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A ROBUST ABC BASED PSS DESIGN FOR A SMIB POWER SYSTEM

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Abstract- An Artificial Bee Colony (ABC) algorithm to optimal tune of the Power System Stabilizer (PSS) in a Single-Machine Infinite-Bus (SMIB) power system is proposed in this paper. In the ABC method the food foraging behavior, memorizing and information sharing characteristics of honey bee swarm is simulated to find the best possible solution within a reasonable computation time. The problem of robustly PSS design is formulated as an optimization problem according to the time domain-based objective function for a wide range of operating conditions and is solved by the ABC technique which is simple, robust and capable to solve difficult combinatorial optimization problems. The proposed ABC based PSS is tested on a SMIB power system through the nonlinear time domain simulation and some performance indices in comparison with the particle swarm optimization based tuned stabilizer and conventional PSS to illustrate its robust performance. Results evaluation show that the proposed stabilizer achieves good robust performance for wide range of system operation conditions and is superior to the other PSSs.

Keywords: PSS Design, ABC Algorithm, Low Frequency Oscillations, SMIB.

I. INTRODUCTION

Stability of power systems is one of the most important aspects in electric system operation .This arises from the fact that the power system must maintain frequency and voltage levels at the nominal values, under any disturbance, like a sudden increase in the load, loss of one generator or switching out of a transmission line during a fault [1]. By the development of interconnection of large electric power systems, there have been spontaneous system oscillations at very low frequencies in order of 0.2-3.0 Hz .Once started, they would continue for a long period of time. In some cases, they continue to grow, causing system separation if no adequate damping is available. Moreover, low frequency oscillations present limitations on the power-transfer capability. To enhance system damping, the generators are equipped with Power System Stabilizer) PSS) that provide supplementary feedback stabilizing signals in the excitation system. PSS augment the power system stability limit and extend the power-transfer capability by enhancing the system damping of low frequency oscillations associated with the electromechanical modes [2].

The lead compensator based stabilizers with fix parameters have practical applications and generally provide acceptable dynamic performance. However, the problem of PSS parameter tuning is a complex exercise. A number of the conventional techniques have been reported in the literature pertaining to design PSS namely: the eigenvalue assignment, mathematical programming, gradient procedure for optimization and also the modern control theory [2-5]. Unfortunately, the conventional techniques are time consuming as they are iterative and require heavy computation burden and slow convergence. In addition, the search process is susceptible to be trapped in local minima and the solution obtained may not be optimal [4]. Also, a set of controller parameters which stabilize the system under a certain operating condition may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations [5]. A more reasonable design of the PSS is based on the gain scheduling and adaptive control theory as it takes into consideration the nonlinear and stochastic characteristics of the power systems [6-7]. This type of stabilizer can adjust its parameters on-line according to the operating condition. Many years of intensive studies have shown that the adaptive stabilizer can not only provide good damping over a wide operating range but more importantly, it can also solve the coordination problem among the stabilizers.

Many random heuristic methods, such as like Tabu search, genetic algorithms, chaotic optimization algorithm, rule based bacteria foraging and particle swarm optimization (PSO) have recently received much interest for achieving high efficiency and search global optimal solution in the problem space and they have been applied to the problem of PSS design [8-11]. These evolutionary based methods are heuristic population-based search procedures that incorporate random variation and selection operators. Although, these methods seem to be good approaches for the solution of the PSS parameter optimization problem, however, when the system has a highly epistatic objective function (i.e. where parameters being optimized are highly correlated), and number of parameters to be optimized is large, then they have degraded effectiveness to obtain the global optimum solution. In order to overcome these drawbacks, an Artificial Bee Colony (ABC) algorithm is proposed for optimal tune of PSS parameters to improve power system low frequency oscillations damping in this paper. The ABC algorithm is a typical swarm-based approach to optimization, in which the search algorithm is inspired by the intelligent foraging behavior of a honey bee swarm process [12] and has emerged as a useful tool for engineering optimization. It incorporates a flexible and well-balanced mechanism to adapt to the global and local exploration and exploitation abilities within a short computation time. Hence, this method is efficient in handling large and complex search spaces [13].

The proposed method has been applied and tested on a weakly connected power system under wide range of operating conditions to show the effectiveness and robustness of the proposed ABC based tuned PSS and their ability to provide efficient damping of low frequency oscillations .To show the superiority of the proposed design approach, the simulations results are compared with the Particle Swarm Optimization (PSO) based designed and classical PSS under different operating conditions through some performance indices. The results evaluation shows that the proposed method achieves good robust performance for wide range of load changes in the presence of very highly disturbance and is superior to the other stabilizers.

II. POWER SYSTEM DESCRIPTION

A power system model consisting of a Single Machine connected to an Infinite Bus (SMIB) through a circuit transmission line is used in the simulation studies. A schematic diagram for the model is shown in Figure 1. The generator is equipped with excitation system and a power system stabilizer. All the relevant parameters are given in Appendix.

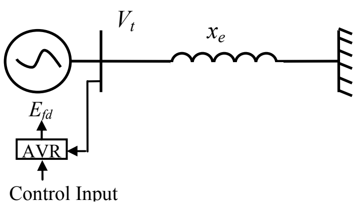

Figure 1. SMIB power system

The synchronous generator is represented by model 1.1, i.e. with field circuit and one equivalent damper winding on q axis. The dynamic equations of the SMIB system considered can be summarized as [14, 11].

$$\begin{cases} \dot{\delta} = \omega_B S_m \\ \dfrac{dS_m}{dt} = \dfrac{1}{2H}(-DS_m + T_m - T_e) \\ \dot{E}'_q = \dfrac{1}{T'_{do}}(E_{fd} + (x_d - x'_d)i_d - E'_q) \\ \dot{E}_{fd} = \dfrac{1}{T_A}(k_A(v_{ref} - v_t + V_s)) - E_{fd}) \end{cases} \quad (1)$$

$$T_e = E'_q i_q + (x'_d - x'_q) i_d i_q \quad (2)$$

A. Structure of PSS

The structure of PSS, to modulate the excitation voltage is shown in Figure 2. The structure consists a gain block with gain K, a signal washout block and two-stage phase compensation blocks. The input signal of the proposed method is the speed deviation ($\Delta\omega$) and the output is the stabilizing signal V_S which is added to the reference excitation system voltage. The signal washout block serves as a high-pass filter, with the time constant T_W, high enough to allow signals associated with oscillations in input signal to pass unchanged. From the viewpoint of the washout function, the value of T_W is not critical and may be in the range of 1 to 20 seconds [11]. The phase compensation block (time constants T_1, T_2 and T_3, T_4) provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals.

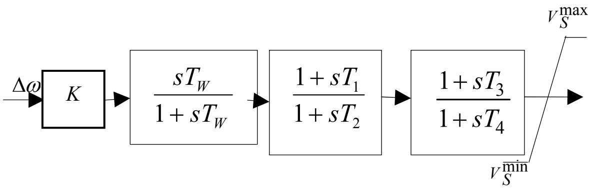

Figure 2. Structure of power system stabilizer

III. ARTIFICIAL BEE COLONY ALGORITHM

Recently, Karaboga and Basturk [15] have described an artificial bee colony algorithm based on the foraging behavior of honey-bees for numerical optimization problems. The algorithm simulates the intelligent foraging behavior of honey bee swarms. It is a very simple, robust and population based stochastic optimization algorithm [16].

The minimal model of forage selection in honey bee swarms intelligence consists of three essential components: food sources, employed foragers and unemployed foragers, and two leading modes of the behavior, recruitment to a nectar source and abandonment of a source, are defined [17]. A food source value depends on many factors, such as its proximity to the nest, richness or concentration of energy and the ease of extracting this energy. The employed foragers are associated with particular food sources, which they are currently exploiting or are ''employed". They carry with them information about these food sources and share this information with a certain probability. There are two types of unemployed foragers, scouts and onlookers. Scouts search the environment surrounding the nest for new food sources, and onlookers wait in the nest and find a food source through the information shared by employed foragers.

In the ABC algorithm, the colony of artificial bees contains of three groups of bees: employed bees, onlookers and scouts. The food source represents a possible solution of the optimization problem and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. Every food source has only one employed bee. Thus, the number of employed bees or the onlooker bees is equal to the number of food sources (solutions).

An onlooker bee chooses a food source depending on the probability value associated with that food source, p_i, calculated by the following expression:

$$p_i = \frac{fit_i}{\sum_{n=1}^{SN} fit_n} \tag{3}$$

where, fit_i is the fitness value of the solution i evaluated by its employed bee, which is proportional to the nectar amount of the food source in the position i and SN is the number of food sources which is equal to the number of employed bees (BN). In this way, the employed bees exchange their information with the onlookers.

In order to produce a candidate food position from the old one, the ABC uses the following expression:

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}) \tag{4}$$

where, $k \in \{1,2,...,BN\}$ and $j \in \{1,2,...,D\}$ are randomly chosen indexes. Although k is determined randomly, it has to be different from i. ϕ_{ij} is a random number between [0, 1]. It controls the production of a neighbour food source position around x_{ij} and the modification represents the comparison of the neighbor food positions visually by the bee. Equation (4) shows that as the difference between the parameters of the x_{ij} and x_{kj} decreases, the perturbation on the position x_{ij} decreases, too. Thus, as the search approaches to the optimum solution in the search space, the step length is adaptively reduced.

The food source whose nectar is abandoned by the bees is replaced with a new food source by the scouts. In the ABC algorithm this is simulated by randomly producing a position and replacing it with the abandoned one. If a position cannot be improved further through a predetermined number of cycles called *limit* then that food source is assumed to be abandoned.

After each candidate source position v_{ij} is produced and then evaluated by the artificial bee, its performance is compared with that of x_{ij}. If the new food has equal or better nectar than the old source, it is replaced with the old one in the memory. Otherwise, the old one is retained. In other words, a greedy selection mechanism is employed as the selection operation between the old and the current food sources.

The main steps of the algorithm are given by [12, 17]:

i) Initialize the population of solutions and evaluate them.

ii) Produce new solutions for the employed bees, evaluate them and apply the greedy selection mechanism.

iii) Calculate the probabilities of the current sources with which they are preferred by the onlookers.

iv) Assign onlooker bees to employed bees according to probabilities, produce new solutions and apply the greedy selection mechanism.

v) Stop the exploitation process of the sources abandoned by bees and send the scouts in the search area for discovering new food sources, randomly.

vi) Memorize the best food source found so far.

vii) If the termination condition is not satisfied, go to step 2, otherwise stop the algorithm.

It is clear from the above explanation that there are three control parameters used in the basic ABC: The number of the food sources which is equal to the number of employed or onlooker bees (SN), the value of *limit* and the Maximum Cycle Number (MCN).

IV. PROBLEM FORMULATION

In case of the above lead-lag structured PSS, the washout time constants is usually specified. In the present study, washout time constant T_W =10 sec is used. The controller gain K and the time constants T_1, T_2, T_3 and T_4 are to be determined. It is worth mentioning that the PSS is designed to minimize the power system oscillations after a large disturbance so as to improve the power system stability. These oscillations are reflected in the deviations in power angle, rotor speed and line power. Minimization of any one or all of the above deviations could be chosen as the objective. In this study, an Integral Square Time of Square Error (ISTSE) of the speed deviations is taken as the objective function expressed as follows:

$$J = \sum_{i=1}^{NP} \int_{t=0}^{t=tsim} t^2 (\Delta\omega)^2 \, dt \tag{5}$$

where, $\Delta\omega$ denotes the rotor speed deviation for a set of PSS parameters, t_{sim} is the time range of the simulation and NP is the total number of operating points for which the optimization is carried out. It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots under different operating condition. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds [9, 11]:

minimize J subject to:

$$\begin{aligned} K^{\min} &\le K \le K^{\max} \\ T_1^{\min} &\le T_1 \le T_1^{\max} \\ T_2^{\min} &\le T_2 \le T_2^{\max} \\ T_3^{\min} &\le T_3 \le T_3^{\max} \\ T_4^{\min} &\le T_4 \le T_4^{\max} \end{aligned} \tag{6}$$

Typical ranges of the optimized parameters are [0.01-50] for K and [0.01-1] for T_1, T_2, T_3 and T_4. The proposed approach employs ABC algorithm to solve this optimization problem and search for an optimal or near optimal set of PSS parameters. The optimization of the PSS parameters is carried out by evaluating the objective cost function as given in Equation (5), which considers a multiple of operating conditions are given in Table 1. The operating conditions are considered for wide range of output power at different power factors. Results of the PSS parameter set values based on the objective function J, by applying a three phase-to-ground fault for 100 ms at generator terminal at t=1 sec using the proposed ABC and PSO algorithms [9] are given in Table 2. The Classical PSS (CPSS) is design using the tuning guidelines given in [14] for nominal operating point. Figure 3 shows the minimum fitness functions evaluating process.

Table 1. Operation conditions

Case No.	P	Q	x_e	H
Case 1 (Base case)	0.8	0.4	0.3	3.25
Case 2	0.5	0.1	0.3	3.25
Case 3	1	0.5	0.3	3.25
Case 4	0.8	0.4	0.6	3.25
Case 5	0.5	0.1	0.6	3.25
Case 6	1	0.5	0.6	3.25
Case 7	0.8	0	0.6	3.25
Case 8	1	-0.2	0.3	3.25
Case 9	0.5	-0.2	0.6	3.25
Case 10	1	0.2	0.3	0.81

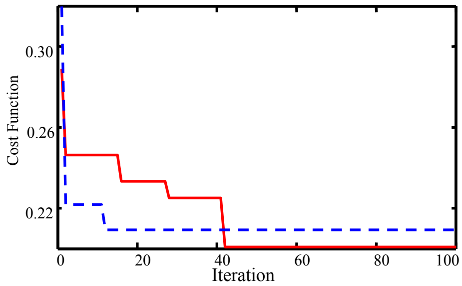

Figure 3. Fitness convergence, Dashed (PSO) and Solid (ABC)

Table 2. Optimal PSS parameters

Method	K_{pss}	T_1	T_2	T_3	T_4
ABC	29.31	0.0941	0.0213	0.0657	0.0011
PSO	20.56	0.098	0.0195	0.0883	0.0103
CPSS	12.5	0.0738	0.0280	0.0738	0.0280

V. SIMULATION RESULTS

The behavior of the proposed ABC based designed PSS (ABCPSS) under transient conditions is verified by applying disturbance and fault clearing sequence under different operating conditions in comparison with the PSO based tuned PSS (PSOPSS) and classical PSS. The disturbances are given at t = 1 sec. System responses in the form of slip (S_m) are plotted. The following types of disturbances have been considered.

Scenario 1: A step change of 0.1 pu in the input mechanical torque.

Scenario 2: A three phase-to-ground fault for 100 ms at the generator terminal.

Figure 4 shows the system response at the lagging power factor operating conditions with weak transmission system for scenario 1. It can be seen that the system with CPSS is highly oscillatory. Both ABC and PSO based tuned stabilizers are able to damp the oscillations reasonably well and stabilize the system at all operating conditions. Figure 5 depicts the responses of same operating conditions but with strong transmission system. System is more stable in this case, following any disturbance. Both PSSs improve its dynamic stability considerably and ABCPSS shows its superiority over PSOPSS and CPSS. System response at the ohmic operating conditions is shown in Figure 6 with the weak and strong transmission system for scenario 1. The proposed ABC based PSS is effective and achieves good system damping characteristics. Also, Figure 7 show the system response at the leading power factor operating conditions with the weak and strong transmission system for scenario 1. Figure 8 refers to a three-phase to ground fault at the generator terminal. Figure 9 depicts the system response in scenario 1 with inertia $H' = H/4$. It can be seen that the proposed ABC based PSS has good performance in damping low frequency oscillations and stabilizes the system quickly. Moreover, it is superior to the PSO and classical based methods tuned stabilizer.

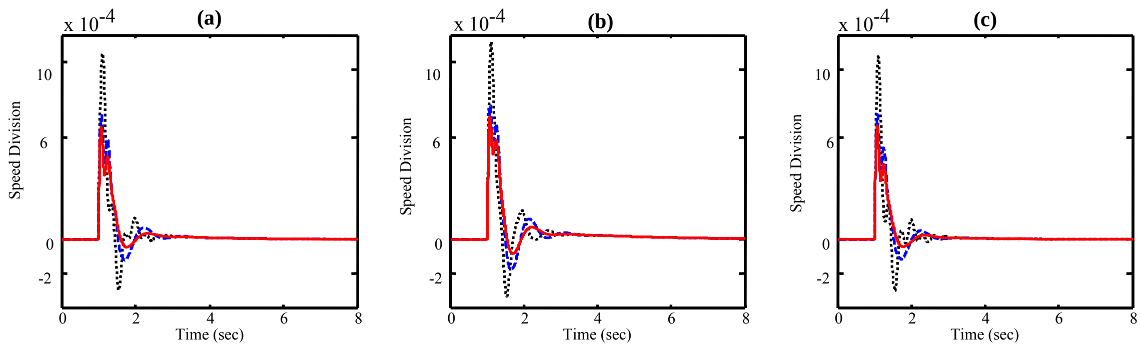

Figure 4. ΔT_m=0.1 (p.u.) under X_e=0.3; CPSS (Dotted), PSOPSS (Dashed) and ABCPSS (Solid)
a) P=0.8, Q=0.4 b) P=0.5, Q=0.1 c) P=1.0, Q=0.5

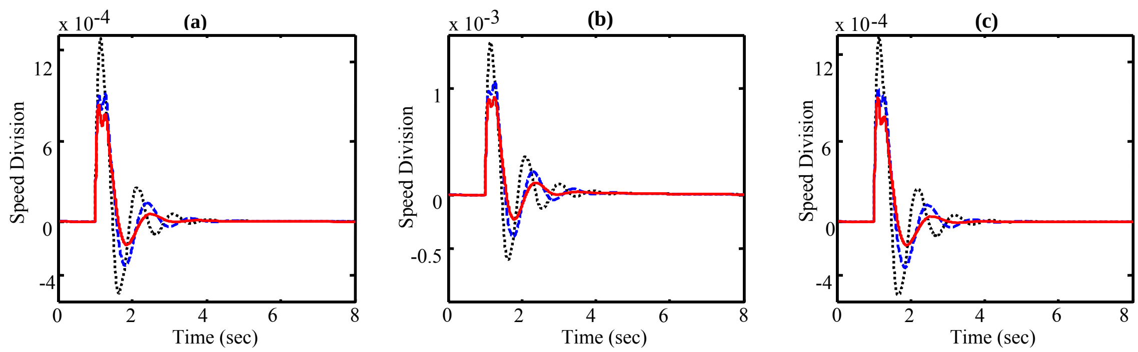

Figure 5. ΔT_m=0.1 (p.u.) under X_e=0.6; CPSS (Dotted), PSOPSS (Dashed) and ABCPSS (Solid)
a) P=0.8, Q=0.4 b) P=0.5, Q=0.1 c) P=1.0, Q=0.5

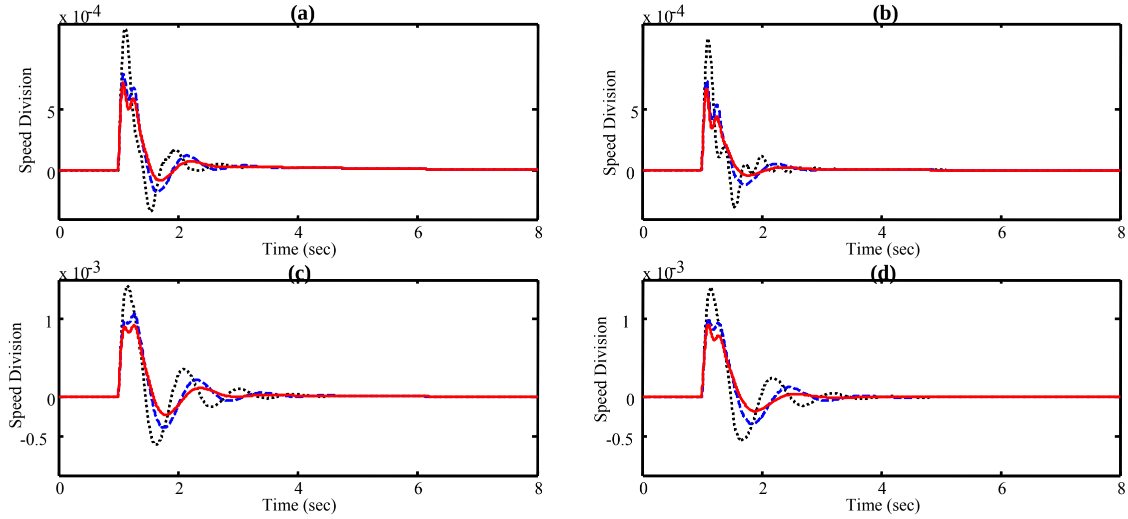

Figure 6. ΔT_m=0.1 (p.u.); CPSS (Dotted), PSOPSS (Dashed) and ABCPSS (Solid)
X_e=0.3; a) P=0.5, Q=0.0 b) P=1.0, Q=0 X_e=0.6; c) P=0.5, Q=0.0 d) P=1.0, Q=0

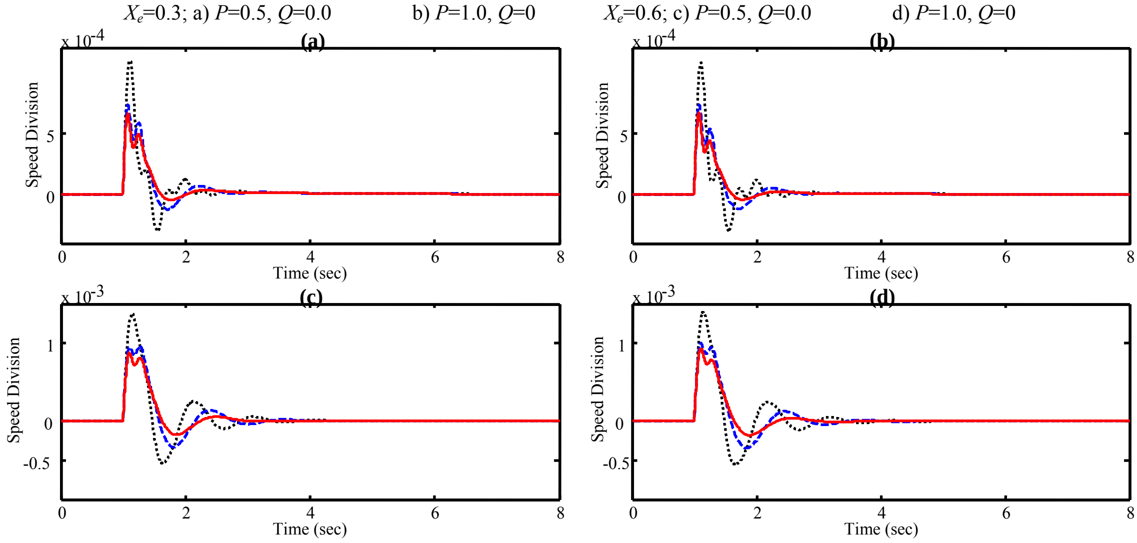

Figure 6. ΔT_m=0.1 (p.u.); CPSS (Dotted), PSOPSS (Dashed) and ABCPSS (Solid)
X_e=0.3; a) P=0.8, Q=-0.2 b) P=1.0, Q=-0.2 X_e=0.6; c) P=0.8, Q=-0.2 d) P=1.0, Q=-0.2

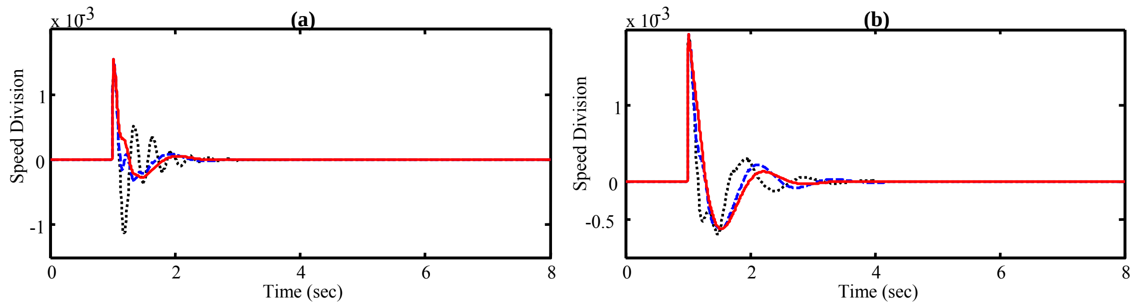

Figure 8. 3-φ to ground fault 100 ms for X_e=0.3, CPSS (Dotted), HBMOPSS (Dashed) and IHBMOPSS (Solid)
a) P=0.8, Q=0.4 b) P=1.0, Q=0.5

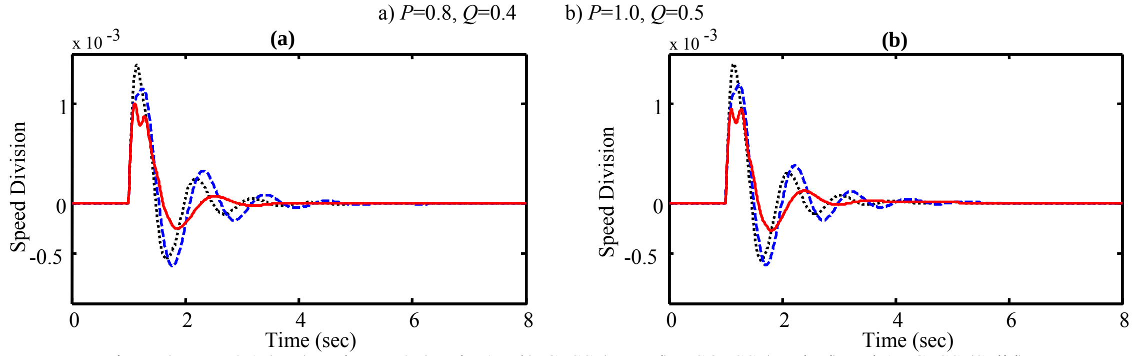

Figure 9. ΔT_m=0.1 (p.u.) under X_e=0.6 and H'=H/4, CPSS (Dotted), PSOPSS (Dashed) and ABCPSS (Solid)
a) P=1.0, Q=0.5 b) P=0.6, Q=0.0

To demonstrate performance robustness of the proposed method, two performance indices: the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD) based on the system performance characteristics are defined as [17]:

$$FD = 10\times[(500\times OS)^2 + (8000\times US)^2 + 0.01\times T_s^2] \quad (11)$$

$$ITAE = 1000\times \int_0^8 t\,|\Delta\omega|dt \quad (12)$$

where, Overshoot (*OS*), Undershoot (*US*) and settling time of rotor angle deviation of machine is considered for evaluation of the *FD*. It is worth mentioning that the lower value of these indices is, the better the system response in terms of time domain characteristics. Numerical results of performance robustness for all operating conditions as given in Table 1 for scenario 1 and 2 are listed in Table 3 and 4, respectively. It can be seen that the values of these system performance characteristics with the proposed ABCPSS are much smaller compared to that PSO and classical based designed PSS. This demonstrates that the overshoot, undershoot, settling time and speed deviations of machine is greatly reduced by applying the proposed ABC based tuned PSS.

Table 3. Performance indices for scenario 1

Case No	ABCPSS		PSOPSS		CPSS	
	ITAE	*FD*	*ITAE*	*FD*	*ITAE*	*FD*
1	0.4668	0.3823	0.5475	0.5330	0.5632	1.4729
2	0.7996	0.4561	0.8842	0.7289	0.9042	1.7696
3	0.3420	0.3830	0.4218	0.5246	0.4465	1.4774
4	0.6726	0.8191	0.9330	1.5374	1.1311	3.4747
5	1.0268	1.0293	1.2791	2.0328	1.4959	4.2209
6	0.6566	0.8854	0.9469	1.6527	1.1631	3.6312
7	0.6726	0.8191	0.9331	1.5374	1.1310	3.4747
8	0.3419	0.3828	0.4218	0.5246	0.4465	1.4774
9	1.0268	1.0293	1.2791	2.0328	1.4959	4.2209
10	0.3420	0.3830	0.4218	0.5246	0.4465	1.4774

Table 4. Performance indices for scenario 2

Case No	ABCPSS		PSOPSS		CPSS	
	ITAE	*FD*	*ITAE*	*FD*	*ITAE*	*FD*
1	0.4633	1.9449	0.4704	2.1544	0.5743	11.4092
2	0.2463	0.8078	0.2486	1.0384	0.3469	5.7607
3	0.5365	3.1867	0.6071	3.2376	0.7134	15.2602
4	0.5520	3.1010	0.7366	3.1061	0.6551	3.8234
5	0.4601	1.3868	0.5053	1.5289	0.4638	1.9659
6	1.0006	5.2021	1.0046	5.2052	0.8964	6.0103
7	0.7034	3.0103	0.7374	3.1149	0.6554	3.8250
8	0.4370	3.1885	0.5085	3.2516	0.7129	15.2359
9	0.4599	1.3857	0.5058	1.5301	0.4634	1.9598
10	0.5073	3.1885	0.6370	3.2394	0.7139	15.2846

VI. CONCLUSIONS

In this paper, ABC optimization technique has been successfully applied for power system stabilizer design in a SMIB power system. To design PSS problem, a nonlinear simulation-based objective function is developed to increase the system damping and then ABC technique is implemented to search for the optimal stabilizer parameters. The proposed ABC algorithm is easy to implement without additional computational complexity. Thereby experiments this algorithm gives quite promising results. The ability to jump out the local optima, the convergence precision and speed are remarkably enhanced and thus the high precision and efficiency are achieved. The effectiveness of the proposed stabilizer, for power system stability improvement, is demonstrated by a weakly connected example power system subjected to severe disturbance. The dynamic performance of ABC based tuned PSS has also been compared with PSO and classical methods based designed PSS to show its superiority. The nonlinear simulation results under wide range of operating conditions show the robustness of ABC based PSS ability to provide efficient damping of low frequency oscillations and its superiority to the other methods. The system performance characteristics in terms of ITAE and FD indices reveal that the proposed stabilizers demonstrates that the overshoot, undershoot, settling time and speed deviations of the machine are greatly reduced under severe disturbance conditions.

APPENDIX
SYSTEM DATA

Generator: R_a=0, x_d= 2.0, x_q = 1.91, x'_d=0.244, x'_q=0.244
f = 50 Hz, T'_{do}=4.18, T'_{qo}=0.75, H=3.25
Transmission line: R= 0, x_e = 0.3
Exciter: K_A=50, T_A=0.05, E_{fdmax}=7.0, E_{fdmin}=-7.0

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