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SMALL-SIGNAL STABILITY ENHANCEMENT OF MULTI-MACHINE POWER SYSTEM USING CUCKOO AND HARMONY SEARCH OPTIMIZATION TECHNIQUES

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ABSTRACT

In this paper, two bio-inspired meta-heuristic optimization techniques, e.g., cuckoo and harmony search optimizations, are proposed to optimally design a power system stabilizer (PSS) for a 3-machine, 9-bus Western System Coordinating Council power system. For simultaneous control of damping factor and damping ratio, an eigenvalue-based multiobjective function is explored to damp out the low-frequency oscillations from the system. The parameters of PSS are designed so that lightly and/or unstable damped mode eigenvalues are placed to a particular D-shape region in the left half of the *s*-plane. These optimisation techniques are used to determine PSS parameters and compared with the same parameters obtained by genetic algorithm, particle swarm optimization. The performance of all intended PSS controllers are observed, for three specific operational cases as well as unforeseen operating cases by eigenvalues analysis; non-linear simulations and performance indices, under a severe disturbance. The comparative analysis has revealed that the cuckoo search optimization based PSS design significantly improved the damping of the system.

Keywords: cuckoo search optimization; genetic algorithm; harmony search optimization; low-frequency oscillations; particle swarm optimization; power system stabilizer.

1. INTRODUCTION

Small-signal stability (SSS) is generally a sluggish, poorly damped, low-frequency oscillation (LFO) phenomenon due to the lack of adequate damping [1]. These oscillations are undesirable for power system operations since these threaten the security and also reduce the expected lifetime of power system assets. In modern power systems, power system stabilizers (PSSs) are usually employed to improve damping performance and SSS of multi-machine power system (MMPS). The fundamental purpose of PSS is to compensate the phase-lagging error between the exciter input and the electrical torque, and generate torque component on the rotor [1]-[3].

In recent years, a lot of research has been carried out in the field of PSS design using meta-heuristic techniques. The aim of these design techniques includes the offline tuning of PSS parameters for MMPS under a broad range of operational conditions. Some of these can be genetic algorithm (GA) [4], simulated annealing [5], Tabu search [6], particle swarm optimization (PSO) [7], evolutionary programming [8], bacteria foraging [9], bat algorithm [10], cultural algorithm [11], harmony search optimization (HSO) [12] and cuckoo search optimization (CSO) [13]. The merits of meta-heuristic techniques over analytical methods are their independency on mathematical modelling of MMPS, and promising abilities to search for a global solution. Some of the relatively new optimization techniques e.g., CSO and HSO are found to be efficient and a few publications reported their work on CSO and HSO based PSS designs (so-called CSOPSS and HSOPSS) which consider a broad range of operational conditions.

In this paper, the ability of two popular and efficient optimization techniques, i.e., CSO and HSO are explored for robust designing of PSS parameters for the 3-machine, 9-bus western system coordinating council (WSCC) power system. In the PSS design methodology, an eigenvalue-based multiobjective function simultaneously considering damping factor and damping ratio is used to place the lightly damped

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and/or unstable eigenvalues to a particular D-shape region in the left half of the *s*-plane. The effectiveness of designed controllers is observed by eigenvalues analysis, time-domain simulations, performance indices for specific operational conditions and some of the unforeseen operating cases under a severe disturbance. Further, the performance of the proposed CSOPSS and HSOPSS are compared with existing GA and PSO based PSS designs (known as GAPSS and PSOPSS). The comparison shows that SSS and damping performance of the system are highly improved by the proposed CSOPSS as compared to GAPSS, PSOPSS and HSOPSS [13].

2. PROBLEM FORMULATION

2.1 *Power System Modelling and Structure of PSS*

A power system model is usually formalized by a set of fourth-order nonlinear differential equations. The linearized incremental models around a specified operating point are generally used in the designing of PSS [13]. The PSSs are feedback controllers and modulate the generator excitation in such a way that the damping torque component of electrical torque comes in phase with rotor speed that reduces LFO [13]. The structure of PSS is given by:

$$\Delta U_i = K_i \left[\frac{sT_w}{1+sT_w} \right] \left[\frac{(1+sT_{1i})}{(1+sT_{2i})} \frac{(1+sT_{3i})}{(1+sT_{4i})} \right] \Delta w_i \tag{1}$$

where Δw_i is rotor speed deviation of *i*th machine in p.u. This structure includes dynamic gain for controlling damping, washout filter as high-pass filter to decrease the terminal voltage error in steady-state and a lagging-leading phase compensator for reducing error between the excitation and electrical torque. An auxiliary output signal ΔU_i is fed to the excitation system. The value of time constant T_w, T_{2i}, and T_{4i} are elected as definite values while the dynamic gain K_i and other time constants T_{1i} and T_{3i} values are to be evaluated.

2.2 *Test Case Study on Three-Machine, Nine-bus WSCC Power System*

The 3-machine, 9-bus WSCC power system and its data are referred from [2].

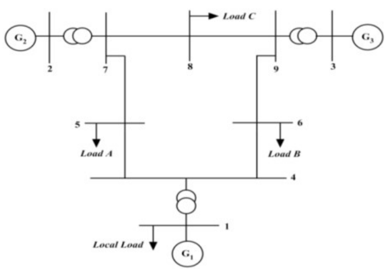

Fig. 1 3-Machine, 9-Bus WSCC Power System

Three different operational conditions of generators and loads are shown in Table I and considered for SSS analysis [10]. The participation factor method [14] is used to identify the optimal locations of installed PSSs in this system. Therefore, the corresponding two generators G_2 and G_3 are the optimal locations for installing PSSs. The PSAT [15] is used for eigenvalue analysis of the system for operational cases 1-3.

Table I: Three operational conditions of generators and loads for WSCC power system

Generator	Case-1		Case-2		Case-3	
	P	*Q*	*P*	*Q*	*P*	*Q*
	(p. u.)					
G₁	0.71	0.62	0.96	0.22	3.57	1.81
G₂	1.63	0.06	1.00	– 0.19	2.20	0.71
G₃	0.85	–0.10	0.45	– 0.26	1.35	0.43
Load						
A	1.25	0.50	0.70	0.35	2.00	0.90
B	0.90	0.30	0.50	0.30	1.80	0.60
C	1.00	0.35	0.60	0.20	1.60	0.65
Load at *G₁*	1.00	0.35	0.60	0.20	1.60	0.65

2.3 *Objective Function*

For guaranteed stability of unstable modes and to ensure the relative stability of poorly damped modes, LFO has to be damped out by increasing the damping performance of WSCC power system. An eigenvalue-based multi-objective function *J* is minimized using meta-heuristic techniques, i.e., GA, PSO, HSO and CSO. To design the six parameters of PSS in such a way that it can simultaneously control both damping factor and damping ratio [13]:

$$J = \sum_{j=1}^{np} \sum_{\sigma_{i,j} \geq \sigma_0} (\sigma_0 - \sigma_{i,j})^2 + \sum_{j=1}^{np} \sum_{\xi_{i,j} \leq \xi_0} (\xi_0 - \xi_{i,j})^2 \tag{2}$$

where *np*, $\sigma_{i,j}$ and $\xi_{i,j}$ are the number of operational cases to be elected in the design problem, the damping factor and the damping ratio of the *i*th eigenvalue of the *j*th operating point respectively. Moreover, σ_0 and ξ_0 are the values of desired damping factor and damping ratio respectively. This will shift the poorly and/or unstable damped eigenvalues of all operating cases to a chosen D-shape region in the left-half of the *s*-plane which is characterized by $\sigma_{i,j} \leq \sigma_0$ and $\xi_{i,j} > \xi_0$.

Minimize *J* subject to:

$$K_i^{\min} \leq K_i \leq K_i^{\max} \tag{3}$$

$$T_{1i}^{\min} \leq T_{1i} \leq T_{1i}^{\max} \tag{4}$$

$$T_{3i}^{\min} \leq T_{3i} \leq T_{3i}^{\max} \tag{5}$$

In this case, the particular values of σ_0 and ξ_0 are selected as –0.5 and 0.1 respectively. The value of washout time constant is chosen as 10 sec, T_{2i} and T_{4i}

are kept constant at numerical values of 0.1 second for reducing the computational burden. The values of designed parameters K, T_1 and T_3 are set in the range of [1-100], [0.01–1] and [0.01–1] respectively.

2.4 Cuckoo Search Optimization

The CSO is a new population-based meta-heuristic search algorithm proposed by Yang and Deb [16]. The cuckoos are popular birds due to their sounds and aggressive reproduction strategy. The algorithm is influenced by a breeding strategy of some cuckoo species in conjunction with Lévy flight behavior of some birds. For simplicity in describing the CSO, three conceptual rules are:

- A set of solutions are represented by each cuckoo laying egg and selecting random nest to dump in.
- A fraction of nests with highest quality fitness egg or the best solution will be carried out to the next iteration.
- The availability of host nests is set by some value and the foreign egg is searched by the host bird with a probability index $p_a \epsilon$ (0, 1) [13-16].

The CSO algorithm for the optimal design of PSS parameters for MMPS is given in [13].

2.5 Harmony Search Optimization

A Harmony Search (HS) is basically a music-based meta-heuristic technique developed by Geem et al. [17]. It is influenced by observing and discovering the perfect state of harmony of music which is determined by an aesthetic standard. The aesthetic qualities indicate the pitch of every musical instrument which is the same as the objective function value evaluated by the set of values assigned to every decision variable. When a musician is correcting himself or herself, there are three possible choices: (i) play any popular tune of music exactly from his or her memory; (ii) play something similar to a known tune; or (iii) compose new or random notes. Geem et al. [17] developed these three options into the three corresponding components: harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and randomization. The HSO algorithm for the optimal design of PSS parameters for MMPS can be referred from [12].

3. PSS DESIGN & SIMULATION RESULTS

In this study, two CSO and HSO algorithms are used for the optimal design of PSS parameters for two generators of WSCC power system. Results are compared with standard techniques, e.g., GA and PSO. Table I shows the eigenvalues and damping ratio of WSCC power system without PSS for unstable and poorly damped modes with three operating cases only. Table II shows the most favourable designed parameters of GAPSS, PSOPSS, HSOPSS and CSOPSS for the two generators. Table III depicts the eigenvalues and damping ratio with designed PSSs, for unstable and/or poorly damped modes, with three operating cases only. The table presents that the designed CSOPSS and HSOPSS place the unstable eigenvalues to the particular D-shape region in the left half of the *s*-plane with improved damping factor and damping ratio as compared to GAPSS, and PSOPSS, for all cases.

Table II: Optimally designed parameters of GAPSSs

	Generators	K	T_1	T_3
With GAPSS	G_2	1	0.464	0.06
	G_3	1	0.61	0.67
With PSOPSS	G_2	1	1	0.156
	G_3	1	0.400	0.06
With HSOPSS	G_2	1.770	1	0.133
	G_3	1.810	0.06	0.714
With CSOPSS	G_2	10.198	0.329	0.06
	G_3	1.857	0.287	0.314

To study the effectiveness of designed PSS controllers in terms of speed deviations, a three-phase 6-cycle fault disturbance at 1 second on bus 7 at the end of line 5-7 with Case-3 is considered. The severe disturbance is cleared without tripping the line. Fig 2 (a) and (b) show the comparison of severe speed deviations Δw_{12} and Δw_{23} with the designed PSS controllers for unforeseen Case-3 only.

From Fig 3, it is clear that the system damping performance with CSOPSSs is much better than that of GAPSSs, PSOPSSs and HSOPSSs for a severe disturbance under the operational Case-3. In addition to the time-domain simulation results, the superior effectiveness of designed CSOPSS controllers are observed by comparing bar charts of integral absolute error (*IAE)* and integral time absolute error *(ITAE)* with other designed PSSs for Cases 1-3 and are shown in Fig 4 (a) and (b) respectively.

The figure reveals that both index values for the CSOPSSs are minimum for the severe disturbance of operational Cases 1 to 3 as compared to the same values obtained by GAPSSs, PSOPSSs and HSOPSSs to settle LFO. These comparisons clearly show that CSOPSS controllers provide a superior damping to damp out LFO with less overshoot and settling time than those of the other designed PSS controllers. The CSO has only two control parameters, the population size n, and the probability index p_a. Once n is fixed, p_a controls the elitism and balance of the randomization in local search.

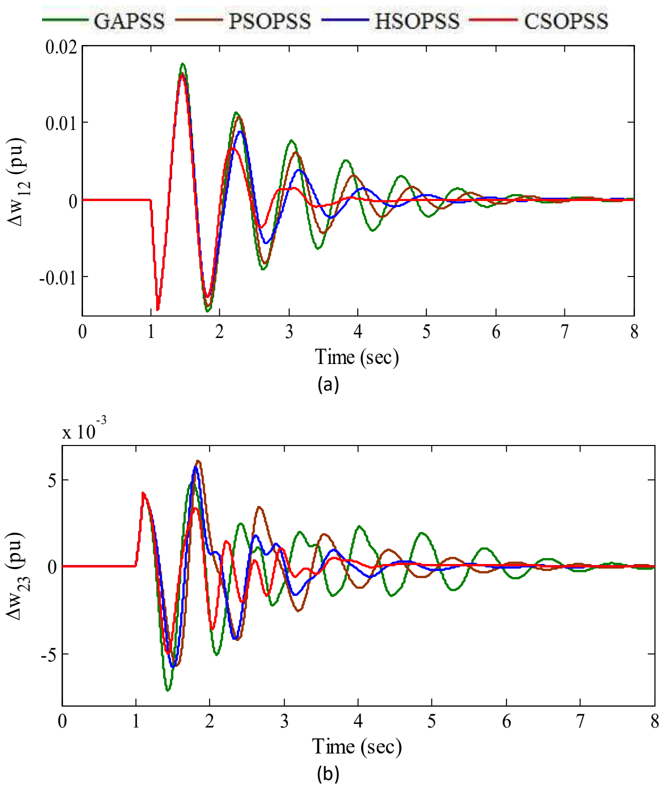

Fig. 2 Speed deviations (a) Δw_{12} and (b Δw_{23} with designed PSS controllers for a severe disturbance under the Case-3

4. *ROBUSTNESS OF DESIGNED PSS*

To investigate the robustness of designed PSSs controllers for WSCC power system, three crucial operating conditions of generators and loads (in cases 4-6) are considered and results shown in Table IV. In this investigation, eigenvalue analysis and various performance indices are evaluated for the same severe disturbance under unforeseen cases 4 to 6. The comparison of eigenvalues and their damping ratio without PSS and with earlier designed PSS for unseen cases 4-6 are shown in Table V.

Table IV: Three unseen operating conditions of generators and loads for WSCC power system

Generator	Case-4		Case-5		Case-6	
	P	***Q***	***P***	***Q***	***P***	***Q***
	(p. u.)					
G₁	0.33	1.12	1.09	0.79	1.41	0.59
G₂	2.00	0.57	2.45	0.57	2.60	0.38
G₃	1.50	0.38	1.27	0.21	1.2	0.02
Load						
A	1.50	0.90	1.90	0.75	2.00	0.60
B	1.20	0.80	1.30	0.45	1.50	0.30
C	1.00	0.50	1.50	0.50	1.60	0.20

From the table it has been observed that the CSOPSSs shift the eigenvalues to a specified D-shape region in the left half of the *s*-plane with better quality damping factor and damping ratio as compared to GAPSSs, PSOPSSs and HSOPSSs for cases 4-6. However, PSOPSSs provide minimum value of damping ratio for cases 4-6. It has also been observed that only HSOPSSs and CSOPSSs satisfy the selected criterion for the value of desired damping factor and damping ratio for robust PSS design. Therefore, the designed CSOPSSs is robust as it provides superior damping performance even for unforeseen operating conditions as compared to other designed PSS controllers.

To examine the robustness performance in terms of speed deviations, the comparison of severe speed deviations Δw_{12} and Δw_{23} with other designed PSS controllers, for severe disturbance of unseen case-6, are shown in Fig. 5 (a) and (b) respectively.

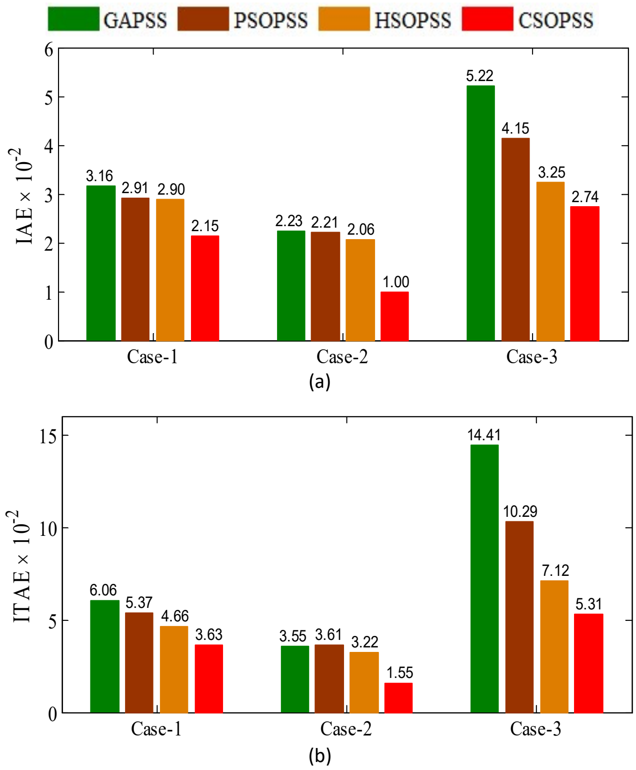

Fig 4 Values of IAE (a) and ITAE (b) with designed PSS controllers for severe disturbance of three unforeseen operational Cases 1-3

From Fig. 5 it may be observed that the controllers designed using CSOPSSs for severe disturbance of unseen cases 4-6 show much better damping because oscillations are damped out quickly as compared to that of other designed PSS controllers.

Table III: Eigenvalues and damping ratio comparison for three operational cases

Cases	Without PSS	With GAPSS	With PSOPSS	With HSOPSS	With CSOPSS
Case-1	– 0.110 ± j 8.588, 0.012 – 0.653 ± j 13.023, 0.050	– 1.778 ± j 8.323, 0.209 – 1.887 ± j 7.160, 0.254	– 1.212 ± j 7.549, 0.158 – 2.007 ± j 14.393, 0.138	– 1.466 ± j 6.856, 0.209 – 2.278 ± j 17.457, 0.129	– 2.982 ± j 19.103, 0.154 – 3.526 ± j 17.245, 0.200
Case-2	– 0.637 ± j 8.515, 0.074 – 1.274 ± j 12.752, 0.099	– 1.659 ± j 7.724, 0.210 – 2.811 ± j 7.480, 0.351	– 1.614 ± j 7.563, 0.208 – 2.669 ± j 14.041, 0.351	– 1.876 ± j 6.935, 0.261 – 2.918 ± j 16.950, 0.169	– 2.563 ± j 7.596, 0.319 – 3.133 ± j 18.265, 0.169
Case-3	**0.158 ± j 8.372, – 0.018** – 0.308 ± j 12.896, 0.024	– 0.961 ± j 7.148, 0.133 – 1.930 ± j 8.508, 0.221	– 0.768 ± j 7.381, 0.103 – 1.570 ± j 14.157, 0.110	– 0.982 ± j 6.791, 0.143 – 1.956 ± j 17.143, 0.113	– 1.852 ± j 7.060, 0.253 – 2.332 ± j 17.774, 0.130

Table V: Eigenvalues and damping ratio comparison for three unforeseen operating cases 4-6 of WSCC power system

Cases	Without PSS	With GAPSS	With PSOPSS	With HSOPSS	With CSOPSS
Case-4	**0.341 ± j 8.339, – 0.040** – 0.109 ± j 12.803, 0.0085	– 0.766 ± j 7.225, 0.105 – 1.829 ± j 8.273, 0.215	– 0.664 ± j 7.530, **0.087** – 1.565 ± j 13.977, 0.111	– 0.939 ± j 6.922, 0.134 – 2.038 ± j 17.156, 0.118	– 1.619 ± j 7.332, 0.215 – 3.119 ± j 18.920, 0.162
Case-5	**0.465 ± j 8.357, – 0.055** – 0.250 ± j 12.931, 0.019	– 1.228 ± j 8.052, 0.150 – 1.327 ± j 7.440, 0.175	– 0.557 ± j 7.442, **0.074** – 1.587 ± j 14.234, 0.110	– 0.828 ± j 6.835, 0.120 – 1.974 ± j 17.283, 0.113	– 1.781 ± j 7.056, 0.244 – 2.587 ± j 17.855, 0.143
Case-6	**0.604 ± j 8.375, – 0.072** – 0.233 ± j 12.981, 0.018	– 0.746 ± j 8.283, **0.089** – 1.692 ± j 7.092, 0.232	**– 0.465** ± j 7.442, **0.062** – 1.495 ± j 14.387, 0.103	– 0.746 ± j 6.827, 0.108 – 1.816 ± j 17.429, 0.103	– 1.761 ± j 6.908, 0.247 – 2.390 ± j 17.777, 0.133

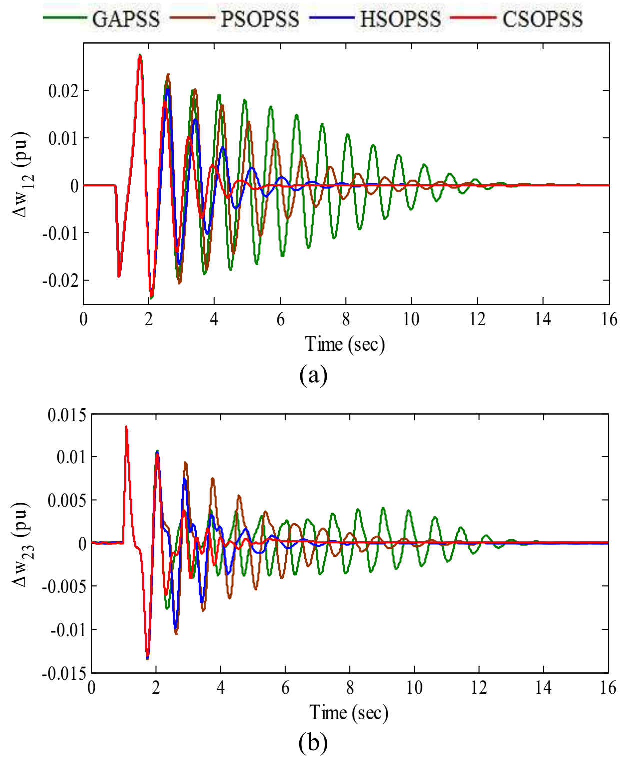

Fig. 5 Speed deviations (a) Δw_{12} and (b Δw_{23} with designed PSS controllers for severe disturbance of operating case-6

In addition to time-domain simulation results, the effectiveness and robustness performance of designed PSS controllers are also observed by comparing bar charts of *IAE* and *ITAE* for severe disturbance of cases 4-6 and are shown in Fig. 6 (a) and (b) respectively. From Fig. 6, it may be observed that the values of both indices for CSOPSSs are minimum and for GAPSSs are maximum for severe disturbance of unseen cases 4-6. It highlights that the designed CSOPSS controllers is most suitable as compared to other designed PSS controllers to damp out LFO with improved stability and damping performances for wide range of operating conditions under severe disturbances even for unforeseen operating cases under same severe disturbance.

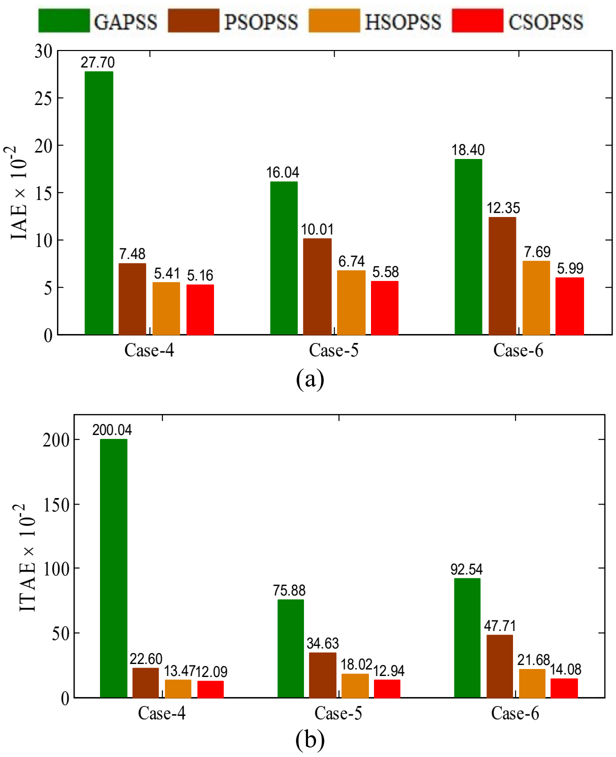

Fig. 6 Values of IAE and ITAE with designed PSS controllers for severe disturbance of three operating case

5. CONCLUSION

In this paper, two meta-heuristic techniques CSO and HSO has been explored for the robust design of PSS parameters of the 3-machines, 9-bus WSCC power system over a wide range of operational conditions. The proposed strategy includes an eigenvalue-based multi-objective function to shift poorly and/or unstable modes to a particular D-shape region in the left half of the s-plane for an improved relative stability. The eigenvalue analysis, simulation results and performance indices have revealed that with CSOPSSs, the system quickly settled down the LFO, even for the severe disturbance under all operational conditions including some of the unforeseen operating conditions as compared to other PSS controllers. This shows that CSOPSS controllers are more robust than other designed PSS controllers. The main merit of the CSO algorithm over other meta-heuristic algorithms is that it has only two control variables.

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