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Optimal Design of Multi-Machine Power System Stabilizer Using Genetic Algorithm

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Abstract

Power system stabilizers (PSSs) are used to generate supplementary control signals for the excitation system to damp electromechanical oscillations. This paper presents an approach based on genetic algorithm for tuning the parameters of PSSs in a multi-machine power system. 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 performance of the proposed PSSs under different disturbances, loading conditions, and system configurations is investigated for different multi-machine power systems. The non-linear simulation results are presented under wide range of operating conditions; disturbances at different locations as well as for various fault clearing sequences to show the effectiveness and robustness of the proposed PSSs and their ability to provide efficient damping of low frequency oscillations.

Keywords: Power System Stabilizer, Electromechanical Oscillations, Genetic algorithm, Multi-machine power system**.**

1. Introduction

Damping of electromechanical oscillations in multi-machine power systems is the most important issue for a secure operation. Rogers *et al.* (1999) have reported that these oscillations may sustain and grow to cause system separation if no adequate damping is available. A well established classification separates them into two types: (i) local mode, corresponds to an oscillations of one or more generators in an area with respect to the rest of the system. Pai (2004) states that the local mode has a frequency of 1-3.0 Hz. (ii) Inter-area mode oscillations, is concerned with the oscillations of a group of generators in one area against a group in another area, usually connected by a long or a weak tie line. Bikash Pal (2005) states that these oscillations usually in a frequency range between 0.2-1 Hz. A common approach to damp these oscillations and improve system dynamic stability is the use of conventional lead-lag power system stabilizers (CPSSs). Rouco (2001) argued that these power system stabilizers are effective in damping local modes, and if carefully optimized may also be effective in damping inter-area modes up to a certain transmission loading .

Design of CPSS is based on the linear control theory which requires a nominal power system model formulated as linear, time invariant system. CPSS based on this approach can be very well tuned to an operating condition and will provide excellent damping over a certain range around the design point. However, CPSS parameters may not be optimal for the whole set of possible operating conditions and configurations. Larsen (1981) and Tse (1993) argued that despite the potential of modern control techniques with different structures, power system utilities still prefer a conventional lead-lag power system stabilizer (CPSS) structure. The reasons behind that might be the ease of online tuning and the lack of assurance of the stability related to some adaptive or variable structure techniques. Kundur *et al*. have presented a comprehensive analysis of the effects of the different CPSS parameters on the overall dynamic performance of the power system. It is shown that the appropriate selection of CPSS parameters results in satisfactory performance during system upsets.

Many different techniques has been reported in the literature pertaining to optimum location and coordinated design problems of CPSSs. Generally, most of these techniques are based on phase compensation and eigen value assignment. Fleming (1981), Abe (1983) and Arredondo(1997) presented different techniques of sequential design of PSSs to damp out one of the electromechanical modes at a time. Generally, the dynamic interaction effects among various modes of the machines are found to have significant influence on the stabilizer settings. Therefore, considering the application of stabilizer to one machine at a time may not finally lead to an overall optimal choice of PSS parameters. Moreover, the stabilizers designed to damp one mode can produce adverse effects in other modes. In addition, the optimal sequence of design is a very involved question. The sequential design of PSSs is avoided by Gooi (1981), Lefebvre(1983), Lim(1985), Chen(1987) and Yu(1990), where various methods for simultaneous tuning of PSSs in multi-machine power systems are proposed. Unfortunately, the proposed techniques are iterative and require heavy computation burden due to system reduction procedure. This gives rise to time consuming computer codes. In addition, the initialization step of these algorithms is crucial and affects the final dynamic response of the controlled system. Hence, different designs assigning the same set of eigen values were simply obtained by using different initializations. Therefore, a final selection criterion is required to avoid long runs of validation tests on the nonlinear model.

Recently, genetic algorithms (GAs) have received much attention as an effect method to find global or near global solution of difficult and complex design problems. Compared with the other conventional methods described above, mathematical properties such as differentiability, convexity and nonlinearity are of no concern. Abdel Magid (1999),Schmitendorf(1992) and Hasanovic (2002) argued that another advantage of GAs is that they can be easily coupled with already developed analysis and simulation tools .

In this paper optimization of the parameters of CPSS using GA is proposed. 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 GA with the eigen value-based multiobjective function. Eigen value analysis and nonlinear simulation results have been carried out to assess the effectiveness of the proposed PSSs under different disturbances, loading conditions, and system configurations. Results obtained from eigenvalues and nonlinear time domain simulation are compared with results that obtained by CPSS.

2. Problem Statement

2.1 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,

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \tag{1}$$

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

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

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

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

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

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.

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

where $\Delta\omega$ is the deviation of the speed of the rotor from synchronous speed. The second term in Eq. (7) 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. Compromising, it may have a value anywhere in the range of 1–20 s . 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:

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

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 eigenvalues in a sector in which as shown in Fig. 1.

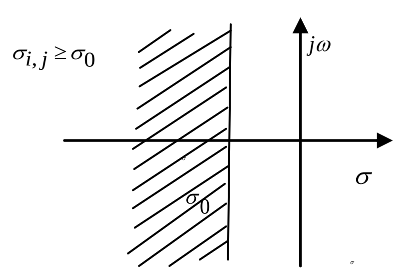

Figure 1: Closed loop eigenvalues in a sector

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

objective function:

$$J_2 = \sum_{j=1}^{np} \sum_{\zeta_{i,j} \le \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \tag{9}$$

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 eigenvalues in a wedge-shape sector in which $\zeta_{i,j} > \zeta_0$ as shown in Fig. 2.

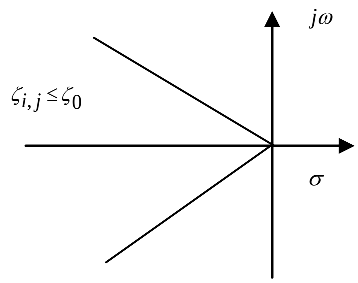

Figure 2: Representation of eigenvalues in wedge shape sector

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

$$J = J_1 + \text{a}. J_2 = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \ge \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 + a \cdot \sum_{j=1}^{np} \sum_{\zeta_{i,j} \le \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \tag{10}$$

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

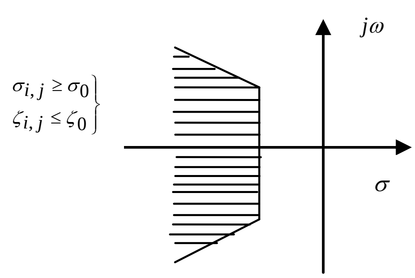

Figure 3: Representation of eigenvalues in D-shape sector

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

$$K_{i_{\min}} \leq K_i \leq K_{i_{\max}}$$

$$T_{1i_{\min}} \leq T_{1i} \leq T_{1i_{\max}}$$

$$T_{2i_{\min}} \leq T_{2i} \leq T_{2i_{\max}}$$

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} .

3. Genetic Algorithm

3.1 Introduction

Genetic Algorithms are general purpose optimization techniques based on principles inspired from the biological evolution using metaphors of mechanisms such as natural selection, genetic recombination and survival of the fittest. They are member of a wider population of algorithm, Evolutionary Algorithms. The idea of evolutionary computing was introduced in the year 1960 by I.Rechenberg in his work "Evolution strategies" ("Evolutionsstrategie", in original). His idea was then developed by other researchers. Genetic Algorithm was invented by John Holland and thereafter numbers of his students and other researchers have contributed in developing this field. With the advent of the GA, many non-linear, large-scale combinatorial optimization problems in power systems have been resolved using the genetic computing scheme. The GA is a stochastic search or optimization procedure based on the mechanics of natural selection and natural genetics. The GA requires only a binary representation of the decision variables to perform the genetic operations, i.e., selection; crossover and mutation. Fig 4 shows the binary representation of decision variables to perform the genetic operations

$$\underbrace{1\ 1\ 0\ 1\ 0}_{x_1}\quad \underbrace{1\ 0\ 0\ 1\ 0\ 0\ 1}_{x_2}\quad \underbrace{0\ 1\ 0}_{x_3}\ \text{------}\ \underbrace{0\ 0\ 1\ 0}_{x_n}$$

Figure 4: Binary representation of decision variables

3.2 Biological Background

All living organisms consist of number of cells. Each cell consists of same set of chromosomes. Chromosomes are strings of DNA and serves as a model for the whole organism. A chromosome's characteristic is determined by the genes. Each gene has several forms or alternatives which are called alleles, producing differences in the set of characteristics associated with that gene. The set of chromosome which defines a phenotype (individual) with certain fitness is called the genotype. The fitness of an organism is measured by success of the organism in its life. According to Darwinian theory the highly fit individuals are given opportunities to reproduce whereas the least fit members of the population are less likely to get selected for reproduction and so “die out”.

3.3Working mechanism of GA:

In nature, a combination of natural selection and procreation permits the development of living species that are highly adapted to their environments. GA is an algorithm that operates on a similar principle. When applied to a problem the standard genetic algorithm proceeds as follows: an initial population of individuals (represented by chromosomes) ‘n’ is generated at random. At every evolutionary step, called as generation, the individuals in the current population are decoded and evaluated according to predefined quality criterion referred to as fitness function. To form a new population (next generation), individuals are selected according to their fitness. Then some or all of the existing members of the current solution pool are replaced with the newly created members. Creation of new members is done by crossover and mutation operators.

3.3.1. Selection: According to Darwin’s evolution theory the best ones should survive and create new offspring. There are many methods to select the best chromosomes, for example roulette wheel selection, rank selection, steady state selection etc. Roulette wheel selection method has been used in this work to select the chromosomes for crossover because of its simplicity and also the fitness values do not differ very much in this work.

Roulette wheel selection: Parents are selected according to their fitness. The better the chromosomes are, the more chances to be selected they have. A roulette wheel (pie-chart) is considered where all chromosomes in the population are placed in according to their normalized fitness. Then a random number is generated which decides the chromosome to be selected.

3.3.2. Crossover: The main operator working on the parents is crossover, which happens for a selected pair with a crossover probability (p_c). Crossover takes two individuals and cuts their chromosome strings at some randomly chosen position, to produce two “head” segments and two “tail” segments. The tail segments are then swapped over to produce two new full-length chromosomes. As a result the two offspring each inherit some genes from each parent. Crossover is not usually applied to all pairs of individuals selected for mating. A random choice is made, where the likelihood of crossover being applied is typically between 0.6 and 1.0. If the crossover is not applied, offsprings are produced simply by duplicating the parents. The crossover operation performed on two parents ‘A’ and ‘B’ is given below

Parent A	0	0	**0**	**0**	**0**	**1**	**0**	**1**
Parent B	**1**	**1**	1	0	1	0	0	1

Child A	0	0	1	0	1	0	0	1
Child B	**1**	**1**	**0**	**0**	**0**	**1**	**0**	**1**

3.3.3. Mutation: Mutation is applied to each child individually after crossover. It randomly alters each gene with a small probability(p_m). Mutation provides a small amount of random search and helps ensure that no point in the search space has a zero probability of being examined. The mutation operation performed on two child strings obtained after crossover operation is given below

Child A	0	1	**0**	1	1
New Child A	0	1	**1**	1	1

These three operators are applied repeatedly until the off springs take over the entire population. When new solution of strings is produced, they are considered as a new generation and they totally replace the parents in order for the evolution to proceed.

It is necessary to produce many generations for the population converging to the near optimum or an optimum solution, the number increasing according to the problem complexity. A linear mapping rule given by Eqn. (11) is used in this work to convert the binary coded strings into their corresponding values of x_1 and x_2.

$$x_i = x_i^L + \frac{x_i^U - x_i^L}{2^{l_i} - 1} \times \text{decoded value of } s_i \qquad (11)$$

Where x_i^L and x_i^U are the problem constraints. In the above equation, the variable x_i is coded in a substring S_i of length l_i. The decoded value of a binary substring S_i is calculated as $\sum_{i=0}^{l-1} 2^i \times S_i$, where $s_i \in (0,1)$.

Elitism: The performance of a simple GA is quite well improved by the elitism procedure. Without elitism, the best results can be lost during the selection, crossover and mutation operations. Hence the best solution (parent string) of every generation is copied to the next so that the possibility of its destruction through a genetic operator is eliminated.

4. Test Case-I

In this test case, the WSCC 3-machine, 9-bus power system shown in Fig. 5 is considered. For illustration and comparison purposes, it is assumed that all generators are equipped with PSSs. Three different operating conditions in addition to the *base case* are considered.

4.1 PSS Design and Eigen value Analysis

To assess the effectiveness and robustness of the proposed GAPSS over a wide range of loading conditions, four operating cases are considered. The generator and system loading levels at these cases are given in Tables 1 and 2, respectively. Table 3 and 4 represent the optimal parameters of conventional PSS and proposed GAPSS respectively. The electromechanical–mode eigen values and corresponding damping ratios without PSSs for all cases are given in Table 5. Table 5 also shows the comparison of eigenvalues and damping ratios for different Cases. It is clear that these modes are poorly damped and some of them are unstable. The electromechanical–mode eigenvalues and the corresponding damping ratios with the proposed GAPSS's for the objective function J is given in the table. It is obvious that the electromechanical–mode eigen values have been shifted to the left in s-plane and the system damping with the proposed GAPSSs greatly improved and enhanced.

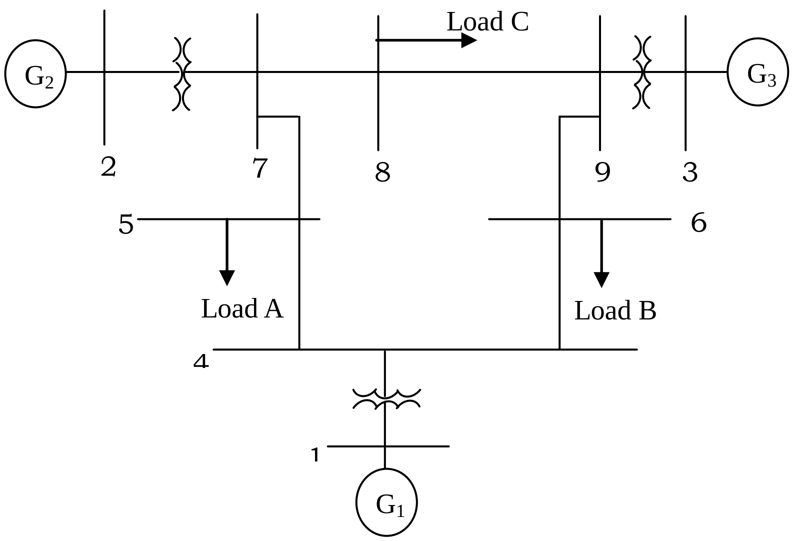

Figure 5: WSCC Three-machine Nine-bus Power System

It is clear that these modes are poorly damped with CPSS and these electromechanical–mode eigenvalues have been shifted to the left in s-plane and the system damping is greatly improved and enhanced with the inclusion of PSS.

Table 1: Loads in PU on system 100-MVA base

Load	Base Case		Case 1		Case 2		Case 3	
	P	Q	P	Q	P	Q	P	Q
A	1.25	0.50	2.0	0.80	0.65	0.55	1.50	0.90
B	0.90	0.30	1.80	0.60	0.45	0.35	1.20	0.80
C	1.0	0.35	1.50	0.60	0.5	0.25	1.00	0.50

Table 2: Generator loadings in PU on the Generator own base

Gen	Base case		Case 1		Case 2		Case 3	
	P	Q	P	Q	P	Q	P	Q
1	0.72	0.27	2.21	1.09	0.36	0.16	0.33	1.12
2	1.63	0.07	1.92	0.56	0.80	-0.11	2.0	0.57
3	0.85	-0.11	1.28	0.36	0.45	-0.20	1.50	0.38

Table 3: Optimal Parameters of Conventional PSS

Gen	K	T_1	T_2
1	4.3321	0.4057	0.2739
2	2.4638	0.3716	0.2990
3	0.3997	0.3752	0.2961

Table 4: Optimal Parameters of Proposed GAPSS

Gen	K	T_1	T_2
1	5.5380	0.4399	0.0100
2	5.5433	0.6958	0.3421
3	14.9741	0.0531	0.4210

Table 5: Comparison of Eigen values and Damping ratios for different cases

	Without PSS	CPSS	GA PSS
Base Case	-0.2367 ±8.5507i, 0.0277 -11.1752 ±10.4687i, 0.7298	-0.8017 ±9.0603i, 0.0881 -11.1414 ±9.4032i, 0.7642	-3.8200 ±10.1200i, 0.3500 -3.7000 ±3.0700i, 0.7700
Case-1	-0.1421 ±8.4615i, 0.0168 -11.2788 ±11.3006i, 0.7064	-0.8024 ±8.9184i, 0.0896 -11.1601 ±10.3813i, 0.7322	-1.0700 ±1.6800i, 0.5400 -3.2400 ±4.1100i, 0.6200
Case-2	-0.8199±8.1535i, 0.1001 -10.4600 ±12.2400i, 0.6497	-1.2583 ±8.4817i, 0.1468 -10.3426 ±11.4081i, 0.6717	-2.7300 ±8.8200i, 0.3000 -9.8300 ±7.1400i, 0.8100
Case-3	**0.0990 ±8.5483i, -0.0116** -11.4841 ±11.0256i, 0.7214	-0.3549 ±8.9847i, 0.0395 -11.3684 ±10.0945i, 0.7478	-0.8800 ±1.5000i 0.5100 -3.7400 ±3.7700i 0.7000

4.2: *Non Linear time domain simulation*

To demonstrate the effectiveness of the proposed GAPSS's over a wide range of loading conditions, two different disturbances are considered as follows.

Case(a): A 6-cycle fault disturbance at bus 7 at the end of line 5–7 with case 1. The fault has been cleared by tripping the line 5-7.

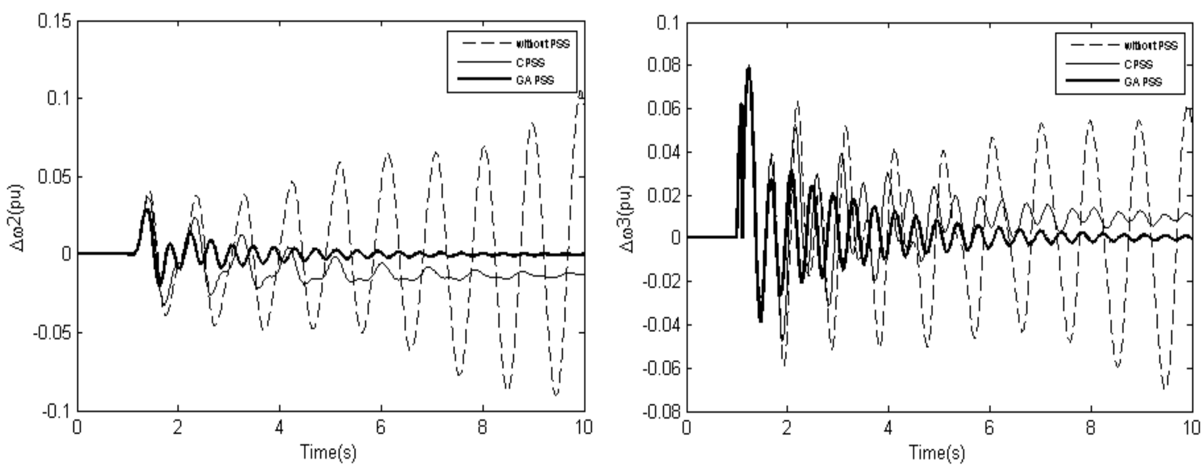

Figure 6: Speed deviation of 2nd and 3rd generators for Case (a)

Case(b): A 6-cycle fault disturbance at bus 7 at the end of line 5–7with case 3. The fault is cleared by tripping the line 5–7 with successful reclosure after 1.0 s

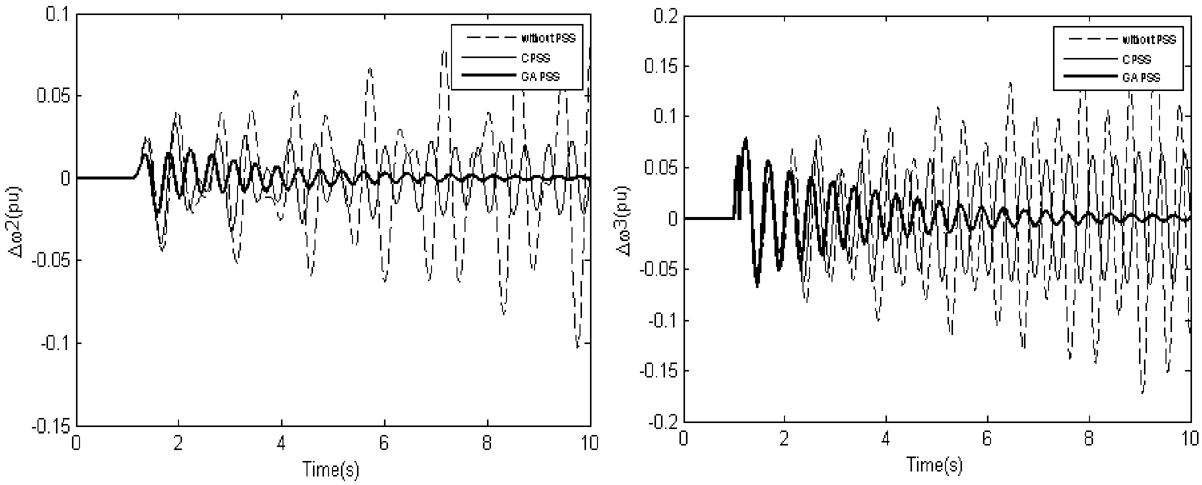

Figure 7: Speed deviation of 2nd and 3rd generators for Case (b)

The system responses to the considered faults with and without the proposed GAPSS's are shown in Figs. 6 and 7 respectively. It is clear that the proposed GAPSS's provide good damping characteristics to low frequency oscillations and greatly enhance the dynamic stability of power systems.

5. Test Case-II

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. 6 shows the configuration of the test system. All generating units are represented by fourth-order model and their static exciters are equipped with PSS. Details of the system data are given Pai(1989).

5.1 PSS Design and Eigen Value Analysis

To design the proposed GAPSS, three different operating conditions that represent the system under severe loading conditions and critical line outages in addition to the base case are considered. Fleming e*t al* (1993) have reported that these conditions are extremely hard from the stability point of view. 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 and proposed genetic optimization algorithm are shown in the Table 6. 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 the proposed approach and CPSS in the system are given in Table 7. The unstable modes for different operating conditions were found out and highlighted in the above Table.

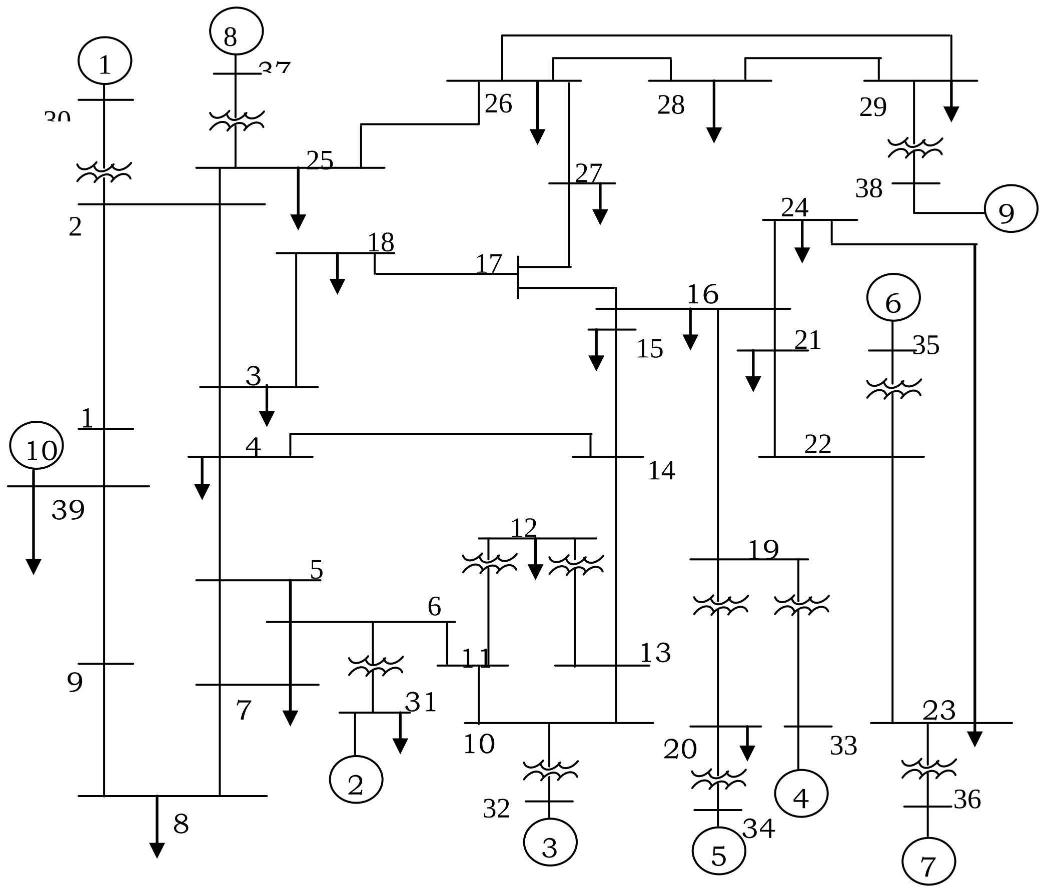

Figure 8: New England 10 generator 39 bus system

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. From the eigenvalue analysis, for the base case it is clear that all modes are well shifted in the D-stability region with ξ_{min} increased from 0.072% to 2.61% and σ_{max} from -0.0046 to -0.3012. Similarly for case-1, ξ_{min} increased from 1.35% to 2.62% and σ_{max} from -0.0826 to -0.3024 ; for case-2, ξ_{min} increased from 0.08% to 2.96% and σ_{max} from -0.0051 to -0.3260 ; and for case-3 ξ_{min} increased from 0.04% to 2.43% and σ_{max} from -0.0023 to -0.2791.

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 6: Parameters of Conventional and Proposed GA method

CPSS Parameters			GA PSS Parameters		
K	T1	T2	K	T1	T2
10.4818	0.6211	0.1789	32.200	0.5333	0.2333
0.6799	0.6185	0.1796	3.6000	0.8000	0.3933
0.2396	0.5778	0.1923	34.800	0.5333	0.2067
1.1531	0.5727	0.1940	24.400	0.5667	0.1267
17.0819	0.6143	0.1809	32.200	0.8667	0.3400
13.4726	0.6163	0.1803	14.000	0.7333	0.3133
4.3773	0.5636	0.1971	32.200	0.5333	0.3667
0.5709	0.6099	0.1822	3.6000	0.5333	0.4200
1.6059	0.5429	0.2046	21.800	0.5333	0.2600
19.8488	0.5027	0.2210	8.8000	0.9000	0.2867

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

	Without PSS	CPSS	GA PSS
Base Case	-1.1878 ±10.6655i, 0.1107	-1.5226 ±11.7232i, 0.1288	-1.1509 ±11.4696i, 0.0998
	-0.3646 ±8.8216i, 0.0413	-1.3326 ±11.2726i, 0.1174	-0.4693 ±11.4972i, 0.0408
	-0.3063 ±8.5938i, 0.0356	-1.9859 ±11.1499i, 0.1753	-0.3012 ±11.5151i, 0.0261
	-0.2718 ±8.1709i, 0.0332	-0.9837 ±9.0350i, 0.1082	-0.9554 ±10.1115i, 0.0941
	-0.0625 ±7.2968i, 0.0086	-0.5380 ±8.5014i, 0.0632	-0.6069 ±8.9271i, 0.0678
	-0.1060 ±6.8725i, 0.0154	-0.1568 ±7.3758i, 0.0213	-1.0313 ±7.9303i, 0.1290
	0.2579 ±6.1069i, -0.0422	-1.0658 ±7.2601i, 0.1452	-0.5381 ±7.1383i, 0.0752
	0.0620 ±6.1767i, -0.0100	**-0.0046 ±6.3800i, 0.0007**	-3.5472 ±2.9544i, 0.7684
	0.0794 ±3.9665i, -0.0200	-1.2016 ±4.5676i, 0.2544	-1.2658 ±2.8107i, 0.4106
Case-1	-1.1888 ±10.6603i, 0.1108	-1.5173 ±11.7109i, 0.1285	-1.1545 ±11.4461i, 0.1004
	-0.3642 ±8.8221i, 0.0412	-1.3362 ±11.2695i, 0.1177	-0.4779 ±11.4935i, 0.0415
	-0.3087 ±8.5753i, 0.0360	-1.9880 ±11.1547i, 0.1755	-0.3024 ±11.5189i, 0.0262
	-0.2727 ±8.1706i, 0.0334	-0.9669 ±9.0331i, 0.1064	-0.9581 ±10.1115i, 0.0943
	-0.0643 ±7.2859i, 0.0088	-0.5240 ±8.4869i 0.0616	-0.6022 ±8.8041i, 0.0682
	-0.1000 ±6.7243i, 0.0149	-0.1593 ±7.3687i, 0.0216	-1.2073 ±7.9923i, 0.1494
	0.2997 ±6.1030i, -0.0490	**-0.0826 ±6.1146i, 0.0135**	-0.4442 ±6.9509i, 0.0638
	0.0824 ±5.7423i, -0.0143	-1.0081 ±6.0958i, 0.1632	-1.2449 ±2.6661i, 0.4231
	0.0844 ±3.8066i, -0.0222	-1.9766 ±6.0065i, 0.3126	-2.1581 ±2.4042i, 0.6680

Case-2	-1.1686 ±10.6268i, 0.1093 -0.3413 ±8.7548i, 0.0390 -0.3013 ± 8.4738i, 0.0355 -0.2575 ± 8.0464i, 0.0320 -0.0615 ±7.3143i, 0.0084 **0.1283 ±6.1862i,** **0.0207** **0.0427 ±6.0556i, -0.0070** **0.2018 ±5.8565i, -0.0344** **0.1659 ±3.7438i, -0.0443**	-1.3152 ±11.2723i, 0.1159 -1.4305 ±11.2210i, 0.1265 -2.0125 ±11.0700i, 0.1789 -0.5674 ±8.4623i, 0.0669 -0.7944 ±8.1979i, 0.0964 -0.1547 ±7.3961i, 0.0209 **-0.0051 ±6.3664i, 0.0008** -0.9179 ±5.9988i, 0.1513 -0.9712 ±3.5259i, 0.2656	-1.1550 ±11.3826i, 0.1010 -0.5047 ±11.4755i, 0.0439 -0.3348 ±11.3197i, 0.0296 -1.0116 ±10.0916i, 0.0997 -0.6046 ±8.2732i, 0.0729 -1.3450 ±7.0309i, 0.1879 -0.3260 ±7.1950i, 0.0453 -1.1795 ±2.8455i, 0.3829 -2.1806 ±2.4528i, 0.6644
Case-3	-1.1645 ±10.6163i, 0.1090 -0.3256 ±8.8902i, 0.0366 -0.2977 ±8.4483i, 0.0352 -0.2587 ±8.0346i, 0.0322 -0.0575 ±7.3333i, 0.0078 **0.1557 ±6.1630i, -0.0253** **0.0586 ±6.0959i, -0.0096** **0.2089 ±5.6778i, -0.0368** **0.2352 ±3.6446i, -0.0644**	-1.3405 ±11.3267i, 0.1175 -1.3380 ±11.2101i, 0.1185 -2.0206 ±11.0315i, 0.1802 -0.5650 ±8.4482i, 0.0667 -0.7508 ±8.1182i, 0.0921 -0.1506 ±7.4154i, 0.0203 **-0.0023 ±6.3596i, 0.0004** -0.6910 ±5.8629i, 0.1171 -0.7668 ±3.3898i, 0.2206	-1.1638 ±11.3603i, 0.1019 -0.5379 ±11.4627i, 0.0469 -0.2791 ±11.4750i, 0.0243 -1.0219 ±10.0795i, 0.1009 -0.6143 ±8.2200i, 0.0745 -1.3956 ±6.9823i, 0.1960 -0.2836 ±7.1579i, 0.0396 -1.1205 ±2.8562i, 0.3652 -2.1899 ±2.4765i, 0.6624

5.2 *Nonlinear time domain simulation*

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

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 G5 & G6 are shown in Fig. 9.

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. 10 shows the oscillations of 4th and 5th generators.

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. 11.

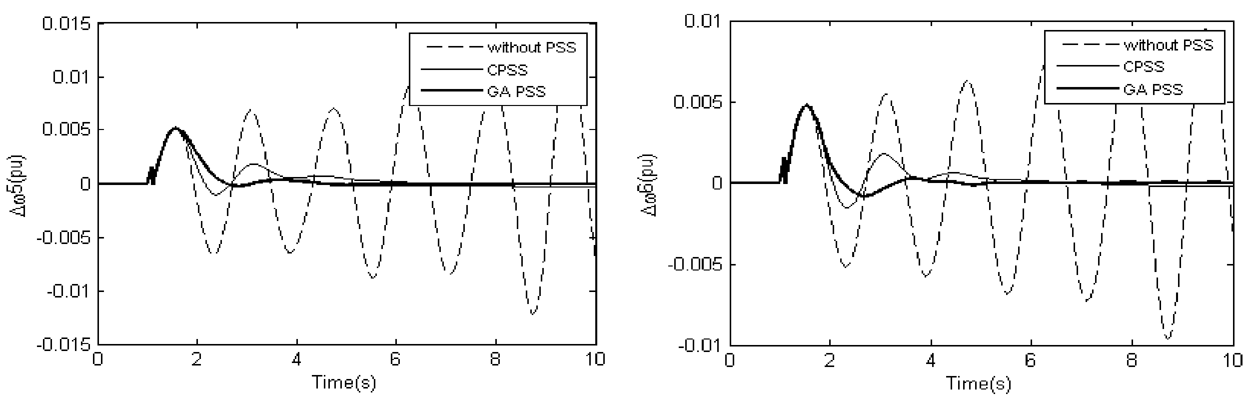

Figure 9. Speed deviations of 5th and 6th generators for Case (a).

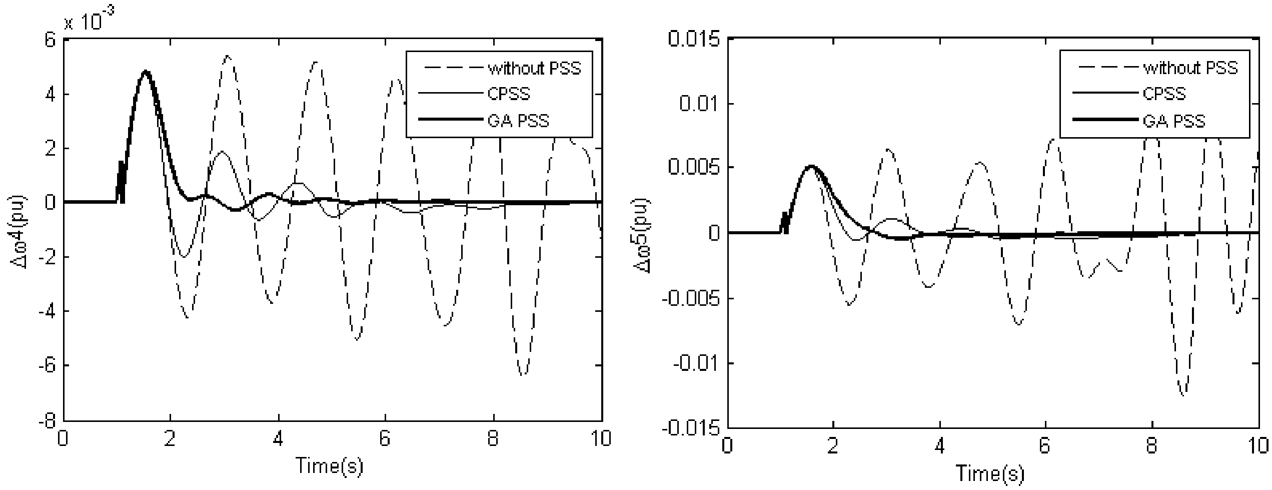

Figure 10. Speed deviations of 4th and 5th generators for Case (b).

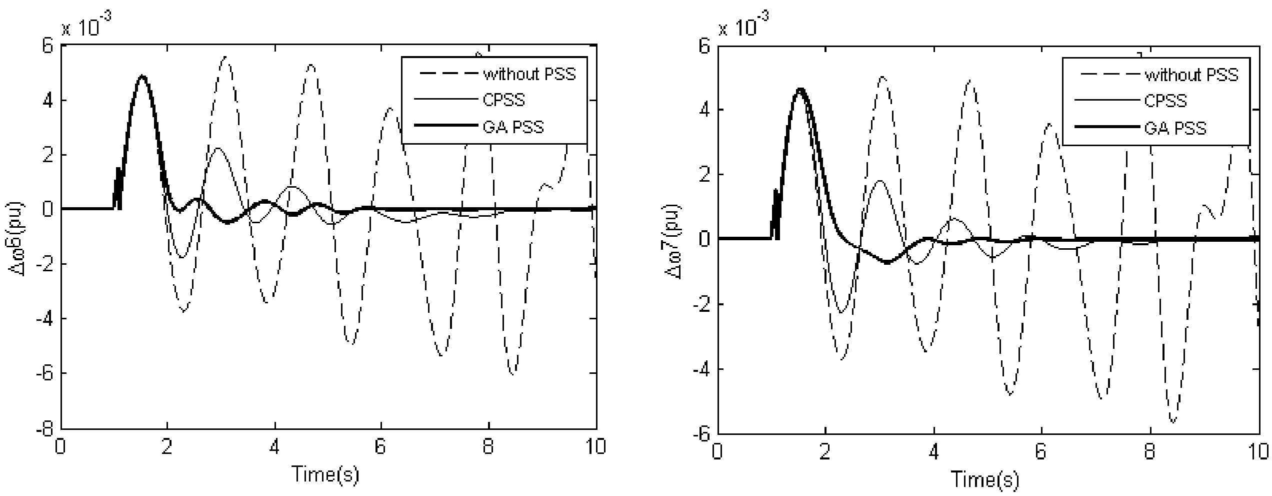

Figure 11. Speed deviations of 6th and 7th generators for Case (c).

In all the above cases, the system performance with the proposed GAPSSs is much better than that of CPSSs and the oscillations are damped out much faster. In addition, the proposed GAPSSs 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.

6. Conclusions

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

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