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Robust design of power system stabilizer using bacterial foraging algorithm

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Abstract: In this paper, a novel bacterial foraging algorithm (BFA) based approach for robust and optimal design of PID controller connected to power system stabilizer (PSS) is proposed for damping low frequency power oscillations of a single machine infinite bus bar (SMIB) power system. This paper attempts to optimize three parameters (K_p, K_i, K_d) of PID-PSS based on foraging behaviour of *Escherichia coli* bacteria in human intestine. The problem of robustly selecting the parameters of the power system stabilizer is converted to an optimization problem which is solved by a bacterial foraging algorithm with a carefully selected objective function. The eigenvalue analysis and the simulation results obtained for internal and external disturbances for a wide range of operating conditions show the effectiveness and robustness of the proposed BFAPSS. Further, the time domain simulation results when compared with those obtained using conventional PSS and Genetic Algorithm (GA) based PSS show the superiority of the proposed design.

Key words: bacterial foraging algorithm, power system stabilizer, power system stability

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 [3]. Among various types of PSSs, the fixed-structure lag-lead type is preferred by the utilities due to its operational simplicity and ease of tuning PSS parameters. However, the robustness of these PSS under changing conditions is a major concern.

The concept of PSSs and their tuning procedures were well explained in literature. A well-tuned lag-lead type PSS can effectively improve dynamic stability. Many approaches [10] have been proposed to tune PSSs, such as the sensitivity approach [4], pole placement technique [7], and the damping torque approach [1].

Global optimization technique like genetic algorithm (GA) [5], Particle Swarm Optimization (PSO) [11], tabu search [6] and simulated annealing (SA) [7] are attracting the attention in the field of PSS parameter optimization in 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 [8]. Bacterial foraging algorithm has been proposed and introduced as a new evolutionary technique in [9]. 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 one for handling the optimization problems [13]. 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 cases 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 new/improved BFA-based optimal determination of PID-PSS parameters is presented which overcomes the shortcomings of previous works. In order to design a robust PSS which guarantees stability of system in a wide range of operating conditions, the objective function is defined such that the resultant time response is restricted to lie within specific bounds as well as limiting the amount of overshooting of power system response when subjected to disturbances. The performance of the BFAPSS is compared with those obtained with other techniques such as conventional and genetic algorithm (GA) by plotting the time response curves for step disturbance. Further, the robustness of the controller so designed is established by choosing any one set of parameters for a particular operating condition and testing its performance with its fixed structure for other operating conditions too.

2. Power system model studied

The system considered in this paper is a synchronous machine connected to an infinite bus through a transmission line, as shown in Figure 1. The linear incremental model of a synchronous machine connected to a large system is shown in Figure 2.

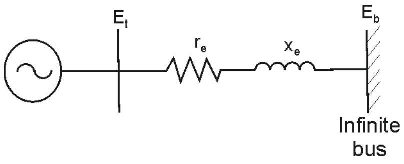

Fig. 1. Single Machine connected to infinite bus system

The state equation under a particular loading condition can be written as [1].

$$dx(t)/dt = A\,x(t) + B\,u(t), \tag{1}$$

$$y(t) = C\,x\,(t). \tag{2}$$

where x(t) is the state vector, u(t) is the control input and y(t) is the output and A, B, C are the matrices of appropriate dimensions.

The following physical variables are chosen as the state and output for the power system under consideration.

$$x\,(t) = [\,\Delta\delta(t)\quad \Delta\omega(t)\quad \Delta Eq'(t)\quad \Delta Efd(t)\,]^T, \tag{3}$$

$$y(t) = [0\ 1\ 0\ 0\,]\,x(t). \tag{4}$$

The system matrices as taken from [1] is given below

$$A = \begin{pmatrix} 0 & 314 & 0 & 0 \\ -K1/M & -D/M & 0 & 0 \\ -K4/M & 0 & -1/K3T''do & 0 \\ -KeK5/Ta & 0 & -KeK6/Te & -1/Te \end{pmatrix}. \tag{5}$$

$$B = [0\ 0\ 0\ Ke/Te], \tag{6}$$

$$C = [0\ 1\ 0\ 0]. \tag{7}$$

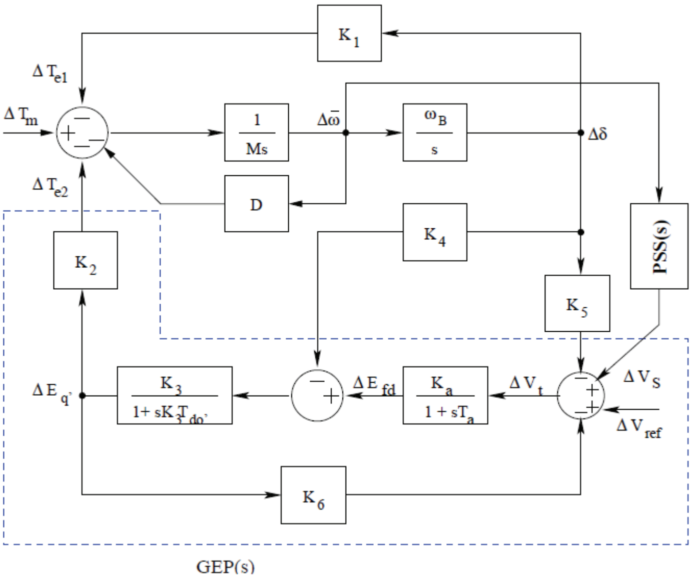

Fig. 2. Linearized model of a synchronous machine with an exciter and stabilizer

The parameters K1-K6 in equation (3) are functions of real power output P and reactive power output Q of the generator [11, 12]. Thus it is observed that the elements of the A matrix change as the operating point of the generator changes. When the system is perturbed it is possible that it becomes unstable or operates with sustained oscillations. It is therefore necessary to design a PSS which will guarantee stability of the system and suppress these unwanted oscillations. Further, it is necessary to change the PSS parameters according to the drift in the operating conditions.

The main objective of this work is to design the power system stabilizer using Bacterial Foraging Algorithm such that the controller structure so designed rejects the internal and external disturbances and is immune to machine parameters variations.

3. Genetic Algorithm

Genetic Algorithms are adaptive methods which may be used to solve search and optimization problems. Over many generations, natural populations evolve according to the principles of natural selection and *survival of the fittest*. By mimicking the process, genetic algorithms are able to `evolve' solutions to real world problems, if they have been suitably encoded. There are many variations of the genetic algorithm but the basic form is the simple genetic algorithm. In this paper, we applied simple Genetic Algorithm for optimizing the PID-PSS parameters. Strings are represented by binary digits and single-point crossover and single mutation is used. The various parameters used in the implementation of GA in the present work are listed below.

Number of variables	3
Population size	100
Chromosome Length	24
Selection	0.5
Probability	0.7
Mutation probability	0.15
Termination criterion	500

To compute the optimum parameter values of PID-PSS shown in Figure 4, a 0.1 step change in reference mechanical torque (ΔTm) is assumed and the performance index in Equation (8) is minimized using Genetic Algorithm. The settling time (ts) and peak overshoot (Δωp) are evaluated for each iteration.

4. Bacterial foraging algorithm

Bacterial foraging algorithm is inspired by an activity called “chemotaxis” exhibited by bacterial foraging behaviors. Motile bacteria such as *E. coli* and *salmonella* propel themselves by rotation of the flagella. To move forward, the flagella rotates counterclockwise and the organism “swims” or “runs” while a clockwise rotation of the flagellum causes the bacterium to randomly “tumble” itself in a new direction and swim again Alternation between “swim” and “tumble” enables the bacterium to search for nutrients in random directions. Swimming is more frequent as the bacterium approaches a nutrient gradient. Tumbling, hence direction changes, is more frequent as the bacterium moves away from some food to search for more. Basically, bacterial chemotaxis is a complex combination of swimming and tumbling that keeps bacteria in places of higher concentrations of nutrients. The foraging strategy of *Escherichia coli* bacteria present in human intestine can be explained by three processes, namely chemotaxis, reproduction, and elimination-dispersal [9].

In Chemotaxis, a unit walk with random direction represents a “tumble” and a unit walk with the same direction in the last step indicates a “run”. C(i) is called the run length unit parameter, is the chemo tactic step size during each run or tumble. With the activity of run or tumble at each step of the chemotaxis process, a step fitness will be evaluated. In the reproduction step, all bacteria are stored in reverse order according to the health status. Here only the first half of the population survives, and a surviving bacterium splits into two identical ones, which are then placed in the same locations. Thus, the population of bacteria keeps constant.

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 Figure (3).

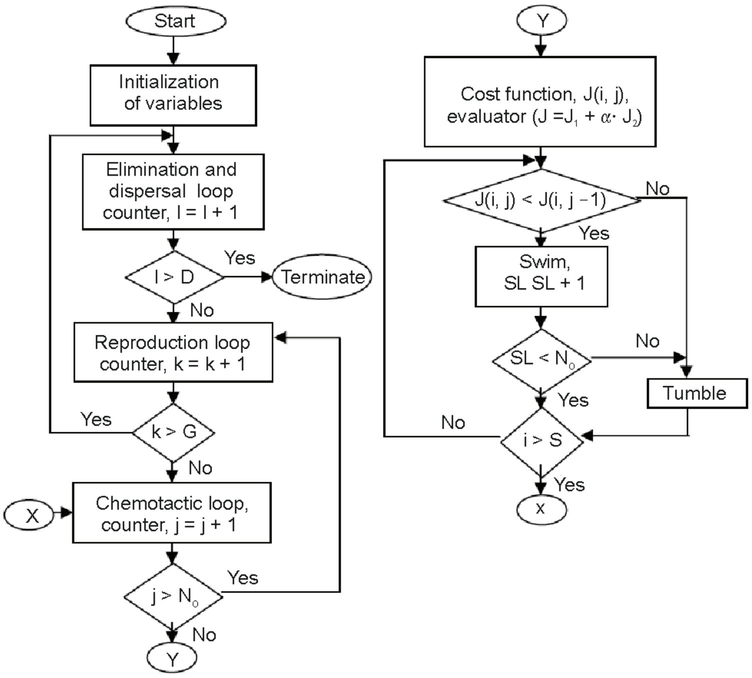

Fig. 3. Flowchart of bacterial foraging algorithm

5. BFA based tuning of PID-PSS

PID (proportional integral derivative) control is one of the earlier control strategies. Its early implementation was in pneumatic devices, followed by vacuum and solid state analog electronics, before arriving at today's digital implementation of microprocessors. It has a simple control structure which was understood by plant operators and which they found relatively easy to tune. Since many control systems using PID control have proved satisfactory, it still has a wide range of applications in industrial control. It has been found possible to set satisfactory controller parameters from less plant information than a complete mathematical model. In the proposed design approach, the PID control structure shown in Figure 4 is used as the power system stabilizer as opposed to the traditional lead-lag controller.

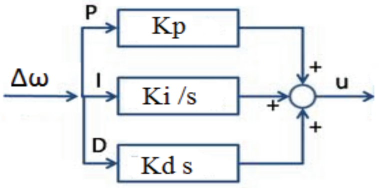

Fig. 4. The PID power system stabilizer

In Figure 4 the speed deviation (Δω) is the input to the controller and u is the supplementary stabilizing signal. The PID parameters Kp, Ki, and Kd are tuned using the BFA technique discussed in section IV. To compute the optimum parameter values, a 0.1 step change in reference mechanical torque (ΔTm) is assumed and the performance index

$$F = 1/(1+\Delta\omega p)\,(1+ts) \tag{8}$$

is minimized using bacterial foraging algorithm. The settling time (ts) and peak overshoot ($\Delta\omega p$) are evaluated for each iteration.

The PID parameters selected using the above objective function is used to form the augmented A matrix as given below:

$$\begin{bmatrix} 0 & 314 & 0 & 0 & 0 \\ -K1/M & 0 & -K2/M & 0 & 0 \\ -K_4/Td0 & 0 & -1/K_3T'd0 & -1/T'd0 & 0 \\ MKe(-K5+MKi/314-KdK1)/MTe & KeKp/Te & -MK6Ke-K2KeKd/MTe & 1/Te & Ke/Te \\ MKi/314-KdK1/MTw & Kp/Tw & -K2Kd/MTw & 0 & -1Tw \end{bmatrix}$$

The following machine parameters are chosen for study xd = 1.6; x'd = 0.32; xq = 1.55 vt0 = 1.05; ω = 100π rad/s; T'd0 = 6.0 s D = 0.0; M = 10.0; re = 0; xe = 0.4; Ke = 50.0; Te = 0.05s; *Tw* = 5s.

The parameters for BFA used in this study are as follows: *N*c = 5, *N*re = 4, *N*ed = 10, *Ns* = 4, *d*att = 0.01, *h*rep = 0.01, *w*att = 0.4, *w*rep = 0.42, *w* = 0.8, *c*1 = 2.0, and *c*2 = 2.0.

6. Tuning results and discussion

Simulation tests were made using a computational program that represents the single machine connected to infinite bus bar system. The simulation program covers wide range of operating conditions covering light, normal and heavy loads. Light load is represented by assuming the synchronous generator delivering 0.7 p.u active power (P) and 0.3 p.u reactive power (Q). The normal operating point is considered when the generator delivers 0.9 p.u active power (P) and 0.3 p.u reactive power (Q). For the case of heavy load, P = 1.2 p.u and Q = 0.2 are chosen. The machine with PID-PSS is represented as 5th order state space model with saturation neglected.

The different operating conditions [2] considered are given in Table 1. The simulation study for the operating conditions mentioned using Bacterial Foraging Algorithm (BFA) is carried out for a step disturbance of 0.1 mechanical torque (ΔTm). Simulation study is also carried out for the mentioned operating conditions for the PSS designed using conventional and Genetic Algorithm (GA).

Table 1. Operating conditions of the machine

Operating conditions			
Operating points	P1	P2	P3
Real power (P)	1.2	0.9	0.7
Reactive power (Q)	0.2	0.3	0.2

Table 2. Eigen value analysis

Operating condition	CPSS	GAPSS	BFAPSS
P = 1.2 Q = 0.2	Kpss = 9.2734 T1 = 0.3806 T2 = 0.1	Kp = 9.984 Ki = 1.722 Kd = 8.784	Kp = 31.58 Ki = 6.3202 Kd = 32.32
Eigen values	−21.2515 ± 4.9661i −0.7438 ± 6.6601i −5.6514	−14.712 ± 15.301i −10.6116 −3.3594 −0.3235	−15.01 ± 29.1567i −13.4750 −6.8227 −0.3272
P = 0.9 Q = 0.3	Kpss = 7.6451 T1 = 0.4874 T2 = 0.1	Kp = 8.352 Ki = 2.941 Kd = 7.294	Kp = 48.98 Ki = 9.0988 Kd = 25.17
Eigen values	−21.3386 ± 4.1240i −0.6869 ± 6.5345i −5.3633	−14.9530 ± 14.300i −9.5003 −2.7187 −0.3125	−14.5016 ± 26.0508i −13.8296 −6.1569 −0.3241
P = 0.7 Q = 0.2	Kpss = 5.571 T1 = 0.6776 T2 = 0.1	Kp = 9.764 Ki = 9.921 Kd = 8.117	Kp = 38.05 Ki = 8.5241 Kd = 36.97
Eigen values	−21.3488 ± 3.3392i −0.6133 ± 6.2708i −5.1956	−15.1088 ± 15.2737i −9.3967 −2.8915 −0.2773	−15.1515 ± 31.322i −13.3897 −7.0191 −0.3264

The conventional PSS parameters are calculated using frequency response method The PSS parameters obtained by the application of conventional, GA and BFA along with the corresponding eigen values are shown in Table 2. From Table 2, it is observed that the real parts of closed loop eigen values obtained using BFAPSS are shifted to the left half of the s-plane which provides more damping. The time response specifications obtained from the transient response curves are shown in Table 3.

Table 3. Settling TIME (ts) max .peak overshoot comparison

Operating Point	GA-PSS		BFA-PSS	
	ts in Sec	ωp	ts in Sec	ωp
P = 1.2 Q = 0.2	2.1	1.1×10^{-4}	3.4	0.57×10^{-4}
P = 0.9 Q = 0.3	3.2	1.15×10^{-4}	1.9	0.63×10^{-4}
P = 0.7 Q = 0.2	2.26	1.1×10^{-4}	2.4	0.53×10^{-4}

From Figures 5 to 7 and Table 3, it is observed that the performance of the PSS designed using BFA is far superior compared to the PSS designed using conventional as well as genetic algorithm (GA).

Figure 8 illustrates the convergence of the objective function with genetic algorithm (GA) and BFA. From the convergence characteristics it is clear that BFA offers superior performance than GA.

Figure 9 shows the speed deviation for different operating conditions with BFA PSS when the system is subjected to 0.1 p.u step disturbance in the reference input voltage ($\Delta Vref$).

In power system the operating condition changes very fast. The controller designed for one operating condition may not give satisfactory performance to other operating conditions. Therefore, it becomes necessary that the controller parameters need to be tuned according to the changes in the operating condition which is very difficult to accomplish online even using very fast computer. Therefore it is necessary to design a PSS which is robust in behaviour. From Table 2 the eigen values obtained for the power system with BFAPSS do not change appreciably which suggest the robustness of the PSS. It is therefore possible to choose the PSS parameters obtained by BFA at any one operating condition which can be chosen and retained for other operating conditions also.

For the study of robustness, the PSS parameters designed using BFA for light load condition is chosen. With these PSS parameters fixed at all operating conditions the dynamic response of the system for 0.1p.u mechanical disturbance (ΔTm) for light, normal and heavy operating conditions are obtained and plotted as shown in Figures10 and 11. From Figure10 and Figure11, it is evident that the oscillations due to disturbances are completely suppressed and the system rejects external disturbances at all operating conditions.

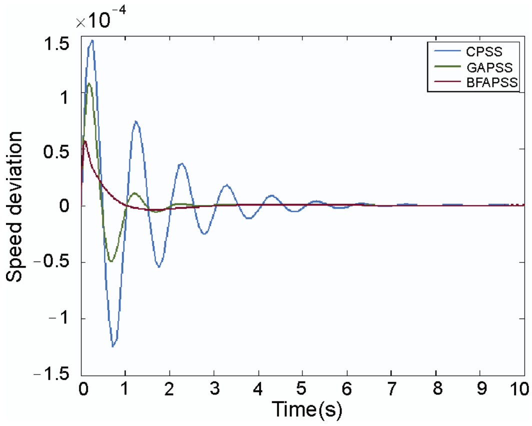

Fig. 5. Speed deviation for operating condition (P = 1.2,Q = 0.2)

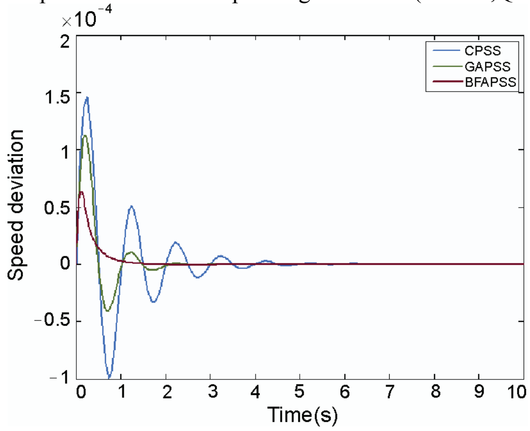

Fig. 6. Speed deviation for operating condition (P = 0.9, Q = 0.3)

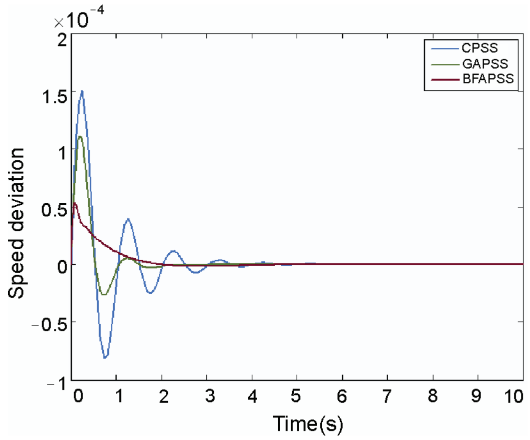

Fig. 7. Speed deviation for operating condition (P = 0.7 Q = 0.2)

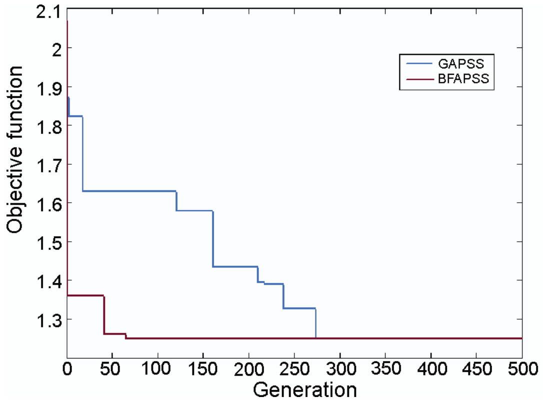

Fig. 8. Convergence comparison of GA and BFA

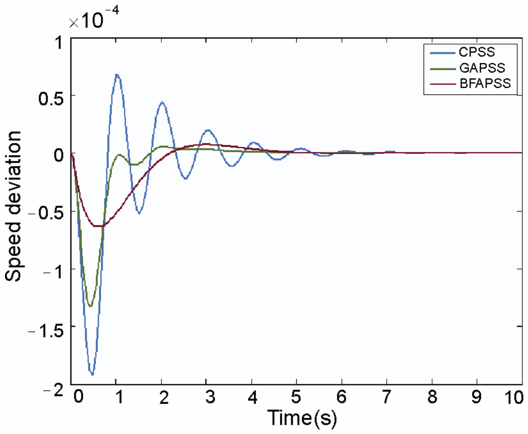

Fig. 9. Speed deviation for different operating conditions for a 0.1 p.u step change in reference input voltage (ΔVref) with BFAPSS

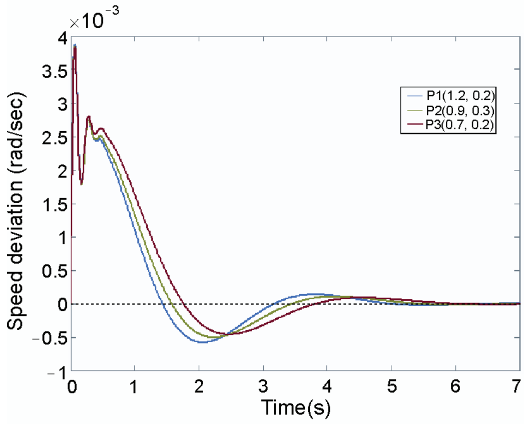

Fig. 10. Speed deviation for different operating conditions using BFA PSS with Kp = 38.0553 Ki = 8.5241 Kd = 36.9748

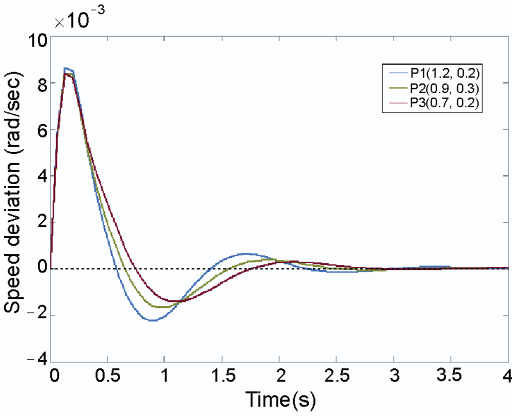

Fig. 11. Speed deviation for different operating conditions using GAPSS with Kp = 9.764 Ki = 9.921 Kd = 8.117

In addition, the system performance with the proposed PSS is much better than that of GAPSS and the oscillations are damped out much faster. This illustrates the potential and superiority of the proposed design approach to obtain an optimal set of PSS parameters.

7. Conclusion

In this study, optimal design of robust power system stabilizer (PSS) for single machine system using Bacterial Foraging Algorithm is proposed. Eigen value 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. Further, from the simulation results it is observed that, when a system is subjected to internal and external disturbances by retaining the same structure and parameter of the controller which was obtained for any one operating condition works effectively over a wide range of loading conditions which is very difficult to accomplish on line. This shows the robustness of the controller designed using BFA. Furthermore, the simulation results also show that the proposed method in this paper gives much improved performance when compared to the performance of conventional and Genetic Algorithm (GA) based design of controller for PSS. Further, the convergence of the objective function in the proposed method is much faster when compared with genetic algorithm (GA).

In this paper, the linear incremental model of single machine connected to infinite bus has been considered for the design of PID controller even though the actual system is highly nonlinear one and therefore it becomes necessary to validate the results obtained here by laboratory test which has been taken for future work. The Bacterial Foraging Algorithm (BFA) remains to be tried out for designing controllers in the capacitive area and also for multi-machine complex power system.

List of symbols

Xe Transmission Line Reactance; *K1-K6* Synchronous machine parameters; *T'd*0 d-axis open circuit field time constant; *M,H* Inertia coefficient (M = 2H); *D* Damping coefficient; x'_d,x_d,x_q Direct axis transient, direct axis and quadraure axis reactances P_m Mechanical power input to machine; *P* Electric power output from machine; *Q* Reactive power output from machine; δ Torque angle; ω Angular velocity E_{fd} Field voltage; E'_q q – axis voltage behind transient reactance; *E* Infinite bus voltage; V_{ref} Reference input voltage; V_t Terminal voltage; *Ke,Te* Exciter gain and time constant

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