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B. Sumanbabu

S. Mishra

B. K. Panigrahi

Ganesh K. Venayagamoorthy
*Missouri University of Science and Technology*

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# Robust Tuning of Modern Power System Stabilizers Using Bacterial Foraging Algorithm

B. Sumanbabu, S. Mishra, B.K. Panigrahi, and G.K. Venayagamoorthy

***Abstract*—IEEE Std 421.5, revised by the IEEE excitation system subcommittee introduced a new type of power system stabilizer model, the multiband power system stabilizers (IEEE PSS4B). Although it requires two input signals, like the widely used IEEE PSS2B, the underlying principle of the new IEEE PSS4B makes it sharply different. This paper presents a method based on Bacterial Foraging Algorithm (BFA) to simultaneously tune these modern power system stabilizers (PSSs) in multimachine power system. Simulation results of multi-machine power system validate the efficiency of this approach. The proposed method is effective for the tuning of multi-controllers in large power systems.**

***Index Terms*—Bacterial Foraging Algorithm (BFA), IEEE PSS2B, IEEE PSS4B, IEEE Std 421.5, inert-area oscillations, power system stability, power system stabilizer (PSS).**

## I. INTRODUCTION

DAMPING of power system oscillations between interconnected areas is very important for the system secure operation. Power system stabilizer (PSS) is the most widely used device for resolving oscillatory stability problems. Today most of the existing PSSs in the system are power acceleration analog devices based on conventional design procedures. But with the introduction of microprocessor based power system stabilizers[3], now the utilities are showing interest in digital based PSS represented as PSS2B in IEEE std 421.5[1].This modern PSS can easily be tuned just like conventional delta-omega PSS, while mitigating two major operational problems which had restricted the application of the old PSS technology utilizing electrical power or terminal frequency, namely the excess VAR modulation during mechanical power reference changes for the first and adverse torsional interactions for the second [4]. A novel PSS structure based on multiple working frequency bands was proposed in [5] and later included in the revised IEEE std 421.5[1] as PSS4B. Three separate bands, respectively dedicated to the low-, intermediate- and high- frequency modes of oscillations, are used in this delta-omega (speed input) PSS. The low band is typically associated with the power system global mode, the intermediate with the inter-area modes, and the high with the local modes.

Researchers have been putting a lot of efforts in the design of optimal PSSs to satisfy different system requirements. Several PSS design techniques are reported in literature, a few are listed in [6]-[14]. Kundur et al [8] have presented a comprehensive approach for conventional tuning of PSS parameters and its effect on the dynamic performance of the power system. The stabilizers designed to damp one particular mode of oscillation can produce adverse effects in the other modes. Thus, the multimodal nature of oscillations and the mutual interaction among generating units should be considered in PSS designs. Local optimization techniques like gradient descent method [11] failed to provide the optimum PSS parameters. Heuristic techniques such as Genetic Algorithms (GAs) [12], tabu search algorithm [13] and simulated annealing [14] have been applied earlier to PSS design. Studies have revealed that GA has a degraded performance if the function to be optimized is epistatic (where parameters to be optimized are much correlated) [15]. Also, the mutation and crossover may be time consuming processes and they may cause the new generation to lose advantages obtained in the last generation.

A new evolutionary computation technique, called Bacterial Foraging Algorithm (BFA) [16] has been proposed in this paper as a solution to the above mentioned problems and drawbacks. In this scheme, the foraging (methods for locating, handling, and ingesting food) behavior of *E. coli* bacteria present in our intestines is mimicked. They undergo different stages such as chemotaxis, swarming, reproduction, and elimination and dispersal. In the chemotaxis stage, it can have tumble followed by a tumble or a tumble followed by a run. On the other hand, in swarming, each *E. coli* bacterium will signal other via attractants to swarm together. Furthermore, in reproduction the least healthy bacteria die and the other healthiest bacteria each split into two bacteria, which are placed in the same location. Besides, in elimination and dispersal, any one bacterium is eliminated from the total set just by dispersing it to a random location on the optimization domain.

In this paper, a bacterial foraging optimization scheme is used for simultanioulу tuning the modern power system stabilizers, PSS2B and PSS4B. The objective function formulated for the optimization takes the time domain information from the MATLAB/SIMULINK models [20]. Two area multimachine power system [17] is considered in

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B. Sumanbabu, S. Mishra, and B.K. Panigrahi are with the Indian Institute of Technology, New Delhi, India (e-mail: sukumar@ee.iitd.ac.in).

G.K. Venayagamoorthy is with the University of Missouri, Rolla, USA.

this work. Simulation results show the effectiveness of the suggested PSS tuning technique.

## II. MODERN PSS MODELS

The standard IEEE models of modern PSS are shown in Fig. 1. Both the stabilizers have the same external inputs (speed and electrical power). However, while PSS2B incorporates a single speed transducer, the PSS4B is equipped with two. The PSS4B measures the rotor speed deviation in two different ways. $\Delta w_{L\text{-}I}$ feeds the low and intermediate bands, while $\Delta w_H$ is dedicated to the high-frequency band. The equivalent models of these two speed transducers are shown in Fig. 2.

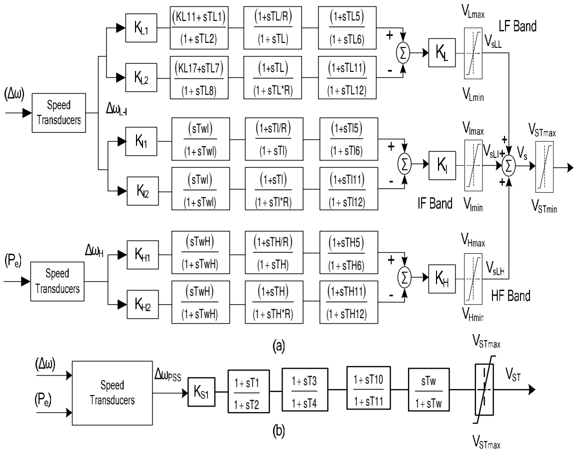

Fig.1. The standard IEEE PSS models. (a) PSS4B (b) PSS2B

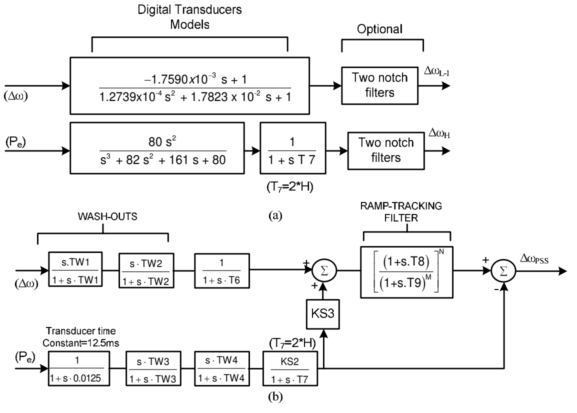

Fig. 2. Speed Transducers. (a) PSS4B (b) PSS2B

In PSS2Bs speed transducer (shown in Fig. 2), for each input there are two washouts can be represented ($T_{W1}$ to $T_{W4}$) along with a transducer or integrator time constants ($T_6$, $T_7$). The indices $M$ and $N$ allow a "ramp tracking" or simpler filter characteristic to be represented. Typical values of M=5, N=1 or M=2, N=4 are in use by several utilities [1], [2].

## III. BACTERIAL FORAGING OPTIMIZATION TECHNIQUE

Natural selection tends to eliminate animals with poor foraging strategies and favor the propagation of genes of those animals that have successful foraging strategies since they are more likely to enjoy reproductive success. After many generations, poor foraging strategies are either eliminated or shaped into good ones. The *E. coli* bacteria that are present in our intestines also undergo a foraging strategy. The control system of these bacteria that dictates how foraging should proceed can be subdivided into four sections namely Chemotaxis, Swarming, Reproduction and Elimination and Dispersal.

A) Chemotaxis: This process is achieved through swimming and tumbling via Flagella. Depending upon the rotation of Flagella in each bacterium, it decides whether it should move in a predefined direction (swimming) or altogether in different directions (tumbling), in the entire lifetime. To represent a tumble, a unit length random direction, say $\phi(j)$, is generated; this will be used to define the direction of movement after a tumble.
In particular

$$\theta^i(j+1,k,l)=\theta^i(j,k,l)+C(i)\phi(j) \tag{1}$$

where $\theta^i(j,k,l)$ represents the $i^{\text{th}}$ bacterium at $j^{\text{th}}$ chemotactic, $k^{\text{th}}$ reproductive and $l^{\text{th}}$ elimination and dispersal step. $C(i)$ is the size of the step taken in the random direction specified by the tumble (run length unit).

B) Swarming: During the process of reaching towards the best food location it is always desired that the bacterium which has searched the optimum path should try to provide an attraction signal to other bacteria so that they swarm together to reach the desired location. In this process, the bacteria congregate into groups and hence move as concentric patterns of groups with high bacterial density. The mathematical representation for swarming can be represented by

$$\begin{aligned} J_{cc}(\theta,P(j,k,l)) &= \sum_{i=1}^{S} J_{cc}^{i}\left(\theta,\theta^i(j,k,l)\right) \\ &= \sum_{i=1}^{S}\left[-d_{attract}\exp\left(-\omega_{attract}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2\right)\right] \\ &+ \sum_{i=1}^{S}\left[h_{repelent}\exp\left(-\omega_{repelent}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2\right)\right] \end{aligned} \tag{2}$$

where $J_{cc}(\theta,P(j,k,l))$ is the cost function value to be added to the actual cost function to be minimized to present a time varying cost function. 'S' is the total number of bacteria and 'p' the number of parameters to be optimized which are present in each bacterium. $d_{attract},\omega_{attract},h_{repelent},\omega_{repelent}$ are different coefficients that are to be chosen properly.

C) Reproduction: The least healthy bacteria die and the other healthiest bacteria each split into two bacteria, which are placed in the same location. This makes the population of bacteria constant.

D) Elimination and Dispersal: It is possible that in the local environment the live of a population of bacteria changes either gradually (e.g., via consumption of nutrients) or suddenly due to some other influence. Events can occur such that all the bacteria in a region are killed or a group is dispersed into a new part of the environment. They have the effect of possibly destroying the chemotactic progress, but they also have the effect of assisting in chemotaxis, since dispersal may place bacteria near good food sources. From a broad perspective, elimination and dispersal are parts of the population-level long-distance motile behavior.

This paper mainly concentrates on use of this new technique to optimize the PSS parameters. Detailed mathematical derivations, theoretical aspect and application to other areas of this new concept are presented in [16], [22], [23] and [24].

## IV. FORMULATION OF OBJECTIVE FUNCTION

In this paper the Bacterial Foraging scheme has been used for the optimization of PSS parameters. Just like any other optimization problem, a cost or an objective function needs to be formulated for the optimal PSS design. The objective in the optimal PSS design is to maximize damping; in other words minimize the overshoots and settling time in system oscillations.

The Integral of Time Squared Error (ITSE) is considered as the cost function to be minimized by the bio-inspired algorithm. Integral of Squared Error (ISE) accounts mainly for error at the beginning of the response and to a lesser degree for the steady state duration. ITSE is a better criterion which keeps account of errors at the beginning but also emphasizes the steady state [21]. The objective function is given by (3).

$$J = \sum_{n=1}^{NP} \int_{t=0}^{t=tsim} A.(t.J_G)\,dt \tag{3}$$

where

$$J_G = \sum_{i=1}^{N} (\Delta w_i(t))^2 \tag{4}$$

where $NP$ is the number of disturbances considered in the design process, $A$ is a weighting factor, $t$ is the simulation time in seconds, $N$ is the number of generators in the system and $\Delta w_i(t)$ is the speed deviation of the i$^{th}$ generator obtained from time domain simulation. Therefore, the design problem can be formulated as the following optimization problem.

Minimize

$$J \tag{5}$$

Subject to

$$z^{\min} \le z \le z^{\max} \tag{6}$$

where $z$ is a vector, which consists of the parameters of the PSS.

The proposed approach employs BF algorithm to solve this optimization problem and search for the optimal set of PSS parameters.

## V. BACTERIAL FORAGING ALGORITHM

The algorithm of the proposed scheme is as follows:

*Step1-Initialization*

i. Number of parameters (p) to be optimized.
ii. Number of bacteria (S) to be used for searching the total region.
iii. Swimming length $N_s$ after which tumbling of bacteria will be undertaken in a chemotactic loop.
iv. $N_c$ the number of iteration to be undertaken in a chemotactic loop. ($N_c > N_s$).
v. $N_{re}$ the maximum number of reproduction to be undertaken.
vi. $N_{ed}$ the maximum number of elimination and dispersal events to be imposed over the bacteria.
vii. $P_{ed}$ the probability with which the elimination and dispersal will continue.
viii. The location of each bacterium P (1-p, 1-S, 1) which is specified by random numbers on [-1, 1].
ix. The value of C ($i$) which is assumed to be constant in our case for all the bacteria to simplify the design strategy.
x. The values of $d_{attract}, \omega_{attract}, h_{repelent}$ and $\omega_{repelent}$.

In this simulation work we have considered S=6, p=24 for PSS4B and 16 for PSS2B, $N_c$=4, $N_s$=4, $N_{re}$=100, Ned=2, Ped=0.25, $d_{attract} = 0.01, \omega_{attract} = 0.04$, $h_{repelent} = 0.01$ and $\omega_{repelent} = 10$.

*Step-2 Iterative algorithm for optimization*

This section models the bacterial population chemotaxis, swarming, reproduction, elimination and dispersal (initially, $j$=$k$=$l$=0). For the algorithm updating $\theta^i$ automatically results in updating of 'P'.

1) Elimination-dispersal loop: $l$=$l$+1
2) Reproduction loop: $k$=$k$+1
3) Chemotaxis loop: $j$=$j$+1
   a) For $i$=1, 2,…, S, calculate cost function value for each bacterium $i$ as follows.
      - Compute value of cost function J ($i$, $j$, $k$, $l$). Let $J_{sw}$ ($i$, $j$, $k$, $l$) = J ($i$, $j$, $k$, $l$) + $J_{cc}(\theta^i(j,k,l), P(j,k,l))$ (i.e., add on the cell-to-cell attractant effect for swarming behavior).
      - Let $J_{last}$= $J_{sw}$ ($i$, $j$, $k$, $l$) to save this value since we may find a better cost via a run.
      - End of For loop
   b) For $i$=1,2,….S take the tumbling/swimming decision

- Tumble: Generate a random vector $\Delta(i) \in \Re^p$ with each element $\Delta_m(i)$ m=1,2,..p, a random number on [-1, 1].
- Move: let

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$

Fixed step size in the direction of tumble for bacterium *i* is considered.

- Compute J(*i*, *j*+1, *k*, *l*) and then let $J_{sw}(i, j+1, k, l)$= J(*i*, *j*+1, *k*, *l* )+ $J_{cc}(\theta^i(j+1,k,l), P(j+1,k,l))$
- Swim :
  i) Let m=0; (counter for swim length)
  ii) While m<$N_s$ (have not climbed down too long)
  - Let m=m+1
  - If $J_{sw}(i, j+1, k, l) < J_{last}$ (if doing better), let $J_{last}= J_{sw}(i, j+1, k, l)$ and let

    $$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}$$

    and use this $\theta^i(j+1,k,l)$ to compute the new J (*i*, *j*+1, *k*, *l*)
  - Else, let m=$N_s$. This is the end of the while statement.

c) Go to next bacterium (*i*+1) if $i \neq S$ (i.e. go to b) to process the next bacterium.

4) If *j* < $N_c$, go to step 3. In this case, continue chemotaxis since the life of the bacteria is not over.

5) Reproduction

a) For the given *k* and *l*, and for each *i*=1, 2,..S, let $J^i_{health} = \min_{j\in\{1...N_c\}} \{J_{sw}(i,j,k,l)\}$ be the health of the bacterium *i* (a measure of how many nutrients it got over its life time and how successful it was at avoiding noxious substance). Sort bacteria in order of ascending cost $J_{health}$ (higher cost means lower health).

b) The $S_r$=S/2 bacteria with highest $J_{health}$ values die and other $S_r$ bacteria with the best value split (and the copies that are made are placed at the same location as their parent)

6) If *k* < $N_{re}$ go to 2, in this case, we have not reached the number of specified reproduction steps, so we start the next generation in the chemotactic loop.

7) Elimination-dispersal: For *i*=1, 2,..S, with probability $P_{ed}$, eliminate and disperse each bacterium (this keeps the number of bacteria in the population constant) to a random location on the optimization domain.

The flow chart of the above algorithm is shown in Fig. 3.

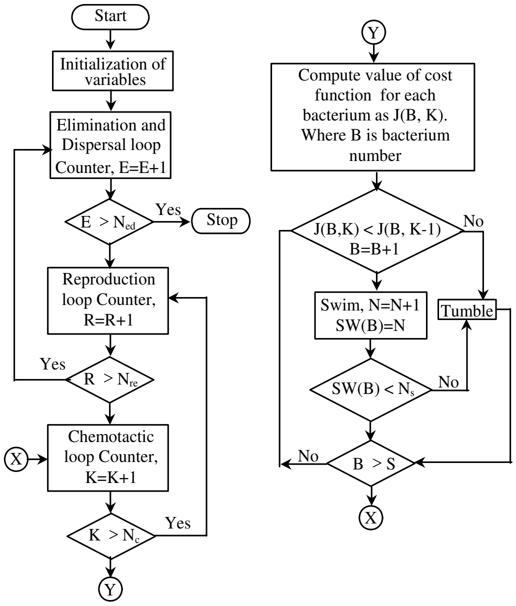

Fig. 3. Flow chart of Bacterial Foraging algorithm

## VI. SIMULATION RESULTS

The two area power system used in this study is simulated in the MATLAB/SIMULINK environment which allows the detailed representation of the power system dynamics. The small two area power system (shown in Fig. 4) consists of two fully symmetrically connected areas linked together by two transmission lines. Each area is equipped with two identical synchronous generators rated 20kV/900 MVA. All generators are equipped with identical sped governors and turbines, exciters and AVRs and PSSs. The loads in the two areas are such that Area 1 is exporting about 413 MW to Area 2. The system data can be found in [17].

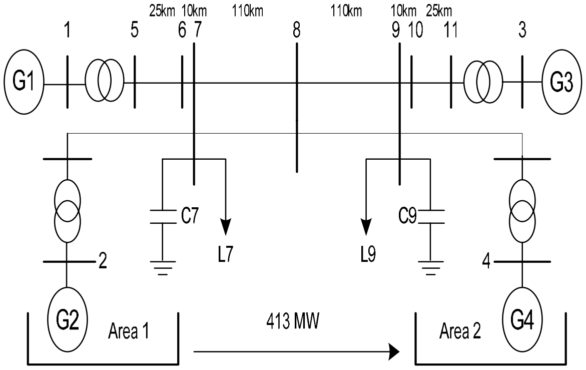

Fig. 4. Two-area multi-machine power system

The optimization is carried by subjecting the power system to different possible contingencies. In this work, a small disturbance of temporary 200ms transmission line outage (one of the tie lines), a large disturbance of three phase short circuit of 200ms duration at the middle of the lines and double cascaded fault are considered (Fig. 4). SIMULINK model is called through *sim* command from MATLAB [20]. The value of $J$ is computed using (3) for the given set of PSS parameters from the time domain information and the bio-inspired algorithm is applied to compute the new set of parameters.

### *A. PSS4B*

Although the PSS4B differential filters parameters may be used in various ways, a simple setting method [19] based on three symmetrical band-pass filters respectively tuned at $F_L$, $F_I$, and $F_H$ is most often used. Their time constants and branch gains are derived from Equation (7), Equation (8), Equation (9), and Equation (10) for the low band case. So we need to tune only six parameters— $F_L$, $F_I$, $F_H$, $K_L$, $K_I$, $K_H$.

$$T_{L2} = T_{L7} = \frac{1}{2\pi F_L \sqrt{R}} \tag{7}$$

$$T_{L1} = T_{L2} / R \tag{8}$$

$$T_{L8} = T_{L7} * R \tag{9}$$

$$K_{L1} = K_{L2} = (R^2 + R)/(R^2 - 2R + 1) \tag{10}$$

$R$ is a constant here equal to 1.2. Remaining values are taken from [19], [2].Similar Expressions are valid for the other two bands also. A total of 24 parameters are tuned simultaneously. The final values of optimized PSS4B parameters are given in Appendix. The minimum value of cost function ($J_{\min}$) against the no. of reproductions is plotted in Fig. 5.

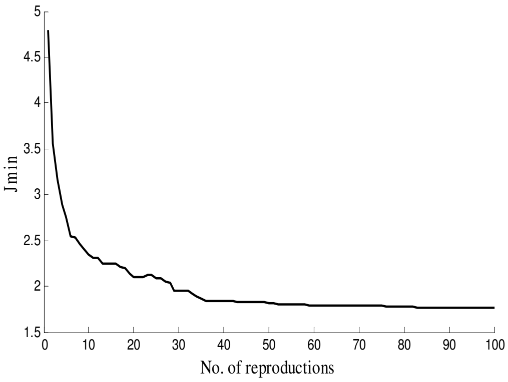

Fig. 5. Variation of the objective function J

To test the robustness of the different optimized parameters, the following two cases are considered.

*Case 1:* A three phase short circuit of 200ms duration is applied at bus 8 in Fig. 4.

*Case 2:* A 100ms three phase short circuit at bus 8 is applied followed by a 100ms line outage between buses 8 and 9 immediately (double cascaded fault) in Fig. 4.

To validate the proposed technique, the results are compared with those obtained from [19]. Simulation results are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9.

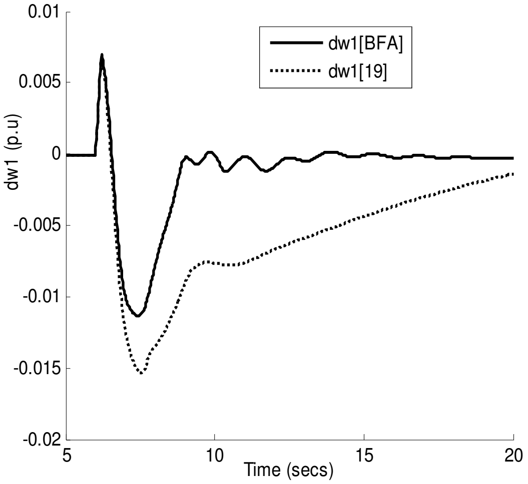

Fig. 6. Speed response of generator G1 for case1

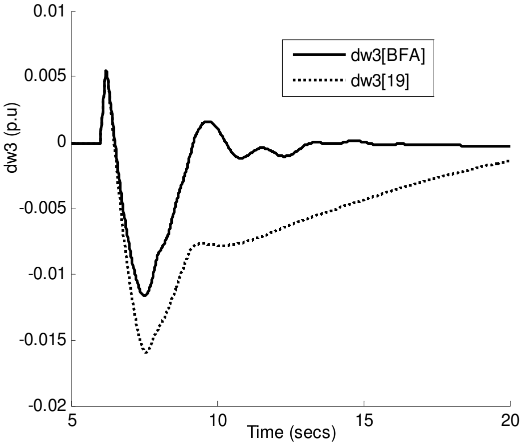

Fig. 7. Speed response of generator G3 for case1

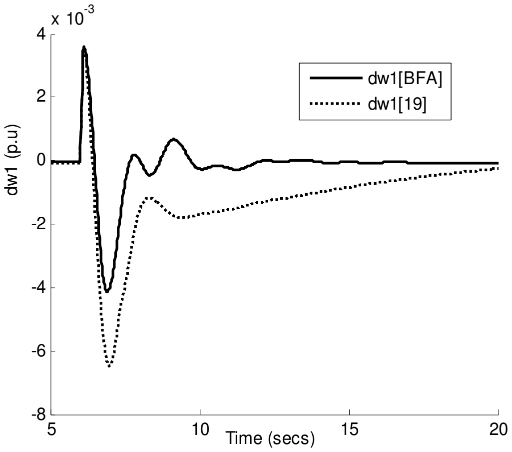

Fig. 8. Speed response of generator G1 for case2

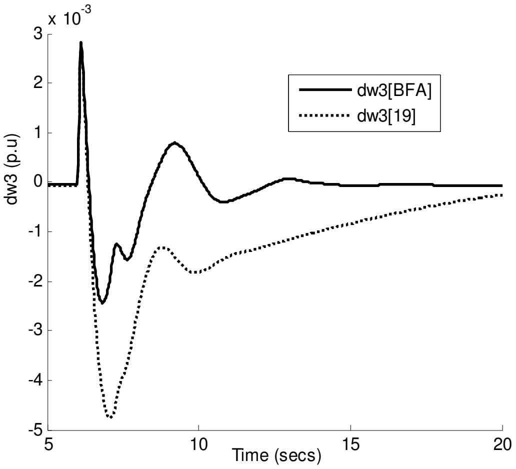

Fig. 9. Speed response of generator G3 for case2

From the results it is quite clear that proposed method of tuning results in better response.

*B. PSS2B*

PSS2B has only six time constants and a gain. Three time constants ($T_1$, $T_3$ and $T_{10}$) and gain ($K_{S1}$) are considered for optimization and remaining values taken from [18] and are held constant. Hence, a total of 16 parameters tuned simultaneously. The final values of optimized PSS2B parameters are given in Appendix. The minimum value of cost function ($J_{min}$) against the no. of reproductions is plotted in Fig. 10.

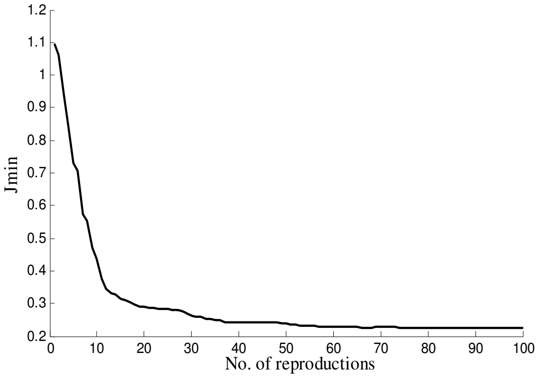

Fig .10. Variation of the objective function J

To test the robustness of the tuned PSS2B parameters similar cases (as above) are considered. To validate the proposed technique, the results are compared with those obtained from [18] and the simulation results are shown in Fig. 11, Fig. 12, Fig. 13 and Fig. 14.

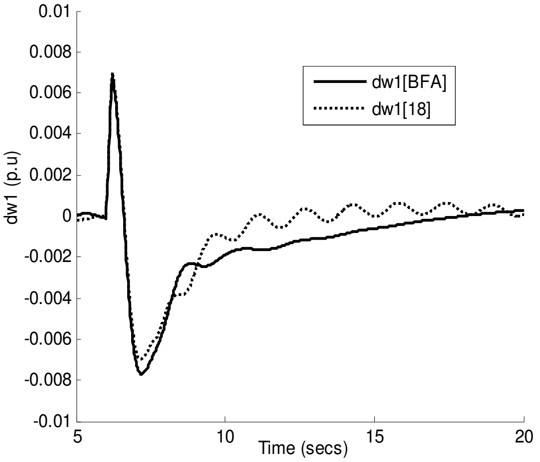

Fig. 11. Speed response of generator G1 for case1

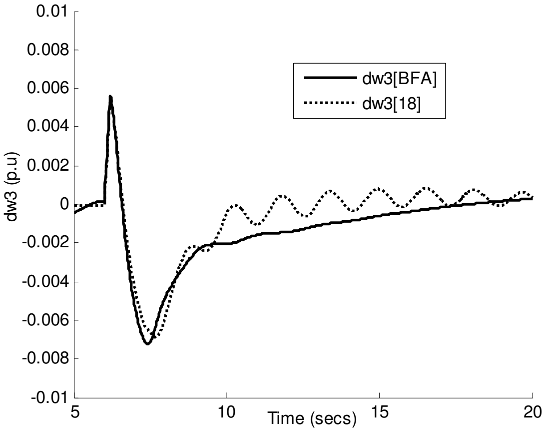

Fig. 12. Speed response of generator G3 for case1

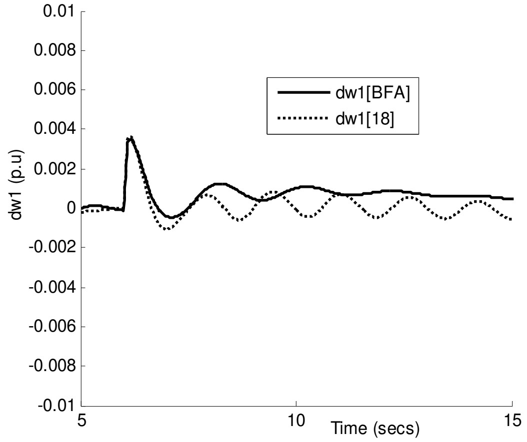

Fig. 13. Speed response of generator G1 for case2

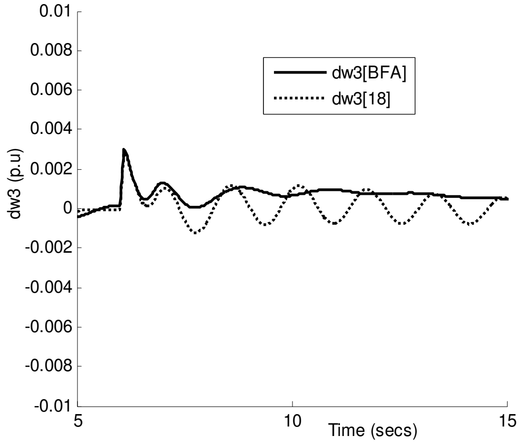

Fig. 14. Speed response of generator G3 for case2

From the results it is seen that proposed method of tuning results in better response.

## VII. CONCLUSION

In this study, bacterial foraging algorithm is proposed to the robust PSS design problem. The proposed design approach employs BFA to search for optimal settings of two modern power system stabilizers. The effectiveness of the suggested technique in enhancing stability of multimachine power systems is verified through simulation results with different disturbances.

## VIII. APPENDIX

### *A. IEEE PSS4B*

TABLE I
BFA OPTIMIZED PSS4B PARAMETERS

| | $F_L$ | $K_L$ | $F_I$ | $K_I$ | $F_H$ | $K_H$ |
|---|---|---|---|---|---|---|
| **G1** | 0.0069 | 24.88 | 0.126 | 34.15 | 15.08 | 162.0 |
| **G2** | 0.028 | 24.69 | 1.341 | 34.72 | 10.51 | 160.9 |
| **G3** | 0.102 | 24.65 | 0.593 | 34.55 | 9.543 | 149.7 |
| **G4** | 0.021 | 24.87 | 0.169 | 34.28 | 9.273 | 159.6 |

### *B. IEEE PSS2B*

TABLE II
BFA OPTIMIZED PSS2B PARAMETERS

| | $K_S$ | $T_1$ | $T_3$ | $T_{10}$ |
|---|---|---|---|---|
| **G1** | 11.4066 | 0.3842 | 0.4025 | 0.3488 |
| **G2** | 15.1902 | 0.2625 | 0.2518 | 0.1600 |
| **G3** | 14.9634 | 0.3636 | 0.0385 | 0.1636 |
| **G4** | 17.1840 | 0.0745 | 0.3526 | 0.7649 |

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## X. BIOGRAPHIES

**B. Sumanbabu** was born in 1983. He received his B.Tech degree in Electrical&Electronics Engineering from N.B.K.R.I.S.T., A.P., India in 2005. Currently he is a graduate student of the Department of Electrical Engineering, IIT Delhi. His current research interests include Power System Stability and Control, FACTS Devices and Artificial Intelligence.

**S. Mishra** (SM’04) received BE degree from University College of Engineering, Burla, Orissa, India and M.E. and PhD degree from Regional Engineering College, Rourkela, Orissa, India, in 1990 and 1992 and 2000 respectively. In 1992, he joined the department of Electrical Engineering, University College of Engineering, Burla, as a lecturer and subsequently became a reader in 2001. Presently he is a faculty at the department of Electrical Engineering, Indian Institute of Technology, Delhi, India. He has been honored with many prestigious awards such as INSA Young Scientist Medal-2002, INAE Young Engineer's award-2002, recognition as DST Young Scientist 2001-2002, etc. His interests are in fuzzy logic and ANN applications to power system control and power quality.