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Bacterial Foraging Algorithm for the Robust Design of Multi-machine Power System Stabilizer

G.Naresh [1], M.Ramalinga Raju [2] and S.V.L.Narasimham[3]

[1]Department of E.E.E., Pragati Engineering College, Surampalem, Andhra Pradesh, India.
[2]Department of E.E.E., University College of Engineering, J.N.T.U. Kakinada, Andhra Pradesh, India.
[3]Department of C.S.E., School of Information Technology, J.N.T.U. Hyderabad, Andhra Pradesh,India.
naresh.elec@gmail.com, rajumanyala@yahoo.com, svlnarasimham@gmail.com

Abstract. In this paper, a novel bacterial foraging algorithm (BFA) based approach for optimal design of the parameters of modern power system stabilizers (PSSs) is proposed for damping low frequency power oscillations of a multi-machine power system. This paper attempts to optimize three constants each of several PSSs present in a multi-machine power system based on foraging behaviour of Escherichia coli bacteria in human intestine. A multi-objective problem is formulated to optimize a composite set of objective functions comprising the damping factor, and the damping ratio of the lightly damped electromechanical modes. The problem of robustly selecting the parameters of the power system stabilizers is converted to an optimization problem which is solved by a bacterial foraging algorithm with the eigenvalue-based multi-objective function. The eigenvalue analysis and non-linear simulation results presented under wide range of operating conditions show the effectiveness and robustness of the proposed BFAPSS 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.

Keywords*:* Power system stabilizer (PSS), Bacterial foraging algorithm (BFA), Multi-machine power system.

1. Introduction

Power systems are highly non-linear and exhibit low frequency oscillations due to poor damping caused by the high-gain, fast-acting automatic voltage regulator (AVR) employed in the excitation system. The power system utilities employ power system stabilizers (PSSs) to introduce supplementary stabilizing signals into the excitation system to increase the damping of the low frequency oscillations. Among various types of PSSs, the fixed-structure lag-lead type is preferred by the utilities due to its operational simplicity ease of tuning PSS parameters. The robustness of these PSS under changing conditions is a major concern in its operation.

The concept of PSSs and their tuning procedures were well explained in [1]. Kundur et al. [2] illustrated that a well-tuned lag-lead type PSS can effectively improve dynamic stability. Many approaches have been proposed to tune PSSs, such as the sensitivity approach [3], pole placement [4], and the damping torque approach [1].

The parameter tuning of PSSs in a multi-machine power system are classified into two major methods viz., sequential tuning and simultaneous tuning. In sequential tuning, the PSS is tuned sequentially, taking one electromechanical mode into consideration at a time [5]. The main disadvantage of this method is that the sequential addition of stabilizers will disturb the previously assigned eigenvalues.

Global optimization technique like genetic algorithm (GA) [6], tabu search [7] and simulated annealing (SA) [8] are attracting the attention in the field of PSS parameter optimization in the recent times. 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 [9]. Bacterial foraging algorithm has been proposed and introduced as a new evolutionary technique in [10]. Passino et al. pointed out that the foraging algorithms can be integrated in the framework of evolutionary algorithms. To overcome the drawbacks of conventional methods for PSS design, a new optimization scheme known as bacterial foraging (BF) is used for the PSS parameter design. This algorithm (BFA) appeared as a promising algorithm for handling the optimization problems. It 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 many analytical methods fail to converge. Considering the strength of this algorithm, it is employed in the present work for the optimal tuning 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, resulting in 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 therefore guarantees that relative stability and time domain specifications are concurrently secured.

The proposed design approach is applied to WSCC 3-machine,9-bus System. The eigenvalue analysis and the nonlinear simulation results are 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 is found that the proposed technique optimizes the parameters faster besides exhibiting better damping performance with the optimized gains when the system is perturbed.

The remainder of the paper is organized as follows: Section (2) focuses on the statement of the problem. Section (3) emphasizes on the basic idea of bacterial foraging algorithm. Results and discussions are carried out in Section (4) and conclusions are made in section(5).

2. Problem Formulation

The complex nonlinear model related to an 'n' machine interconnected power system can be described by a set of differential algebraic equations by assembling the models for each generator, load, and other devices, such as controls in the system, and connecting them appropriately via the network algebraic equations. All machines are represented as fourth-order models and equipped with fast acting exciters [11]. For a given operating condition, the multi-machine power system is linearized around the operating point.

2.1. PSS Structure

The PSS considered is a speed-based two-stage fixed-structure lag-lead compensator. Thus, for the ith generator, the PSS is of the form [12]

$$G_{PSS,i}(s) = K_{s,i}\left[\frac{sT_W}{1+sT_W}\right]\left[\frac{(1+sT_{1,i})}{(1+sT_{2,i})}\right]^2 \tag{1}$$

where T_W is the washout time constant. In the design of a PSS, washout time constant T_W is usually pre-specified, and PSS gain $K_{s,i}$ and time constants $T_{1,i}$ and $T_{2,i}$ are to be optimized. The signal washout block serves as a high-pass filter with time constant T_W, high enough to allow signals in the range of 0.2–2.0 Hz associated with rotor oscillations in an input signal to pass unchanged.

From the viewpoint of the washout function, the value of T_W is not critical and may be kept constant in the range 1–20 sec [13].

2.2. Objective Function

In case of conventional lead-lag PSS, washout time constant is usually pre-specified. In the present study, T_W is taken arbitrarily as 10. The parameters of PSS are selected so as to minimize the following objective function

$$J = J1 + \alpha \, . \, J2 \tag{2}$$

where,

$$J1 = \sum_{j=1}^{NP} \sum_{\sigma_{i,j} \geq \sigma_0} [\sigma_0 - \sigma_{i,j}]^2 \tag{3}$$

$$J2 = \sum_{j=1}^{NP} \sum_{\xi_{i,j} \geq \xi_0} [\xi_0 - \xi_{i,j}]^2 \tag{4}$$

Where, α is arbitrarily chosen as 10 [13], $\sigma_{i,j}$ is the real part of the ith eigenvalue of the jth operating point and $\xi_{i,j}$ is the damping ratio of the ith eigenvalue of the jth operating point, subject to the constraints that finite bounds are placed on the power system stabilizer parameters.

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, where the constraints are the PSS parameter bounds as given below:

Minimize J subject to

$$K_{i\min} \leq K_i \leq K_{i\max} \;\; ; \; T_{1i\min} \leq T_{1i} \leq T_{1i\max} \;\; ; \; T_{2i\min} \leq T_{2i} \leq T_{2i\max} \tag{5}$$

The proposed approach employs BFA to solve this optimization problem and search for optimal or near optimal set of PSS parameters $\{K_i, T_{1i}, T_{2i}; \text{ i=1, 2 …n}\}$. Typical ranges of the optimized parameters are [0.01 to 40] for K_i and [0.01 to 1.0] for T_{1i} and T_{2i}.

3. Bacterial Foraging Algorithm

The survival of species in any natural evolutionary process depends upon their fitness criteria, which relies upon their food searching and motile behavior. The law of evolution supports those species who have better food searching ability and either eliminates or reshapes those with poor search ability. The genes of those species who are stronger gets propagated in the evolution chain since they posses ability to reproduce even better species in future generations. So a clear understanding and modeling of foraging behavior in any of the evolutionary species, leads to its application in any non-linear system optimization algorithm. The foraging strategy of *Escherichia coli* bacteria present in human intestine can be explained by four processes, namely chemotaxis, swarming, reproduction, elimination–dispersal [10].

In this algorithm, cost function value is taken as objective function and the bacterium having minimum cost function (*J*) is retained for the next generation. For swarming, the distances of all the bacteria in a new chemotactic stage are evaluated from the global optimum bacterium till that point. To speed up the convergence, a simple heuristic rule to update one of the coefficients (C) of BFO algorithm is formulated.

The flow chart of the iterative algorithm is shown in the following fig(1).

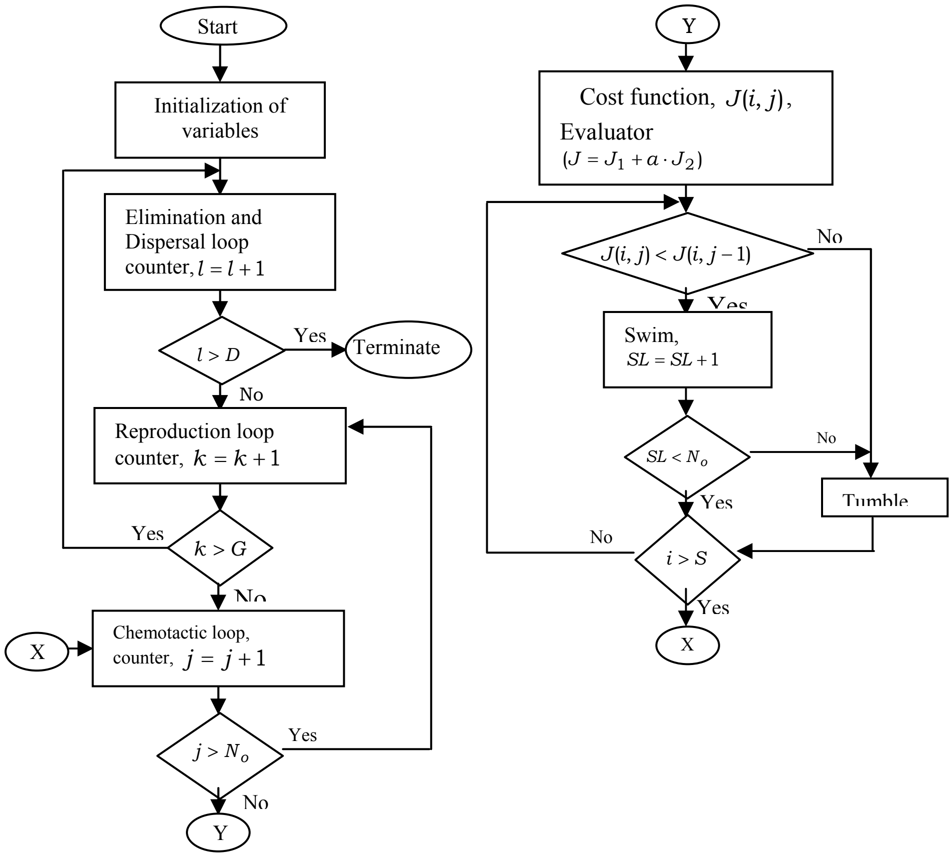

Fig 1. Flowchart of Bacterial Foraging Algorithm

4. Test System

In this paper, the WSCC 3-machine, 9-bus power system shown in Figure 2 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.

To assess the effectiveness and robustness of the proposed BFAPSS 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 and BFAPSS 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 BFAPSS. It is clear that some of these modes are poorly damped and some of them are unstable

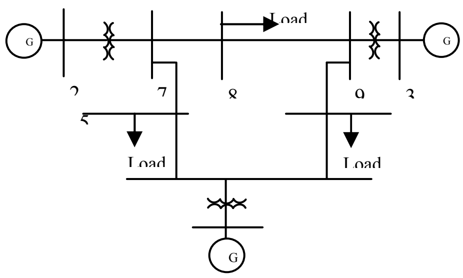

Fig. 2: WSCC Three-machine Nine-bus Power System

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: Tuned Parameters of CPSS, GAPSS and BFAPSS

Gen#	Parameters of CPSS			Parameters of GAPSS			Parameters of BFAPSS		
	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	20.0797	0.2304	0.010
G2	2.4638	0.3716	0.2990	5.5433	0.6958	0.3421	22.0051	0.2313	0.010
G3	0.3997	0.3752	0.2961	14.9741	0.0531	0.4210	4.7671	0.1592	0.2054

Table 4: Comparison of Eigenvalues and Damping ratios for different schemes

	Base Case	Case-1	Case-2	Case-3
Without PSS	-0.2367 ± 8.5507i, 0.0277 -11.1752 ±10.4687i, 0.7298	-0.1421 ± 8.4615i, 0.0168 -11.2788 ±11.3006i, 0.7064	-0.8199 ± 8.1535i, 0.1001 -10.4600 ±12.2400i, 0.6497	**0.0990 ± 8.5483i, -0.0116** -11.4841 ±11.0256i, 0.7214
CPSS	-0.8017 ± 9.0603i, 0.0881 -11.1414 ± 9.4032i, 0.7642	-0.8024 ± 8.9184i, 0.0896 -11.1601 ±10.3813i, 0.7322	-1.2583 ± 8.4817i, 0.1468 -10.3426 ±11.4081i, 0.6717	-0.3549 ± 8.9847i, 0.0395 -11.3684 ±10.0945i, 0.7478
GAPSS	-3.6954±3.0702i, 0.7691 -3.8231±10.1249, 0.3532	-1.0697±1.6823i, 0.5365 -3.2448±4.1112i, 0.6195	-3.0903±1.6258i, 0.8849 -2.7319±8.8153i, 0.2960	-0.8841±1.5046i, 0.5065 -3.7374±3.7711i, 0.7039
BFA PSS	-1.7519± 1.2459i, 0.8149 -3.1050±6.6844i, 0.4212	-1.7406±2.7162i, 0.5395 -3.1544±6.5586i, 0.4334	-3.6223±11.1469i, 0.3090 -2.8899±6.8011i, 0.3910	-1.4305±2.2934i, 0.5292 -3.0389±6.6939i, 0.4133

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 with the inclusion of PSS.

Non Linear Time Domain Simulation

To demonstrate the effectiveness of the PSSs tuned using the proposed BFAPSS over a wide range of operating conditions, the following disturbance are considered for nonlinear time simulations. System performance is demonstrated by using the performance index, Integral of Time multiplied Absolute value of Error(*ITAE*), given by

$$ITAE = \int_0^{10} t.(|\Delta\omega_1| + |\Delta\omega_2| + |\Delta\omega_3| + ... + |\Delta\omega_{10}|)dt \quad (6)$$

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

Contingency (a): A 6-cycle fault disturbance at bus 7 at the end of line 5–7 with case 1, cleared by tripping the line 5–7 with successful reclosure after 1.0 s

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

The system responses to the considered faults with and without the proposed BFAPSS's are shown in Figs. 3 and 4 respectively. It is clear that the proposed BFAPSS's provide good damping characteristics to low frequency oscillations and greatly enhance the dynamic stability of power systems.

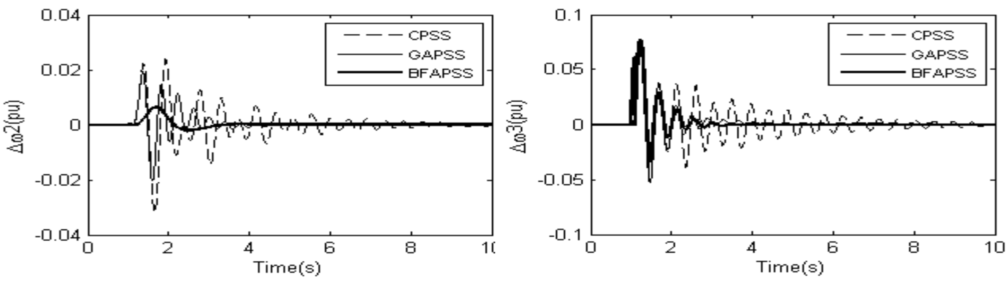

Figure. 3: Speed deviation of 2nd and 3rd generators for Contingency (a)

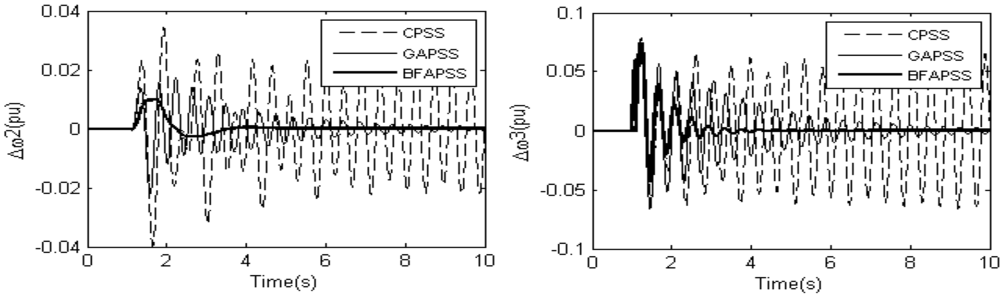

Figure.4: Speed deviation of 2nd and 3rd generators for Contingency (b)

The performance index (*ITAE)* obtained for the above contingencies using GAPSS and BFAPSS are given table 5.

Table 5. Values of Performance Index

	Contingency 1	Contingency 2
ITAE (GAPSS)	10.1642	55.4441
ITAE(BFAPSS)	6.1242	8.9750

Therefore the system performance characteristic in terms of '*ITAE*' index reveals the solution quality of the proposed BFAPSSs over GAPSSs.

5. Conclusions

In this study, optimal multi-objective design of robust multi-machine power system stabilizers (PSSs) using Bacterial Foraging Algorithm is proposed. 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 Bacterial Foraging Algorithm for optimal design 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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