# APPLICATION OF HARMONY SEARCH ALGORITHM FOR ROBUST DESIGN OF POWER SYSTEM STABILIZERS IN MULTI-MACHINE POWER SYSTEMS

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***Abstract:*** *In this paper, a novel harmony search algorithm (HSA) based approach for optimal design of the parameters of conventional power system stabilizers (PSSs) is proposed for damping low frequency power oscillations of multi-machine power systems. Based on the the natural phenomena of musicians' behavior when they collectively play their musical instruments to come up with a pleasing harmony, this paper attempts to optimize three constants each of several PSS present in multi-machine power systems. A multi-objective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of lightly damped electromechanical modes. The eigenvalue analysis and non-linear simulation results presented under wide range of operating conditions show the effectiveness and robustness of the proposed controller and its ability to provide efficient damping of low frequency oscillations. Further, all these time domain simulation results are compared with conventional PSS and genetic algorithm based PSS to show the superiority of the proposed design approach.*

***Key words:*** *Dynamic Stability, Power System Stabilizer, Multi-objective Optimization, Harmony Search Algorithm*

## 1. Introduction

The oscillations in the frequency range of 0.2 Hz to 3.0 Hz are observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1]. Conventional power system stabilizers (CPSS) were developed to aid in damping these oscillations via modulation of generator excitation. An appropriate selection of PSS parameters results in satisfactory performance during system disturbances [2]. The problem of PSS parameter tuning is a complex exercise. Numerous conventional techniques have been reported in the literature pertaining to design problems of conventional power system stabilizers namely: the eigenvalue assignment, mathematical programming, gradient procedure, phase compensation method and root locus method [3]. The main drawbacks of conventional techniques are time consuming as they are iterative, computationally complex and slow rate of convergence [4-5].

Recently, global optimization technique like genetic algorithm (GA) [6] and other heuristic techniques like tabu search [7], simulated annealing (SA) [8], bacterial foraging algorithm [9] etc., have attracted the attention in the field of PSS parameter optimization. But when the system has a highly *epistatic* objective function (i.e., where the parameters being optimized are highly correlated) and number of parameters to be optimized are large, GA has been reported to exhibit degraded efficiency [10]. Harmony Search has been proposed and introduced as a new evolutionary technique by Z.W.Geem et al [11]. To overcome the drawbacks of conventional methods for PSS design, a new optimization scheme known as harmony search (HSA) is used for the PSS parameter design. This HSA appeared as a promising algorithm for solving this constrained optimization problem. This harmony search algorithm is a computational intelligence based technique that is not largely affected by the size and nonlinearity of the problem and can converge to the optimal solution in many problems where most analytical methods fail to converge. In view of the above, HSA is employed in the present work to optimally tune the parameters of the PSS.

In this paper, a comprehensive assessment of the effects of PSS-based damping controller has been carried out. A multi-objective problem is formulated to optimize a composite set of two eigenvalue-based objective functions comprising the desired damping factor, and the desired damping ratio of the lightly damped and undamped electromechanical modes. The use of the first objective function will result in PSSs that shift the lightly damped and undamped electromechanical modes to the left-hand side of a vertical line in the complex s-plane; hence, improving the damping factor. The use of the second objective function will yield PSSs settings that place these modes in a wedge-shape sector in the complex s-plane, thus improving the damping ratio of these modes. Consequently, the use of the multi-objective function will therefore guarantee that the relative stability and the time domain specifications are concurrently secured.

The proposed design approach has been applied to two multi-machine power systems. The eigenvalue analysis and the nonlinear simulations have been carried out to assess the effectiveness of the proposed PSSs under different disturbances, loading conditions, and system configurations. With the proposed scheme, the damping performance for various disturbances is compared with corresponding performances in GA. It was found that the proposed technique not only optimizes the parameters faster, but also with the optimized gains the HSA shows better damping performance when the system is perturbed.
The remainder of the paper is organized as follows: Section (2) focuses on the statement of the problem, structure of PSS and objective function used. Section (3) emphasizes on the basic idea of harmony search algorithm. Results and discussions are carried out in section (4) and conclusions are given in section (5).

## 2. Statement of the Problem

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 given by $x_i = [\delta_i \quad \omega_i \quad E'_{qi} \quad E'_{di} \quad E'_{fdi} \quad v_{1i} \quad v_{2i} \quad v_{si}]^t$ 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,

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

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

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

$$\frac{dE'_{di}}{dt} = \frac{1}{T'_{q0_i}}[-E'_{di} + I_{qi}(X_{qi} - X'_{qi})] \qquad (4)$$

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

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

where,

$d$ and $q$ direct and quadrature axes,

$\delta_i$ and $\omega_i$ 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 e.m.f 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 reactances 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 eigenvalues of the system are computed and the desired objective function is formulated using only the unstable or lightly damped electromechanical eigenvalues, keeping the constraints of all the system modes stable under any condition.

*PSS Structure:*

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

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

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 [12]. 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 $T_{2i} = T_{4i}$ .

*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 $i^{th}$ eigenvalue 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 $\sigma_0$ . This will place the closed-loop eigenvalues in a sector in which as shown in Figure 1.

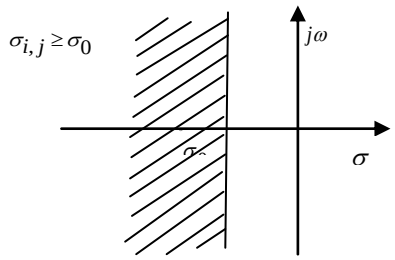


Figure 1: Closed loop eigenvalues in a sector

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

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

where $\zeta_{i,j}$ is the damping ratio of the $i^{th}$ eigenvalue 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 Figure 2.

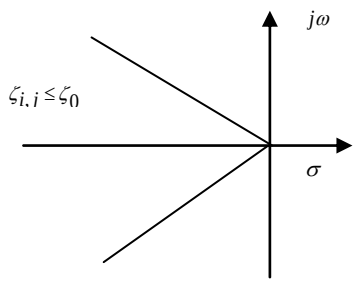


Figure 2: Representation of eigenvalues in wedge shape sector

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

$$J = J_1 + \alpha . J_2$$
$$= \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 + \alpha \cdot \sum_{j=1}^{np} \sum_{\zeta_{i,j} \leq \zeta_0} [\zeta_0 - \zeta_{i,j}]^2 \qquad (10)$$

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

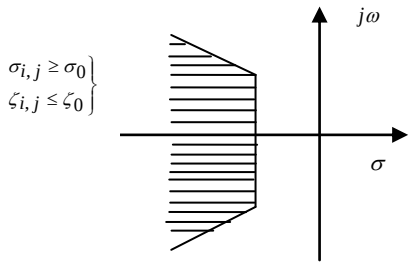


Figure 3: Representation of eigenvalues in D-shape sector

In this work $\sigma_0$ and $\zeta_0$ are taken as -2.0, 20% and $\alpha$ is chosen at 10 [13]. 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 a constrained optimization problem '*J*' given in relation (10), where the constraints are the PSS parameter bounds:

Minimize $J$ subject to

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

The proposed approach employs HSA 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 …n}. Typical ranges of the optimized parameters are [0.01, 50] for $K_i$ and [0.01 1.0] for $T_{1i}$ and $T_{2i}$ .

## 3. Harmony Search Algorithm

The Harmony Search Algorithm is a new meta heuristic population search algorithm proposed by Geem et al. It was inspired by the improvisation process of the musicians who collectively play their musical instruments (population members) to come out with a fantastic harmony (global optimum). The HSA is simple in concept, less in parameters and easy in implementation. This algorithm has been successfully applied to various discrete optimization problems such as travelling salesperson problem, tour routing, music composition, sudoku puzzle solving, water network design, and structural design. The flow chart of the HSA [14] is shown in the Figure 4.

The main steps of Harmony Search Algorithm are as follows

1. Initialize the optimization problem and algorithm parameters.
2. Initialize the harmony memory.
3. Improve a new harmony.
4. Update the new harmony.
5. Check for termination condition.

*Step 1: Algorithm Parameters:*

The HSA parameters that are to be specified are Harmony Memory Size (HMS), Harmony Memory Considering Rate (HMCR), Pitch Adjusting Rate ($R_{pa}$) and Band width ($b_i$). The Harmony Memory (HM) is a memory location where all the solution vectors are stored. Here HMCR, $R_{pa}$ and $b_i$ to be used to improve the solution vector.

*Step 2: Initialize Harmony Memory:*

In this step, the HM matrix is filled with as many randomly generated solution vectors as the HMS. The elements in the HM are determined with randomly generated solution vectors. For instance the $i^{th}$ variable $x_i$ can be generated as

$$x_i = x_i^L + rand(1) * (x_i^U - x_i^L) \quad (12)$$

where *rand(1)* is a randomly generated number between 0 and 1 and $x_i^L$ and $x_i^U$ are the lower and upper bounds of the each decision variable.

*Step 3: Improvise a New Harmony:*

A new Harmony vector $\bar{x} = (x_1^{'}, x_2^{'}, \ldots, x_N^{'})$ is generated based on three criteria, memory consideration, Pitch adjustment, Random selection Further every component obtained by memory consideration is pitch adjusted with a Pitch Adjusting Rate of $R_{pa}$. If pitch adjustment is enforced $x_i^{'}$ is replaced as $x_i^{'} = x_i^j + rand(1) * b_i$, where $b_i$ is the distance bandwidth of the variable in the new vector.

*Step 4: Update the New Harmony*

If the new solution vector is better than the worst one in the HM judged in terms of objective function value the worst one will be replaced by the new one in the HM.

*Step 5: Check for the Termination Condition*

The HSA 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 criterion is employed in this work.

## 4. Results and Discussion

The proposed HSA-based approach was implemented using MATLAB 7.6 and the simulations were executed on 2.27 GHz, 4GB RAM and Intel Core i3 PC. This HSA is applied on Western System Coordinating Council (WSCC) 3-machine, 9-bus system and New England 10-machine, 39-bus system for designing the optimal parameters of the PSS. For illustration and comparison purposes, it is assumed that all generators are equipped with PSSs.

**Test Case 1:**
In this test case, the WSCC 3-machine, 9-bus power system shown in Figure 5 is considered. Power flow, transmission line and dynamic data for the generators can be found in [15], and all generators are represented by fourth order model.

*Eigenvalue analysis***:**

For eigenvalue analysis, three different operating conditions in addition to the *base case* are considered. To assess the effectiveness and robustness of the proposed HSAPSS 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. The parameters of CPSS, GAPSS and HSAPSS used in the simulation of the system are shown in Table 3. Table 4 also shows the comparison of eigenvalues and damping ratios for different cases using CPSS, GAPSS and HSAPSS. It is clear that some of these modes are poorly damped and some of them are unstable. It is clear that the electromechanical–mode eigenvalues have been shifted to the left in s-plane and the system damping with the proposed HSAPSSs greatly improved and enhanced. It is clear that these modes are poorly damped with CPSS and GAPSS 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 HSAPSS.

*Nonlinear time domain simulations:*

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

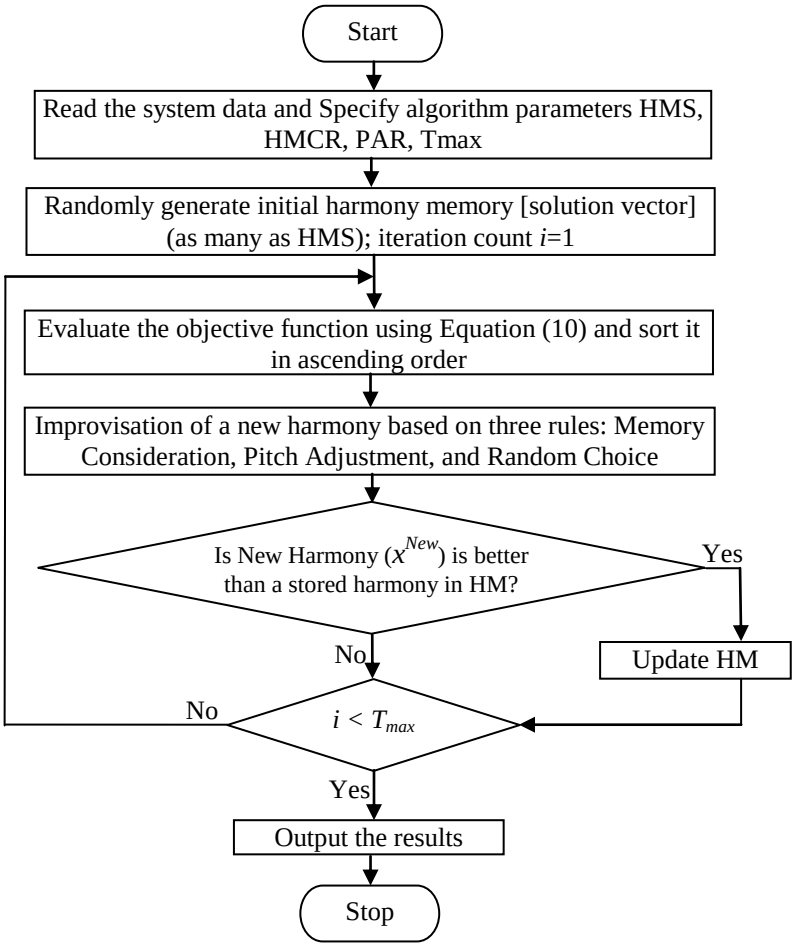


Fig. 4: Flow chart of Harmony Search Algorithm

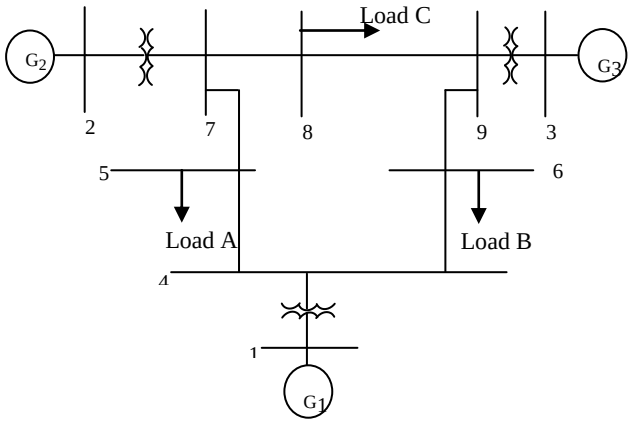


Fig. 5: WSCC 3-machine, 9-bus system

Table 1: Generator loadings in PU on the Generator own base

| | Case 1 | | Case 2 | | Case 3 | | Case 4 | |
|---|---|---|---|---|---|---|---|---|
| Gen# | P | Q | P | Q | P | Q | P | Q |
| G1 | 0.72 | 0.27 | 2.21 | 1.09 | 0.36 | 0.16 | 0.33 | 1.12 |
| G2 | 1.63 | 0.07 | 1.92 | 0.56 | 0.80 | -0.11 | 2.0 | 0.57 |
| G3 | 0.85 | -0.11 | 1.28 | 0.36 | 0.45 | -0.20 | 1.50 | 0.38 |

Table 2: Loads in PU on system 100-MVA base

| Load | Case 1 | | Case 2 | | Case 3 | | Case 4 | |
|---|---|---|---|---|---|---|---|---|
| | 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 3: Tuned Parameters of CPSS, GAPSS and HSAPSS

| Gen# | Parameters of CPSS | | | Parameters of GAPSS | | | Parameters of HSAPSS | | |
|---|---|---|---|---|---|---|---|---|---|
| | K | $T_1$ | $T_2$ | K | $T_1$ | $T_2$ | K | $T_1$ | $T_2$ |
| G1 | 4.3321 | 0.4057 | 0.2739 | 5.5380 | 0.4399 | 0.010 | 5.8994 | 0.7338 | 0.2879 |
| G2 | 2.4638 | 0.3716 | 0.2990 | 5.5433 | 0.6958 | 0.3421 | 1.2067 | 0.6128 | 0.1537 |
| G3 | 0.3997 | 0.3752 | 0.2961 | 14.9741 | 0.0531 | 0.4210 | 1.4989 | 0.5949 | 0.4307 |

Table 4: Comparison of eigenvalues and damping ratios for different schemes

| | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Without PSS | -0.2367 ± 8.5507i, 0.0277<br>-11.1752 ±10.4687i, 0.7298 | -0.1421 ± 8.4615i, 0.0168<br>-11.2788 ±11.3006i, 0.7064 | -0.8199 ± 8.1535i, 0.1001<br>-10.4600 ±12.2400i, 0.6497 | **0.0990 ± 8.5483i, -0.0116**<br>-11.4841 ±11.0256i, 0.7214 |
| CPSS | -0.8017 ± 9.0603i, 0.0881<br>-11.1414 ± 9.4032i, 0.7642 | -0.8024 ± 8.9184i, 0.0896<br>-11.1601 ±10.3813i, 0.7322 | -1.2583 ± 8.4817i, 0.1468<br>-10.3426 ±11.4081i, 0.6717 | -0.3549 ± 8.9847i, 0.0395<br>-11.3684 ±10.0945i, 0.7478 |
| GAPSS | -3.6954±3.0702i, 0.7691<br>-3.8231±10.1249, 0.3532 | -1.0697±1.6823i, 0.5365<br>-3.2448±4.1112i, 0.6195 | -2.7319±8.8153i, 0.2960<br>-3.0903±1.6258i, 0.8849 | -0.8841±1.5046i, 0.5065<br>-3.7374±3.7711i, 0.7039 |
| HSA PSS | -2.5582±6.1578i, 0.3836<br>-9.5891±9.1187i, 0.7246 | -2.1758±6.1127i, 0.3353<br>-9.6848±9.4635i, 0.7152 | -2.8304±6.6086i, 0.3937<br>-8.4893±11.0647i, 0.6087 | -2.1239±6.9096i, 0.2938<br>-9.6355±9.8268i, 0.7001 |

**Case (a):** A 6-cycle fault disturbance at bus 7 at the end of line 5–7 with case 2. The fault is cleared by tripping the line 5–7 with successful reclosure after 1.0 sec.

**Case (b):** A 6-cycle fault disturbance at bus 7 at the end of line 5–7with case 4. The fault is cleared by tripping the line 5–7 with successful reclosure after 1.0 sec.

The system responses to the considered faults with CPSS, GAPSS and the proposed HSAPSS's are shown in Figures 6 and 7 respectively. It is clear that the proposed HSAPSS's provide good damping characteristics to low frequency oscillations and greatly enhance the dynamic stability of power systems.

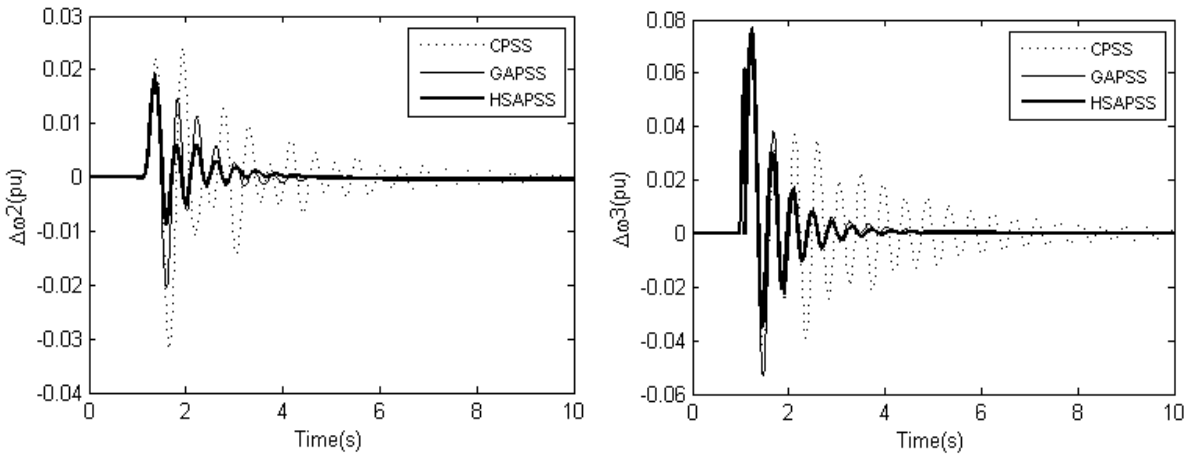


Fig. 6. Speed deviation of 2nd and 3rd generators for Case(a)

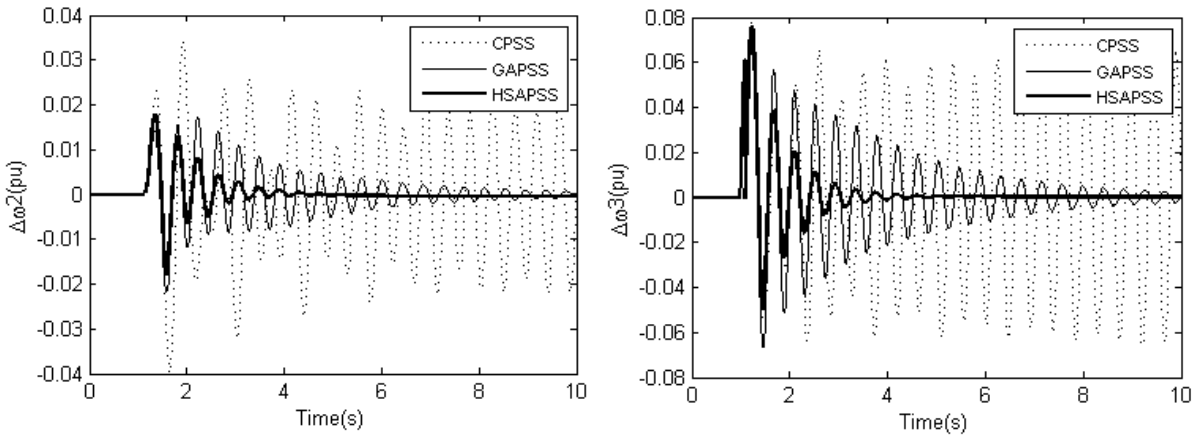


Fig.7. Speed deviation of 2nd and 3rd generators for Case(b)

**Test Case 2:**

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. Figure 8 shows the configuration of the test system. All generating units are represented by fourth-order model and their single time constant exciters are equipped with PSS. Details of the system data are given in [16].

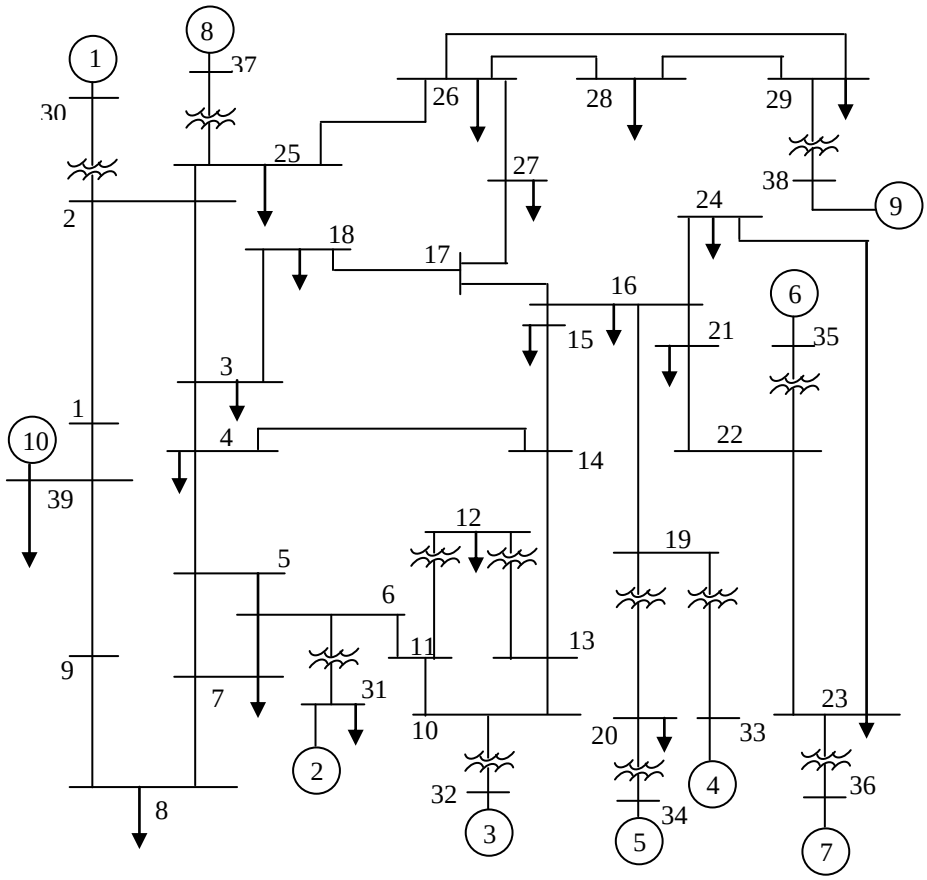

Fig. 8. New England 10-machine, 39-bus system

Table 5: Test conditions considered for eigenvalue analysis

| **Condition** | **Description** |
|---|---|
| Case-1 | Base Case (All lines in service) |
| Case-2 | outage of line connecting bus no. 14 and 15 |
| Case-3 | outage of line connecting bus no. 21 and 22 |
| Case-4 | increase in generation of G7 by 25% and loads at buses 16 and 21 by 25%, with the outage of line 21–22. |

Table 6: Tuned Parameters of CPSS, GAPSS and HSAPSS

| Gen# | Parameters of CPSS | | | Parameters of GAPSS | | | Parameters of HSAPSS | | |
|---|---|---|---|---|---|---|---|---|---|
| | K | $T_1$ | $T_2$ | K | $T_1$ | $T_2$ | K | $T_1$ | $T_2$ |
| G1 | 10.4818 | 0.6211 | 0.1789 | 32.200 | 0.5333 | 0.2333 | 26.9029 | 0.7576 | 0.2123 |
| G2 | 0.6799 | 0.6185 | 0.1796 | 3.6000 | 0.8000 | 0.3933 | 17.3491 | 0.6815 | 0.2149 |
| G3 | 0.2396 | 0.5778 | 0.1923 | 34.800 | 0.5333 | 0.2067 | 6.0655 | 0.6862 | 0.1947 |
| G4 | 1.1531 | 0.5727 | 0.1940 | 24.400 | 0.5667 | 0.1267 | 8.4120 | 0.5775 | 0.1613 |
| G5 | 17.0819 | 0.6143 | 0.1809 | 32.200 | 0.8667 | 0.3400 | 15.8577 | 0.8289 | 0.1191 |
| G6 | 13.4726 | 0.6163 | 0.1803 | 14.000 | 0.7333 | 0.3133 | 24.4729 | 0.5425 | 0.2522 |
| G7 | 4.3773 | 0.5636 | 0.1971 | 32.200 | 0.5333 | 0.3667 | 12.1195 | 0.8616 | 0.2846 |
| G8 | 0.5709 | 0.6099 | 0.1822 | 3.6000 | 0.5333 | 0.4200 | 6.0688 | 0.5412 | 0.1586 |
| G9 | 1.6059 | 0.5429 | 0.2046 | 21.800 | 0.5333 | 0.2600 | 7.0212 | 0.8249 | 0.3463 |
| G10 | 19.8488 | 0.5027 | 0.2210 | 8.8000 | 0.9000 | 0.2867 | 24.7258 | 0.8810 | 0.1228 |

*Eigenvalue analysis:*

To design the proposed HSAPSS, 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 [17]. They are given in Table 5.

The tuned parameters of the ten PSS using conventional root locus approach, genetic optimization algorithm and proposed harmony search optimization method 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 and poorly damped modes for different operating conditions were found out and highlighted in this Table.

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

| | Without PSS | CPSS | GAPSS | HSAPSS |
|---|---|---|---|---|
| Case 1 | -1.1878 ±10.6655i, 0.1107 | -1.5226 ±11.7232i, 0.1288 | -1.1509 ±11.4696i, 0.0998 | -6.9166 ±11.2619i, 0.5233 |
| | -0.3646 ± 8.8216i, 0.041 | -1.3326 ±11.2726i, 0.1174 | -0.4693 ±11.4972i, 0.0408 | -2.5759 ±12.3901i, 0.2035 |
| | -0.3063 ± 8.5938i, 0.0356 | -1.9859 ±11.1499i, 0.1753 | **-0.3012 ±11.5151i, 0.0261** | -1.4931 ±10.9778i, 0.1348 |
| | -0.2718 ± 8.1709i, 0.0332 | -0.9837 ± 9.0350i, 0.1082 | -0.9554 ±10.1115i, 0.0941 | -1.5339 ±10.0695i, 0.1506 |
| | -0.0625 ± 7.2968i, 0.0086 | -0.5380 ± 8.5014i, 0.0632 | -0.6069 ± 8.9271i, 0.0678 | -2.1232 ± 9.9980i, 0.2077 |
| | -0.1060 ± 6.8725i, 0.0154 | -0.1568 ± 7.3758i, 0.0213 | -1.0313 ± 7.9303i, 0.1290 | -2.0791 ± 8.7607i, 0.2309 |
| | **0.2579 ± 6.1069i, -0.0422** | -1.0658 ± 7.2601i, 0.1452 | -0.5381 ± 7.1383i, 0.0752 | **-0.8202 ± 8.0773i, 0.1010** |
| | **0.0620 ± 6.1767i, -0.0100** | **-0.0046 ± 6.3800i, 0.0007** | -3.5472 ± 2.9544i, 0.7684 | -1.1084 ± 2.9929i, 0.3473 |
| | **0.0794 ± 3.9665i, -0.0200** | -1.2016 ± 4.5676i, 0.2544 | -1.2658 ± 2.8107i, 0.4106 | -1.7888 ± 3.0374i, 0.5075 |
| Case 2 | -1.1888 ±10.6603i, 0.1108 | -1.5173 ±11.7109i, 0.1285 | -1.1545 ±11.4461i, 0.1004 | -6.9176 ±11.2394i, 0.5242 |
| | -0.3642 ± 8.8221i, 0.0412 | -1.3362 ±11.2695i, 0.1177 | -0.4779 ±11.4935i, 0.0415 | -2.6122 ±12.3308i, 0.2072 |
| | -0.3087 ± 8.5753i, 0.0360 | -1.9880 ±11.1547i, 0.1755 | **-0.3024 ±11.5189i, 0.0262** | -1.4989 ±10.9431i, 0.1357 |
| | -0.2727 ± 8.1706i, 0.0334 | -0.9669 ± 9.0331i, 0.1064 | -0.9581 ±10.1115i, 0.0943 | -1.6757 ±10.1017i, 0.1636 |
| | -0.0643 ± 7.2859i, 0.0088 | -0.5240 ± 8.4869i, 0.0616 | -0.6022 ± 8.8041i, 0.0682 | -2.2733 ± 9.9294i, 0.2232 |
| | -0.1000 ± 6.7243i, 0.0149 | -0.1593 ± 7.3687i, 0.0216 | -1.2073 ± 7.9923i, 0.1494 | -2.0239 ± 8.3519i, 0.2355 |
| | **0.2997 ± 6.1030i, -0.0490** | **-0.0826 ± 6.1146i, 0.0135** | -0.4442 ± 6.9509i, 0.0638 | **-0.8482 ± 8.0841i, 0.1043** |
| | **0.0824 ± 5.7423i , -0.0143** | -1.0081 ± 6.0958i, 0.1632 | -1.2449 ± 2.6661i, 0.4231 | -1.7821 ± 3.0475i, 0.5048 |
| | **0.0844 ± 3.8066i, -0.0222** | -1.9766 ± 6.0065i, 0.3126 | -2.1581 ± 2.4042i, 0.6680 | -1.0948 ± 2.8291i, 0.3609 |

| | | | | |
|---|---|---|---|---|
| Case 3 | -1.1686 ±10.6268i, 0.1093 | -1.3152 ±11.2723i, 0.1159 | -1.1550 ±11.3826i, 0.1010 | -6.9037 ±11.2848i, 0.5219 |
| | -0.3413 ± 8.7548i, 0.0390 | -1.4305 ±11.2210i, 0.1265 | -0.5047 ±11.4755i, 0.0439 | -2.7434 ±12.1487i, 0.2203 |
| | -0.3013 ± 8.4738i, 0.0355 | -2.0125 ±11.0700i, 0.1789 | -0.3348 ±11.3197i, **0.0296** | -1.4852 ±10.9934i, 0.1339 |
| | -0.2575 ± 8.0464i, 0.0320 | -0.5674 ± 8.4623i, 0.0669 | -1.0116 ±10.0916i, 0.0997 | -2.1480 ±10.0737i, 0.2085 |
| | -0.0615 ± 7.3143i, 0.0084 | -0.7944 ± 8.1979i, 0.0964 | -0.6046 ± 8.2732i, 0.0729 | -2.3250 ± 8.6751i, 0.2589 |
| | **0.1283 ± 6.1862i, -0.0207** | -0.1547 ± 7.3961i, 0.0209 | -1.3450 ± 7.0309i, 0.1879 | -1.5756 ± 8.4816i, 0.1826 |
| | **0.0427 ± 6.0556i, -0.0070** | **-0.0051 ± 6.3664i, 0.0008** | **-0.3260 ± 7.1950i,** 0.0453 | **-0.8129 ± 7.9985i, 0.1011** |
| | **0.2018 ± 5.8565i, -0.0344** | -0.9179 ± 5.9988i, 0.1513 | -1.1795 ± 2.8455i, 0.3829 | -1.7833 ± 3.0384i, 0.5062 |
| | **0.1659 ± 3.7438i, -0.0443** | -0.9712 ± 3.5259i, 0.2656 | -2.1806 ± 2.4528i, 0.6644 | -1.0759 ± 2.9554i, 0.3421 |
| Case 4 | -1.1645 ±10.6163i, 0.1090 | -1.3405 ±11.3267i, 0.1175 | -1.1638 ±11.3603i, 0.1019 | -6.9013 ±11.2962i, 0.5213 |
| | -0.3256 ± 8.8902i, 0.0366 | -1.3380 ±11.2101i, 0.1185 | -0.5379 ±11.4627i, 0.0469 | -2.7880 ±12.0419i, 0.2256 |
| | -0.2977 ± 8.4483i, 0.0352 | -2.0206 ±11.0315i, 0.1802 | **-0.2791 ±11.4750i, 0.0243** | -1.4728 ±11.0195i, 0.1325 |
| | -0.2587 ± 8.0346i, 0.0322 | -0.5650 ± 8.4482i, 0.0667 | -1.0219 ±10.0795i, 0.1009 | -2.1741 ±10.0235i, 0.2120 |
| | -0.0575 ± 7.3333i, 0.0078 | -0.7508 ± 8.1182i, 0.0921 | -0.6143 ± 8.2200i, 0.0745 | -2.3513 ± 8.7216i, 0.2603 |
| | **0.1557 ± 6.1630i, -0.0253** | -0.1506 ± 7.4154i, 0.0203 | -1.3956 ± 6.9823i, 0.1960 | -1.5396 ± 8.3645i, 0.1810 |
| | **0.0586 ± 6.0959i, -0.0096** | **-0.0023 ± 6.3596i, 0.0004** | -0.2836 ± 7.1579i, 0.0396 | **-0.8289 ± 7.9591i, 0.1036** |
| | **0.2089 ± 5.6778i, -0.0368** | -0.6910 ± 5.8629i, 0.1171 | -1.1205 ± 2.8562i, 0.3652 | -1.7778 ± 3.0349i, 0.5054 |
| | **0.2352 ± 3.6446i, -0.0644** | -0.7668 ± 3.3898i, 0.2206 | -2.1899 ± 2.4765i, 0.6624 | -1.0613 ± 2.9243i, 0.3412 |

*Nonlinear time domain simulations:*

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

$$ITAE = \int_0^{10} t.(|\Delta\omega_1| + |\Delta\omega_2| + ... + ... + |\Delta\omega_{10}|)dt \quad (12)$$

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 G3 & G4 are shown in Figure 9. For this case, genetic algorithm based PSS gives $ITAE_{(GA)}$=7.0502 and harmony search algorithm based PSS gives $ITAE_{(HSA)}$=6.1335.

**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. Figure 10 shows the oscillations of G5 and G6 generators. For this case, genetic algorithm based PSS gives $ITAE_{(GA)}$=7.2017 and harmony search algorithm based PSS gives $ITAE_{(HSA)}$=6.2648.

**Case(c):** A six-cycle three-phase fault, very near to the 14th bus in the line 14–15 with 20% increase in load is simulated. The fault is cleared by tripping the line 14–15. The speed deviation of generators G7 & G8 are shown in Figure 11. For this case, genetic algorithm based PSS gives $ITAE_{(GA)}$=7.8205 and harmony search algorithm based PSS gives $ITAE_{(HSA)}$=5.6751.

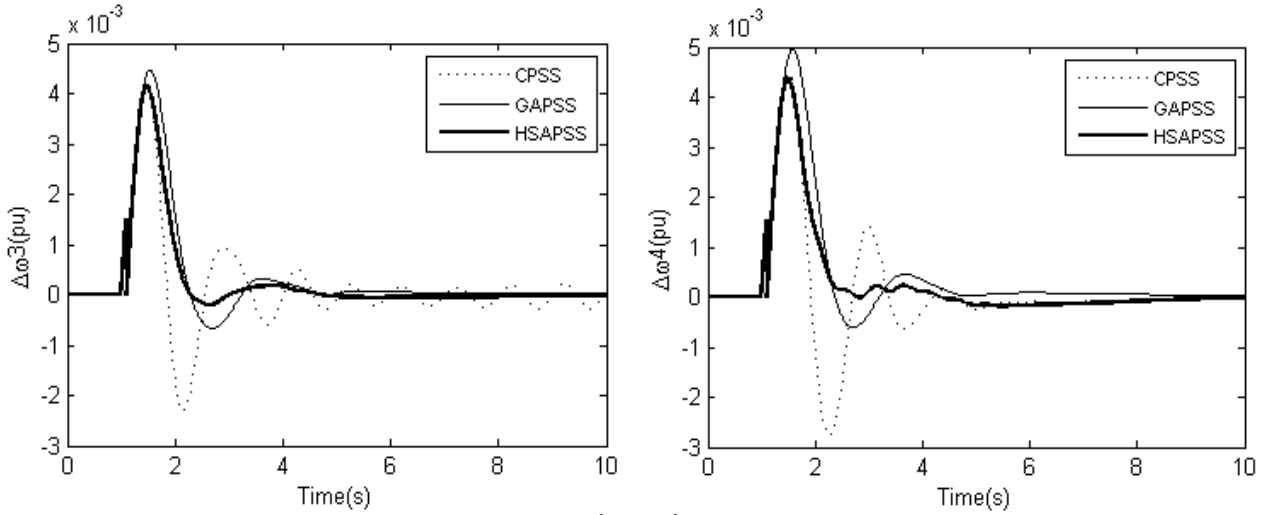


Fig. 9. Speed deviation of 3rd and 4th generators for Case(a)

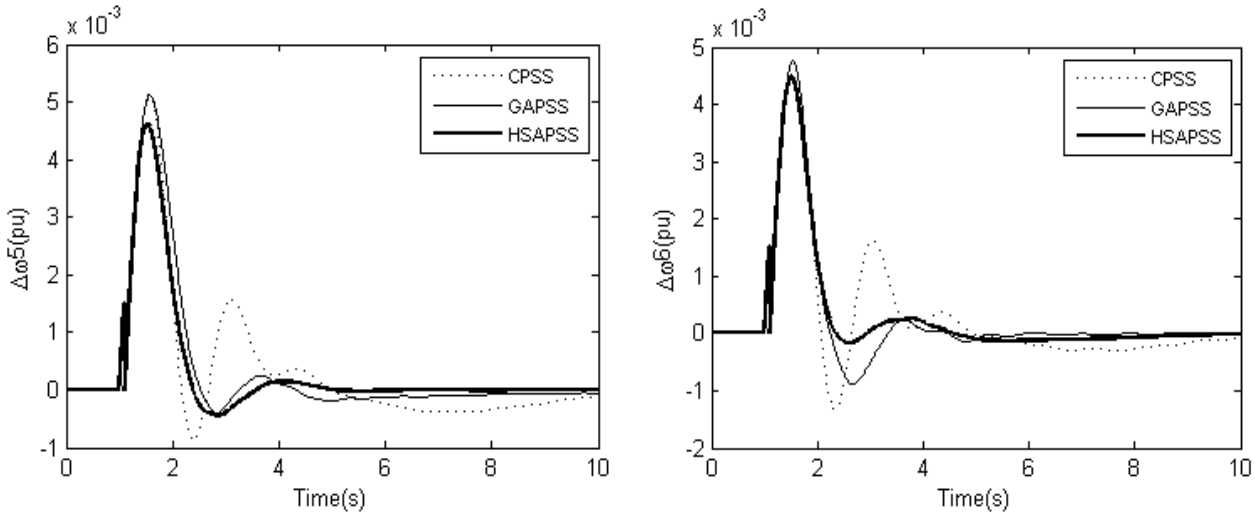


Fig. 10. Speed deviation of 5th and 6th generators for Case (b)

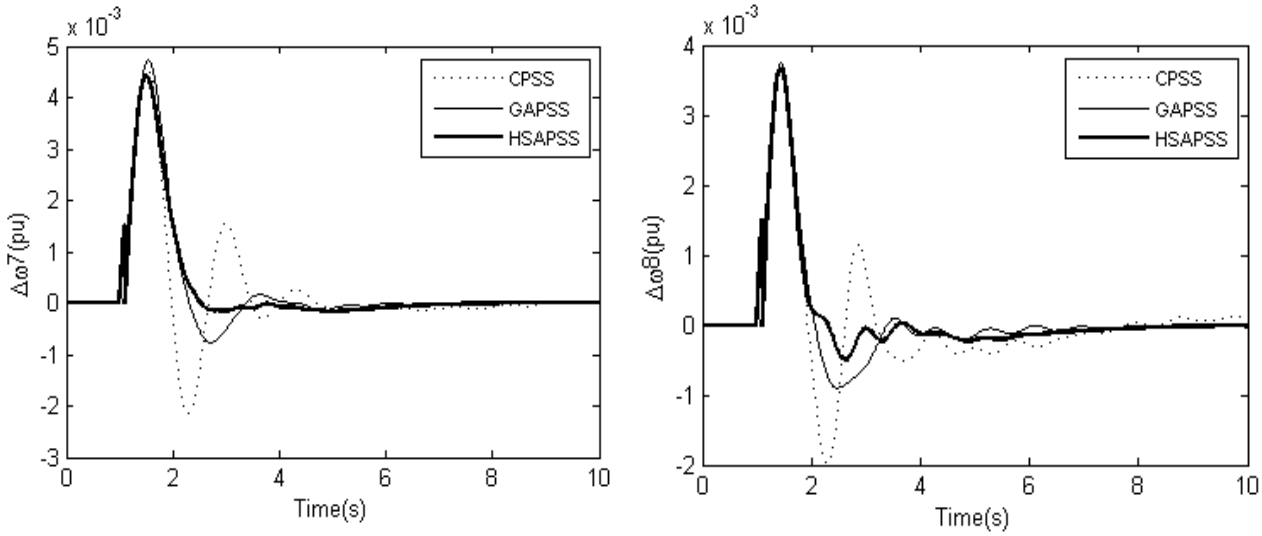


Fig. 11. Speed deviation of 7th and 8th generators for Case(c)

In all the above cases, the performance index (*ITAE)* with the proposed HSAPSSs is much smaller than that of GAPSSs. In addition, the HSAPSSs 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.

## 5. Conclusions

In this study, optimal multi-objective design of robust multi-machine power system stabilizers using Harmony Search Algorithm is proposed. The approach effectiveness is validated on two multi-machine power systems. In this paper, the performance of proposed HSA based PSS is compared with conventional speed-based lead-lag PSS and GA based PSS. The problem of tuning the parameters of the power system stabilizers is converted to an optimization problem which is solved by HSA with the eigenvalue-based multi-objective function. Eigenvalue 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 Harmony Search Algorithm for optimal design of PSS parameters. The nonlinear time-domain simulation results show the effectiveness of HSAPSSs over a wide range of loading conditions and system configurations.

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