. Power systems continually undergo changes in the load and generation patterns and in the transmission network. This results in an accompanying change in small signal dynamics of the system. The fixed parameter controllers, tuned for a particular operating condition, usually give good performance at that operating condition. Their performance, at other operating conditions, may at best be satisfactory, and may even become inadequate when extreme situations arise. In addition to that, conventional optimization methods that make use of derivatives and gradients are not able to locate or identify the global optimum [3-4].

Over the last decades, interests have been focused on the optimization of the PSS parameters to provide adequate performance for all operating conditions. Hence, many optimization techniques such as Simulated Annealing (SA) [5], Genetic Algorithms (GA) [6], Particle swarm optimization (PSO) [7] have been used to find the optimum set of parameters to effectively tune the PSS. The results obtained were observed to be promising and confirm the potential of these algorithms for optimal PSS design. However, every such technique is found to have its own pros and cons. Simulated Annealing algorithm has demonstrated to be an effectual means in escaping from local minima, but, its repeatedly annealing schedule is observed to be very slow especially if the objective function is expensive to compute. GA, a population-based search algorithm, which works with a population of strings that represent different potential solutions, has the ability to arrive at the global solution point swiftly, as it can handle the search space from different directions simultaneously. Crossover and mutation operators between chromosomes, makes the GA far less sensitive of being trapped in local optima. However, GA has shown degraded performance when dealing with highly epistatic problems. Also, it pains from premature convergence which can highly affect the effectiveness of the optimal solution [8]. PSO, a stochastic, population based algorithm, modelled with swarm intelligence is very simple to implement with much less parameters to train. However, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Also, the algorithm cannot work out the problems of scattering and optimization [9].

Moreover, the algorithm suffers from slow convergence in refined search stage which may lead it to possible entrapment in local minima. Several other meta-heuristic algorithms such as, Bacterial foraging algorithm [10,11], Artificial bee colony algorithm [12], Harmony search algorithm [13], were also proposed for optimal design of PSS to overcome the disadvantages of the above described approaches.

In this paper, a new population-based search algorithm, Gravitational search algorithm (GSA), which is based on the metaphor of gravitational interaction between the masses, is proposed for optimal tuning of PSS parameters. To investigate the potential of the proposed approach in shifting the unstable and poorly damped electromechanical modes to the left in S-plane under wide varied operating conditions, an eigenvalue based objective function reflecting the combination of damping factor and damping ratio is formulated. Finally, the Eigen value analysis and non-linear simulations have been carried out to access the effectiveness of the proposed GSAPSS under different disturbances and loading conditions. Finally the supremacy in the performance of the proposed GSAPSS over CPSS, GAPSS and PSOPSS is acknowledged.

II. PROBLEM STATEMENT

1.1. *Power System Model*

A power system can be modelled by a set of nonlinear differential equations as $\dot{X} = f(X, U)$, where X is the vector of the state variables, and U is the vector of input variables. In this study, all the generators in the power system are represented by their fourth order model and the problem is to design the parameters of the power system stabilizers so as to stabilize a system of 'N' generators simultaneously. The fourth order power system model is represented by a set of non-linear differential equations given for any i^{th} machine,

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \quad (1)$$

$$\frac{d\omega_i}{dt} = \frac{\omega_s}{2H}(P_{mi} - P_{ei}) \quad (2)$$

$$\frac{dE'_{qi}}{dt} = \frac{1}{T_{d0_i}}[-E'_{qi} - I_{di}(X_{di} - X'_{di}) + E_{fdi}] \quad (3)$$

$$\frac{dE'_{di}}{dt} = \frac{1}{T'_{q0i}}[-E'_{di} + I_{qi}(X_{qi} - X'_{qi})] \quad (4)$$

$$\frac{dE_{fdi}}{dt} = \frac{1}{T_{ai}}[-E_{fdi} + K_{ai}(V_{refi} - V_{ti})] \quad (5)$$

$$T_{ei} = E'_{di}I_{di} + E'_{qi}I_{qi} - (x'_{qi} - x'_{di})I_{di}I_{qi} \quad (6)$$

where d and q direct and quadrature axes,

δ_i and ω_i are rotor angle and angular speed of the machine,

P_{mi} and P_{ei} the mechanical input and electrical output power,

E'_{di} and E'_{qi} are the d-axis and q-axis transient emf due to field flux ,

E_{fdi}, I_{di} and I_{qi} are the field voltage, d-axis stator current and q- axis stator current,

X_{di}, X'_{di} and X_{qi}, X'_{qi} are reactance along d-q axes,

T'_{d0}, T'_{q0} are d-q axes open circuit time constants,

K_{ai}, T_{ai} are AVR gain and time constant

V_{refi}, V_{ti} are the reference and terminal voltages of the machine

For a given operating condition, the multi-machine power system is linearized around the operating point. The closed loop Eigen values of the system are computed and the desired objective function is formulated using only the unstable or lightly damped electromechanical Eigen values, keeping the constraints of keeping all the system modes stable under any condition.

2.2 PSS Structure

The speed based conventional PSS is considered in the study. The transfer function of the PSS is as given below.

$$U_i(s) = K_i \frac{sT_{wi}}{1+sT_{wi}}\left[\frac{(1+sT_{1i})(1+sT_{3i})}{(1+sT_{2i})(1+sT_{4i})}\right]\Delta\omega_i(s) \quad (7)$$

Where $\Delta\omega$ is the deviation of the speed of the rotor from synchronous speed

The second term in Eq. (6) is the washout term with a time constant of T_W. The third term is the lead–lag compensation to counter the phase lag through the system. The washout block serves as a high-pass filter to allow signals in the range of 0.2–2.0 Hz associated with rotor oscillations to pass unchanged. This can be achieved by choosing a high value of time constant (T_W). However, it should not be so high that, it may create undesirable generator voltage excursions during system-islanding [14]. Compromising, it may have a value anywhere in the range of 1–20 s [15]. On the other hand, the lead–lag block present in the system provides phase lead (some rare cases lag also) compensation for the phase lag that is introduced in the circuit between the exciter input (i.e. PSS output) and the electrical torque. In this study the parameters to be optimized are $\{K_i, T_{1i}, T_{2i}; i=1,2\ 3,...m\}$,assuming $T_{1i} = T_{3i}$ and $T_{2i} = T_{4i}$.

2.3 Objective Function

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

$$J_1 = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 \qquad (8)$$

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} Eigen value of the j^{th} operating point, subject to the constraints that finite bounds are placed on the power system stabilizer parameters. The relative stability is determined by the value of σ_0. This will place the closed-loop eigen values in a sector in which as shown in Fig. 1.

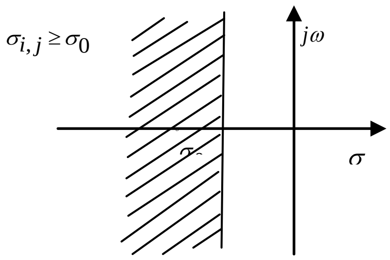

Figure 1: Closed loop eigen values in a sector

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

$$J_2 = \sum_{j=1}^{np} \sum_{\zeta_{i,j} \leq \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \qquad (9)$$

where $\zeta_{i,j}$ is the damping ratio of the i^{th} Eigen value of the j^{th} operating point. This will place the closed-loop Eigen values in a wedge-shape sector in which $\zeta_{i,j} > \zeta_0$ as shown in Fig. 2.

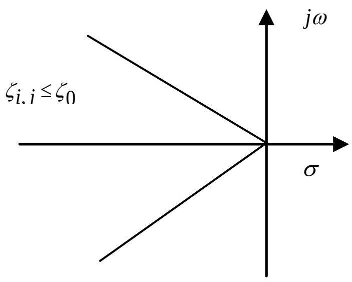

Figure 2: Representation of Eigen values in wedge shape sector

3) The single objective problems described may be converted to a multiple objective problem by assigning distinct weights to each objective. In this case, the conditions $\sigma_{i,j} \leq \sigma_0$ and $\zeta_{i,j} \geq \zeta_0$ are imposed simultaneously. The parameters of the PSS may be selected to minimize the following objective function:

$$J = J_1 + a.J_2$$

$$= \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 + a \cdot \sum_{j=1}^{np} \sum_{\zeta_{i,j} \leq \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \qquad (10)$$

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

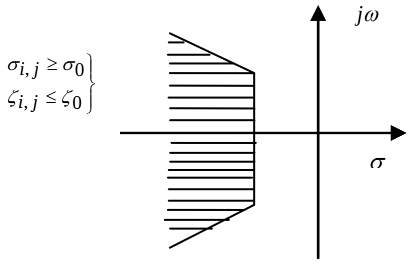

Figure 3: Representation of Eigen values in D-shape sector

It is necessary to mention here that only the unstable or lightly damped electromechanical modes of oscillations are relocated. The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS parameter bounds:

Minimize J subject to

$$K_{i_{min}} \leq K_i \leq K_{i_{max}}$$
$$T_{1i_{min}} \leq T_{1i} \leq T_{1i_{max}}$$
$$T_{2i_{min}} \leq T_{2i} \leq T_{2i_{max}} \qquad (11)$$

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} ; i=1,2 3,...m} where 'm 'is the number of machines. Typical ranges of the optimized parameters are [0.01,50] for K_i and [0.01 to 1.0] for T_{1i} and T_{2i} .

III.GRAVITATIONAL SEARCH ALGORITHM

3.1 Overview

The basic idea which motivates the proposed approach is based on the interaction of masses in the universe in accordance with Newtonian gravity law. The gravitation is the attraction of masses by other masses. The amount of attraction depends on the amount of masses and the distance between them. This gravity law defined by Newton is as follows, "Every particle in the universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them". It is formulated by the following equation.

$$F = G\frac{M_1 M_2}{R^2} \quad (12)$$

In this equation, F is the gravitational force (in N), G is the gravitational constant with a value of 6.67259×10^{-11} (in N(m2/kg2)), M_1 and M_2 are the masses of first and second particles, respectively(in kg),and R is the straight-line distance between the two particles (inm).

According to Newton's second law of motion, when a force (here it is gravitational force), F, is applied to a particle, its acceleration, a, depends only on the force and its mass, M [16] as,

$$a = \frac{F}{M} \quad (13)$$

Thus, there is an attracting gravity force on every particles of the universe where the effect of bigger and the closer particle is higher. An increase in the distance between two particles means decreasing the gravity force between them.

The proposed algorithm, GSA, is inspired by the above physical phenomenon. The agents are considered as objects and their performance is measured by their masses. All these objects attract each other by the gravity force, and this force causes a global movement of all objects towards the objects with heavier masses. The masses co-operate using the direct form of communication, gravitational force. By lapse of time, we expect that masses be attracted by the heaviest mass. This mass will present an optimum solution in the search space.

To describe GSA, consider a system with N masses (agents) and d dimensions. The solution set X which consists of randomly generated positions of N masses for d dimensions is shown below,

$$X = \begin{bmatrix} X_{11} & X_{12} & . & . & X_{1d} \\ X_{21} & X_{22} & . & . & X_{2d} \\ . & . & . & . & . \\ . & . & . & . & . \\ X_{N1} & X_{N2} & . & . & X_{Nd} \end{bmatrix} \quad (14)$$

Here, N is the total number of agents, d is the number of dimensions in the optimization problem. The position of the i^{th} mass can be defined as

$$X_i = \begin{bmatrix} X_{i1} & X_{i2} & . & . & X_{id} \end{bmatrix} \quad (15)$$

Here, X_{id} is the position of i^{th} mass in the d^{th} dimension. The positions of masses correspond to the solutions of the problems.

The mass of each agent is calculated after computing the fitness of that current agent as:

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (16)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_i(t)} \quad (17)$$

Where, $M_i(t)$ and $fit_i(t)$ represents mass and fitness value of agent i at t. $worst(t)$, $best(t)$ depends on the optimization problem.

i.e., for a minimization problem,

$$best(t) = \min\ fit_i(t); i \in \{1,...N\} \quad (18)$$

$$worst(t) = \max\ fit_i(t); i \in \{1,...N\} \quad (19)$$

(or)for maximization problem,

$$best(t) = \max\ fit_i(t); i \in \{1,...N\} \quad (20)$$

$$worst(t) = \min\ fit_i(t); i \in \{1,...N\} \quad (21)$$

Now, the gravitational force acting on mass i from mass j is given as,

$$F_i^d = G(t) * \frac{M_i(t) M_j(t)}{R_{ij}(t) + \varepsilon}\left(X_j^d(t) - X_i^d(t)\right) \quad (22)$$

Here, G is the gravitational constant, initialized at the beginning and will reduce with time in order to control the search accuracy, $R_{ij}(t)$ is the Euclidian distance between two agents i, j as defined in (2), ε is a small constant added to avoid division by zero.

Thus, by the law of motion as stated earlier, the acceleration of agent as in (2) is given by

$$a_i^d(t) = \frac{F_i^d(t)}{M_i^d(t)} \quad (23)$$

Later, the next velocity of an agent $V_i^d(t+1)$ is calculated as a fraction of its current velocity $V_i^d(t)$ added to its Acceleration $a_i^d(t)$ as,

$$V_i^d(t+1) = rand * V_i^d(t) + a_i^d(t) \quad (24)$$

Here, $rand$ is a uniform random variable with limits $[0,1]$ Finally, the next position of an agent is calculated as,

$$X_i^d(t+1) = X_i^d(t) + V_i^d(t+1) \quad (25)$$

3.2 IMPLEMENTATION

Based on the above discussion, the proposed GSA is implemented for tuning the parameters of PSS as a multi objective optimization problem.

The implementation of the proposed technique to tune the parameters of PSS was clearly summarized as a flow chart in Fig (4).

The GSA will be terminated when the termination condition is met. This may be usually a sufficiently a good objective function value or a maximum number of iterations. The maximum number of iterations (n_{max}) criterion is employed in this work and n_{max} is taken as 100. The number of agents is taken as 50.

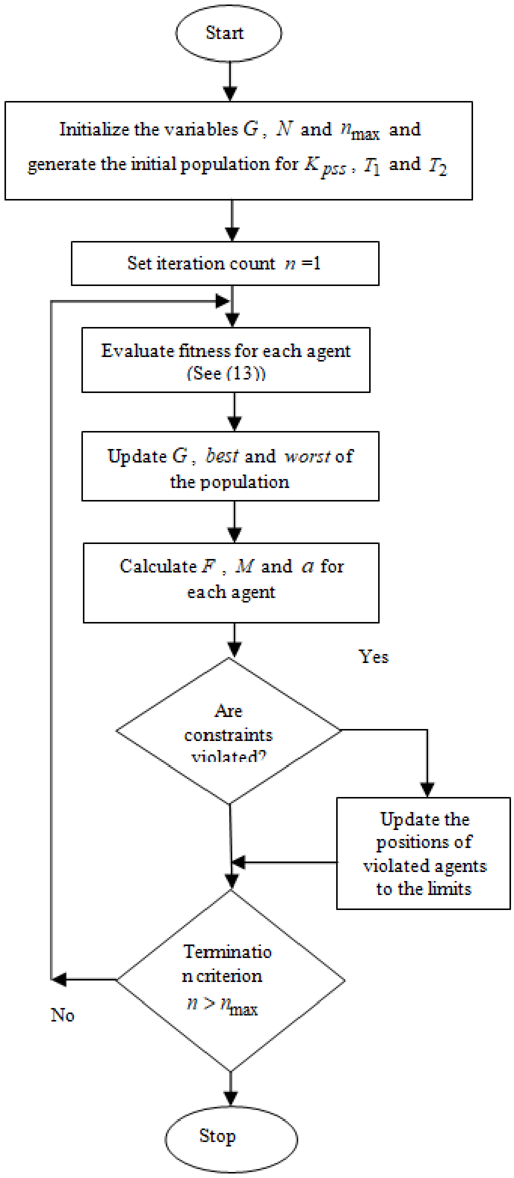

Figure 4: Flowchart of Gravitational search Algorithm

IV. RESULTS AND DISCUSSION

To demonstrate the effectiveness of the proposed method on a larger and more complicated power system, the readily accessible 10-generator 39-bus New England system is adopted. Fig. 5 shows the configuration of the test system. All generating units are represented by fifth-order model and their static exciters are equipped with PSS. Details of the system data are given in [17].

4.1 Eigen value analysis:

To design the proposed GSAPSS, three different operating conditions that represent the system under severe loading conditions and critical line outages in addition to the base case are considered. These conditions are extremely hard from the stability point of view [18]. They can be described as;

1) base case (all lines in service);
2) outage of line connecting bus no. 14 and 15;
3) outage of line connecting bus no. 21 and 22;
4) Increase in generation of G7 by 25% and loads at buses 16 and 21 by 25%, with the outage of line 21–22.

The tuned parameters of the ten PSS using conventional root locus approach, genetic algorithm, particle swarm optimization and proposed gravitational search algorithm are shown in the Table 1.

The small signal analysis of the test system was carried out without connecting the PSS. The electromechanical modes and the damping ratios obtained for all the above cases with CPSS, GAPSS, PSOPSS and proposed GSAPSS in the system are given in Table 2. The unstable modes for different operating conditions were found out and highlighted in the above Table.

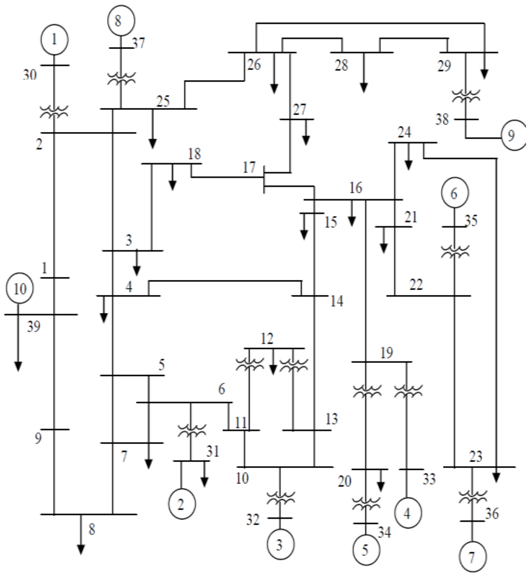

Figure 5: New England 10 generator 39 bus system

Table 1: Parameters of Conventional, GA, PSO and Proposed GSA

CPSS Parameters			GAPSS Parameters			PSOPSS Parameters			GSAPSS Parameters		
K	T1	T2	K	T1	T2	K	T1	T2	K	T1	T2
10.4818	0.6211	0.1789	32.200	0.5333	0.2333	18.6720	0.5800	0.2333	21.6662	0.5196	0.3605
0.6799	0.6185	0.1796	3.6000	0.8000	0.3933	34.6680	0.8200	0.3400	15.2803	0.7703	0.1198
0.2396	0.5778	0.1923	34.800	0.5333	0.2067	13.3400	0.8733	0.2067	8.2745	0.7309	0.1212
1.1531	0.5727	0.1940	24.400	0.5667	0.1267	0.01	0.5533	0.3400	9.8961	0.6767	0.1803
17.0819	0.6143	0.1809	32.200	0.8667	0.3400	10.6740	0.5800	0.2333	21.6873	0.6116	0.1704
13.4726	0.6163	0.1803	14.000	0.7333	0.3133	18.6720	0.6867	0.2867	12.0312	0.7325	0.0659
4.3773	0.5636	0.1971	32.200	0.5333	0.3667	2.6760	0.6600	0.2600	21.5175	0.6297	0.1902
0.5709	0.6099	0.1822	3.6000	0.5333	0.4200	8.0080	0.6867	0.3400	9.0397	0.6101	0.0859
1.6059	0.5429	0.2046	21.800	0.5333	0.2600	26.6700	0.7667	0.2067	11.0246	0.5656	0.1827
19.8488	0.5027	0.2210	8.8000	0.9000	0.2867	24.0040	0.7667	0.3933	16.9712	0.9669	0.2204

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It is clear that these electromechanical modes are poorly damped and some of them are unstable. Here 30 parameters are optimized namely, K_i , T_{1i} *and* T_{3i} ; i=1,2,3,..10. The time constant T_w is set to be 10. In this study σ_0 and ξ_0 are chosen to be -1.0 and 0.2 respectively. Several values for weight 'a' were tested. The results presented here are for a=10.

For base case from the Eigen value analysis, it is clear that all modes are well shifted in the D-stability region with ξ_{min} increased from -4.22% to 16.09% 0.0764 and σ_{max} from 0.2579 to -1.6941.

Similarly for case-1, ξ_{min} increased from -4.9% to 16.14% and σ_{max} from 0.2997 to -1.7396; for case-2, ξ_{min} increased from -4.43% to 16.27% and σ_{max} from 0.2018 to -1.7204 ; and for case-3 ξ_{min} increased from -6.44% to 16.35% and σ_{max} from 0.2352 to -1.7094.

Therefore, it is obvious that the critical mode Eigen values have been shifted to the left in s-plane and the system damping is greatly improved and enhanced with the proposed GAPSSs.

Table 7: Comparison of eigenvalues and damping ratios for different cases

	Case -1	Case-2	Case -3	Case -4
Without PSS	-1.1878 ±10.6655i, 0.1107	-1.1888 ±10.6603i, 0.1108	-1.1686 ±10.6268i, 0.1093	-1.1645 ±10.6163i, 0.1090
	-0.3646 ± 8.8216i, 0.0413	-0.3642 ± 8.8221i, 0.0412	-0.3413 ± 8.7548i, 0.0390	-0.3256 ± 8.8902i, 0.0366
	-0.3063 ± 8.5938i, 0.0356	-0.3087 ± 8.5753i, 0.0360	-0.3013 ± 8.4738i, 0.0355	-0.2977 ± 8.4483i, 0.0352
	-0.2718 ± 8.1709i, 0.0332	-0.2727 ± 8.1706i, 0.0334	-0.2575 ± 8.0464i, 0.0320	-0.2587 ± 8.0346i, 0.0322
	-0.0625 ± 7.2968i, 0.0086	-0.0643 ± 7.2859i, 0.0088	-0.0615 ± 7.3143i, 0.0084	-0.0575 ± 7.3333i, 0.0078
	-0.1060 ± 6.8725i, 0.0154	-0.1000 ± 6.7243i, 0.0149	**0.1283 ± 6.1862i, -0.0207**	**0.1557 ± 6.1630i, -0.0253**
	0.2579 ± 6.1069i, -0.0422	**0.2997 ± 6.1030i, -0.0490**	**0.0427 ± 6.0556i, -0.0070**	**0.0586 ± 6.0959i, -0.0096**
	0.0620 ± 6.1767i, -0.0100	**0.0824 ± 5.7423i, -0.0143**	**0.2018 ± 5.8565i, -0.0344**	**0.2089 ± 5.6778i, -0.0368**
	0.0794 ± 3.9665i, -0.0200	**0.0844 ± 3.8066i, -0.0222**	**0.1659 ± 3.7438i, -0.0443**	**0.2352 ± 3.6446i, -0.0644**
Conventional PSS	-1.5226 ±11.7232i, 0.1288	-1.5173 ±11.7109i, 0.1285	-1.3152 ±11.2723i, 0.1159	-1.3405 ±11.3267i, 0.1175
	-1.3326 ±11.2726i, 0.1174	-1.3362 ±11.2695i, 0.1177	-1.4305 ±11.2210i, 0.1265	-1.3380 ±11.2101i, 0.1185
	-1.9859 ±11.1499i, 0.1753	-1.9880 ±11.1547i, 0.1755	-2.0125 ±11.0700i, 0.1789	-2.0206 ±11.0315i, 0.1802
	-0.9837 ± 9.0350i, 0.1082	-0.9669 ± 9.0331i, 0.1064	-0.5674 ± 8.4623i, 0.0669	-0.5650 ± 8.4482i, 0.0667
	-0.5380 ± 8.5014i, 0.0632	-0.5240 ± 8.4869i, 0.0616	-0.7944 ± 8.1979i, 0.0964	-0.7508 ± 8.1182i, 0.0921
	-0.1568 ± 7.3758i, 0.0213	-0.1593 ± 7.3687i, 0.0216	-0.1547 ± 7.3961i, 0.0209	-0.1506 ± 7.4154i, 0.0203
	-1.0658 ± 7.2601i, 0.1452	**-0.0826 ± 6.1146i, 0.0135**	**-0.0051 ± 6.3664i, 0.0008**	**-0.0023 ± 6.3596i, 0.0004**
	-0.0046 ± 6.3800i, 0.0007	-1.0081 ± 6.0958i, 0.1632	-0.9179 ± 5.9988i, 0.1513	-0.6910 ± 5.8629i, 0.1171
	-1.2016 ± 4.5676i, 0.2544	-1.9766 ± 6.0065i, 0.3126	-0.9712 ± 3.5259i, 0.2656	-0.7668 ± 3.3898i, 0.2206
GAPSS	-1.1509 ±11.4696i, 0.0998	-1.1545 ±11.4461i, 0.1004	-1.1550 ±11.3826i, 0.1010	-1.1638 ±11.3603i, 0.1019
	-0.4693 ±11.4972i, 0.0408	-0.4779 ±11.4935i, 0.0415	-0.5047 ±11.4755i, 0.0439	-0.5379 ±11.4627i, 0.0469
	-0.3012 ±11.5151i, 0.0261	**-0.3024 ±11.5189i, 0.0262**	-0.3348 ±11.3197i, **0.0296**	**-0.2791 ±11.4750i, 0.0243**
	-0.9554 ±10.1115i, 0.0941	-0.9581 ±10.1115i, 0.0943	-1.0116 ±10.0916i, 0.0997	-1.0219 ±10.0795i, 0.1009
	-0.6069 ± 8.9271i, 0.0678	-0.6022 ± 8.8041i, 0.0682	-0.6046 ± 8.2732i, 0.0729	-0.6143 ± 8.2200i, 0.0745
	-1.0313 ± 7.9303i, 0.1290	-1.2073 ± 7.9923i, 0.1494	-1.3450 ± 7.0309i, 0.1879	-1.3956 ± 6.9823i, 0.1960
	-0.5381 ± 7.1383i, 0.0752	-0.4442 ± 6.9509i, 0.0638	**-0.3260 ± 7.1950i,** 0.0453	-0.2836 ± 7.1579i, 0.0396
	-3.5472 ± 2.9544i, 0.7684	-1.2449 ± 2.6661i, 0.4231	-1.1795 ± 2.8455i, 0.3829	-1.1205 ± 2.8562i, 0.3652
	-1.2658 ± 2.8107i, 0.4106	-2.1581 ± 2.4042i, 0.6680	-2.1806 ± 2.4528i, 0.6644	-2.1899 ± 2.4765i, 0.6624
PSOPSS	-0.9915 ±11.5183i, 0.0858	-0.9168 +11.6394i, 0.0785	-0.6179 ±11.5357i, **0.0535**	-0.6119 ±11.5859i, **0.0527**
	-0.5632 ±11.4961i, **0.0489**	-0.8251 +11.2328i, 0.0733	-0.9475 ±11.4362i, 0.0826	-0.9591 ±11.4054i, 0.0838
	-0.6291 ±10.9112i, 0.0576	-0.6219 +10.9108i, **0.0569**	**-0.6076 ±10.5625i,** 0.0574	**-0.5862 ±10.6328i,** 0.0550
	-0.6834 ± 9.1428i, 0.0745	-0.7473 + 9.0848i, 0.0820	-0.6441 ± 8.9993i, 0.0714	-0.6408 + 8.9672i, 0.0713
	-0.5136 ± 8.9236i, 0.0575	**-0.5132 + 8.9283i,** 0.0574	-0.7516 ± 8.7792i, 0.0853	-0.7675 + 8.7534i, 0.0874
	-0.8267 ± 8.1990i, 0.1003	-0.8192 + 8.1967i, 0.0994	-0.7348 ± 7.3412i, 0.0996	-0.6984 + 7.2067i, 0.0965
	-1.6706 ± 5.7218i, 0.2803	-1.8578 + 5.3899i, 0.3259	-2.0102 ± 5.0676i, 0.3687	-2.2909 + 5.0736i, 0.4115
	-1.8618 ± 3.9108i, 0.4298	-1.7728 + 3.8749i, 0.4160	-1.5293 ± 4.1431i, 0.3463	-1.2519 + 4.0795i, 0.2934
	-1.6860 ± 2.3731i, 0.5792	-1.6719 + 2.3755i, 0.5756	-1.6825 ± 2.3776i, 0.5776	-1.6807 + 2.3779i, 0.5772
GSAPSS	-2.3839 ±12.1489i, 0.1926	-3.5974 ±13.2498i, 0.2620	-2.4048 ±12.0169i, 0.1962	-2.4092 ±11.9944i, 0.1969
	-1.7425 ±10.6879i, **0.1609**	-2.3598 ±12.1237i, 0.1911	-1.7545 ±10.6376i, **0.1627**	-1.7582 ±10.6104i, **0.1635**
	-2.0266 ± 9.5388i, 0.2078	-1.7476 ±10.6834i, **0.1614**	-1.9679 ± 9.4833i, 0.2032	-1.9203 ± 9.5042i, 0.1980
	-3.0727 ± 7.8507i, 0.3645	-1.9953 ± 9.4884i, 0.2058	-2.8786 ± 7.8106i, 0.3458	-2.9048 ± 7.8205i, 0.3482
	-3.9310 ± 5.4583i, 0.5844	-2.8412 ± 7.8042i, 0.3421	-3.9318 ± 5.4390i, 0.5858	-3.9397 ± 5.4247i, 0.5876
	-3.0714 ± 5.4133i, 0.4935	-3.0658 ± 5.4133i, 0.4928	-3.0602 ± 5.4160i, 0.4919	-3.0614 ± 5.4148i, 0.4922
	-2.7128 ± 4.7631i, 0.4949	-2.7104 ± 4.7786i, 0.4934	-2.7036 ± 4.7913i, 0.4914	-2.7015 ± 4.7993i, 0.4905
	-2.9894 ± 4.6979i, 0.5369	-1.7547 ± 2.8701i, 0.5216	-2.9866 ± 4.7132i, 0.5353	-2.9874 ± 4.7217i, 0.5347
	-1.6941 ± 2.8920i, 0.5055	**-1.7396 ± 2.1330i,** 0.6320	**-1.7204 ± 2.8837i,** 0.5123	**-1.7094 ± 2.8331i,** 0.5166

4.2 *Nonlinear time domain simulation:*

To demonstrate the effectiveness of the PSSs tuned using the proposed multi objective function over a wide range of operating conditions, the following disturbance is considered for nonlinear time simulations.To show the system performance using the proposed method, the performance index, Integral of Time multiplied Absolute value of Error(*ITAE*) is being used and is given by

$$ITAE = \int_0^{10} t.(\left|\Delta\omega_1\right| + \left|\Delta\omega_2\right| + \left|\Delta\omega_3\right| + ... + \left|\Delta\omega_{10}\right|)dt$$

(26)

It is worth mentioning that the lower the value of this index is, better the system response in terms of time domain characteristics.

Case (a): A six-cycle three-phase fault, very near to the 14th bus in the line 4–14, is simulated. The fault is cleared by tripping the line 4–14. The speed deviation of generators G2& G3 are shown in Fig. 6.

Case (b): A six-cycle fault disturbance at bus 33 at the end of line 19-33 with the load at bus-25 doubled. The fault is cleared by tripping the line 19-33 with successful reclosure after 1.0 s. Fig. 7 shows the oscillations of 4thand 5thgenerators.

Case (c) Another critical five cycle three-phase fault is simulated very near to the 22nd bus in the line 22–35 with load at bus-21 increased by20%, in addition to 25th bus load being doubled as in Case(b). The speed deviations of generators G7& G8 are shown in Fig. 8.

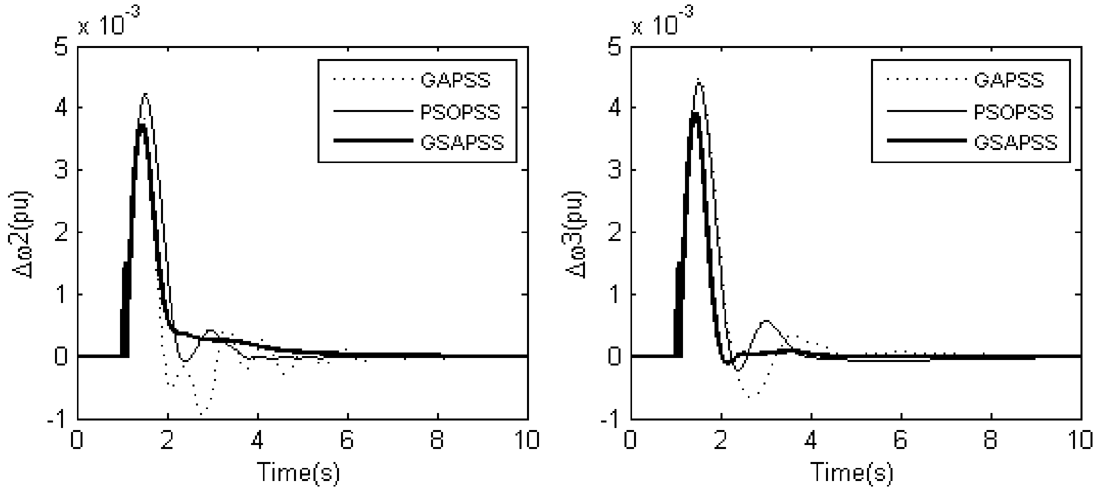

Fig 6: Speed deviations of 2ndand 3rdgenerators for Case (a).

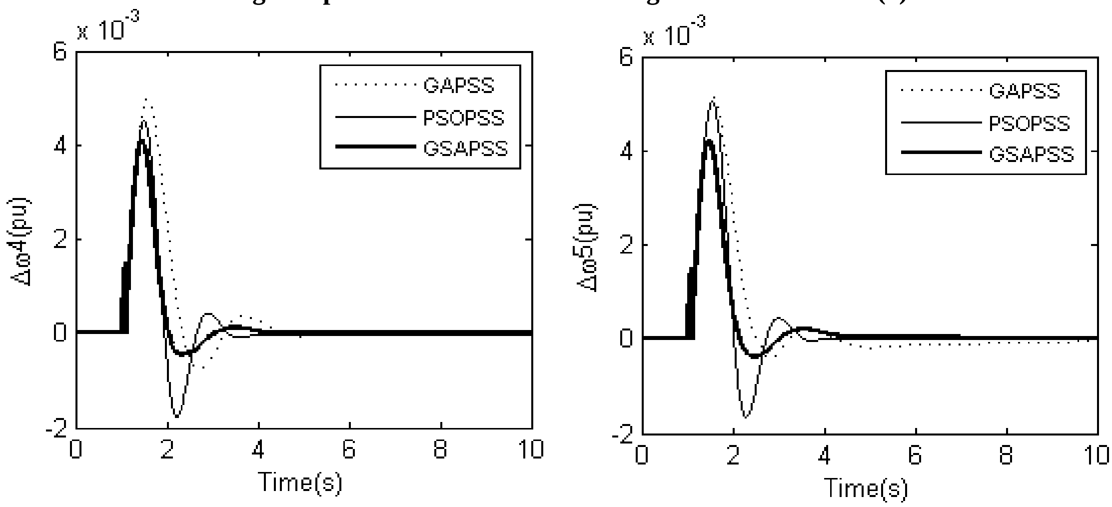

Fig 7: Speed deviations of 4thand 5th generators for Case (b).

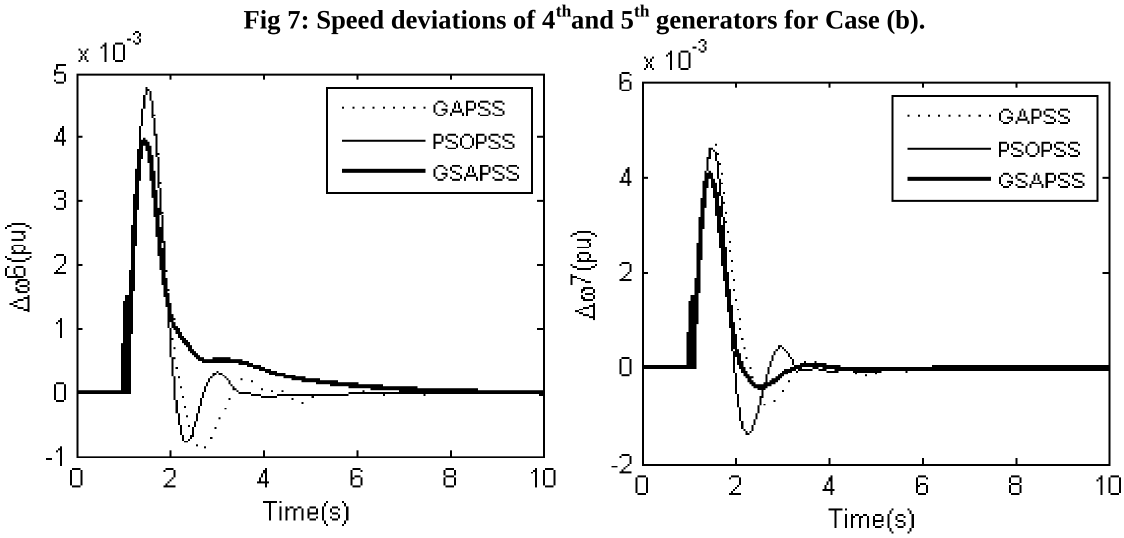

Fig 8: Speed deviations of 6th and 7th generators for Case (c).

In all the above cases, the system performance with the proposed GSAPSS is much better than that of PSOPSS, GAPSS and CPSS and the oscillations are damped out much faster. In addition, the proposed GSAPSSs are quite efficient to damp out local and inter area modes of oscillations. This illustrates the potential and superiority of the proposed design approach to get optimal set of PSS parameters.

Table 8: Values of Performance Index (ITAE)

	Performance Index		
	GAPSS	**PSOPSS**	**GSAPSS**
Contingency (a)	7.0502	6.7726	5.0979
Contingency (b)	7.2017	6.7284	4.8425
Contingency (c)	7.1769	6.6971	4.8042

It is also clear from the above table that performance indices for GSA based PSS are less than the corresponding values of GA and PSO based PSS

V. CONCLUSIONS

In this study, optimal multi objective design of robust multi-machine power system stabilizers (PSS) using GSA is proposed. The approach effectiveness is validated New England multi-machine power system. In this paper, the performance of proposed GSAPSS is compared with conventional speed-based lead-lag PSS, GA based PSS and PSO based PSS. A multi objective 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 tuning the parameters of the power system stabilizers is converted to an optimization problem which is solved by GSA with the eigenvalue-based multi-objective function. Eigen value analysis under different operating conditions reveals that undammed and lightly damped oscillation modes are shifted to a specific stable zone in the s-plane. These results show the potential of GSA for optimal settings of PSS parameters. The nonlinear time-domain simulation results show that the proposed GSAPSS work effectively over a wide range of loading conditions and system configurations.

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