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Robust Design of Power System Stabilizer using Harmony Search Algorithm

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Original scientific paper

In this paper, a novel Harmony Search algorithm (HSA) 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 the three parameters (K_p, K_i, K_d) of PID-PSS via a music-based metaheuristic optimization algorithm inspired by the observation that the aim of music is to search for a perfect state of harmony. The problem of robustly selecting the parameters of the PSS is converted to an optimization problem which is solved by a Harmony Search 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 Harmony Search Algorithm based PSS (HSAPSS). Further, the time domain simulation results when compared with those obtained using conventional PSS (CPSS) and Genetic Algorithm based PSS (GAPSS) show the superiority of the proposed design.

Key words: Harmony Search Algorithm, Power System Stabilizer, Power System Stability

Robusna sinteza stabilizatora elektroenergetskog sustava korištenjem algoritma traženja harmonije. U ovom radu je predloženo korištenje novog algoritma traženja harmonije za robusnu i optimalnu sintezu PID regulatora stabilizatora elektroenergetskog sustava s ciljem prigušenja niskih frekvencija harmonika snage električnog stroja spojenog na beskonačnu sabirnicu. U radu se optimiraju tri parametra (Kp, Ki, Kd) PID stabilizatora elektroenergetskog sustava korištenjem na glazbi baziranog metaheurističkog optimizacijskog algoritma inspiriranog zapažanjem kako je u glazbi cilj pronaći perfektno stanje harmonije. Problem robusnog izbora parametera PID regulatora je transformiran u optimizacijski problem koji se riješava korištenjem algoritma traženja harmonije s pažljivo odabranom funkcijom cilja. Analiza svojstvenih vrijednosti i simulacijski rezultati uz unutarnje i vanjske poremećaje za širok spektar radnih uvjeta pokazuju učinkovitost i robusnost predloženog stabilizatora baziranog na algoritmu traženja harmonije. Nadalje, simulacijski rezultati u vremenskoj domeni uspoređeni sa stabilizatorima projektiranim konvencionalnim pristupom te korištenjem genetskog algoritma pokazuju superiornost predloženog pristupa.

Ključne riječi: algoritam traženja harmonije, stabilizator elektroenergetskog sustava, stabilnost elektroenergetskog sustava

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 and ease of tuning PSS parameters. However, the robustness of these PSS under changing operating conditions is a major concern in its operation.

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 have been proposed to tune PSSs, such as the sensitivity approach [2], pole placement technique [5], and the damping torque approach [1]. Global optimization techniques like Genetic Algorithm (GA) [5], Particle Swarm Optimization (PSO) [6], tabu search [7] and simulated annealing (SA) [8] are attracting the attention in the field of

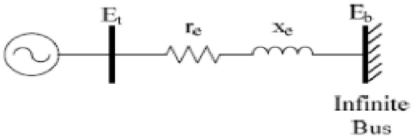

Fig. 1. Single Machine connected to Infinite Bus System

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 [9].To overcome the drawbacks of conventional methods for PSS design, a new optimization scheme known as Harmony Search (HS) is used for the PSS parameter design [10]. This algorithm (HSA) appeared as a promising one 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 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 HSA-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 HSAPSS 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 Fig. 1. The linear incremental model of a synchronous machine connected to a large system is shown in Fig. 2.

The state equation under a particular loading condition can be written as [11].

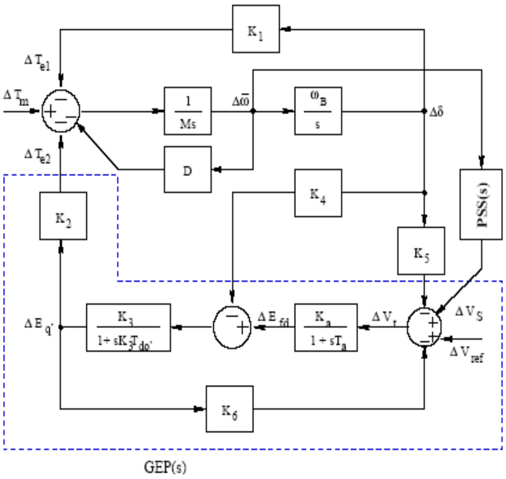

Fig. 2. Linearized model of a synchronous machine with an exciter and stabilizer

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t), \quad (1)$$

$$y(t) = Cx(t). \quad (2)$$

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.

$$x(t) = \left[\begin{array}{cccc} \Delta\delta(t) & \Delta\omega(t) & \Delta E'_q(t) & \Delta E_{fd}(t) \end{array} \right]^T \quad (3)$$

$$y(t) = \left[\begin{array}{cccc} 0 & 1 & 0 & 0 \end{array} \right] x(t) \quad (4)$$

The system matrices as taken from [11] is given below

$$A = \left[\begin{array}{cccc} 0 & 314 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & 0 & 0 \\ -\frac{K_4}{M} & 0 & -\frac{1}{K_3}T'_{d_0} & 0 \\ -\frac{K_eK_5}{T_e} & 0 & -\frac{K_eK6}{T_e} & -\frac{1}{Te} \end{array} \right], \quad (5)$$

$$B = \left[\begin{array}{cccc} 0 & 0 & 0 & \frac{K_e}{T_e} \end{array} \right], \quad (6)$$

$$C = \left[\begin{array}{cccc} 0 & 1 & 0 & 0 \end{array} \right]. \quad (7)$$

The parameters K_1-K_6 in equation (5) 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 Harmony Search 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 Fig.3, a 0.1 step change in reference mechanical torque (T_m) is assumed and the performance index in equation (9) is minimized using Genetic Algorithm. The settling time (t_s) and peak overshoot ($\Delta omega_p$) are evaluated for each iteration.

4 HARMONY SEARCH ALGORITHM

Harmony search is a music-based metaheuristic optimization algorithm. It was inspired by the observation that the aim of music is to search for a perfect state of harmony [13, 15]. This harmony in music is analogous to find the optimality in an optimization process. The search process in optimization can be compared to a jazz musician's improvisation process.

When a musician is improvising, he or she has three possible choices: (1) play any famous piece of music (a series of pitches in harmony) exactly from his or her memory; (2) play something similar to a known piece (thus adjusting the pitch slightly); or (3) compose new or random notes. Zong Woo Geem et al. formalized these three options into quantitative optimization process in 2001, and the three corresponding components become: usage of harmony memory, pitch adjusting, and randomization [10, 13, 15].

The usage of harmony memory is important, as it is similar to the choice of the best-fit individuals in genetic algorithms (GA). This will ensure that the best harmonies will be carried over to the New Harmony memory. In order to use this memory more effectively, it is typically assigned as a parameter *racceptÎ*$[0, 1]$, called harmony memory accepting or considering rate. If this rate is too low, only few best harmonies are selected and it may converge too slowly. If this rate is extremely high (near 1), almost all the harmonies are used in the harmony memory, then other harmonies are not explored well, leading to potentially wrong solutions. Therefore, typically, we use $raccept = 0.7 \sim 0.95$.

The second component is the pitch adjustment determined by a pitch bandwidth *brange* and a pitch adjusting rate *rpa* [14]. Though in music, pitch adjustment means to change the frequencies, it corresponds to generate a slightly different solution in the Harmony Search algorithm [6]. In theory, the pitch can be adjusted linearly or nonlinearly, but in practice, linear adjustment is used. So we have

$$x_{new} = x_{old} + b_{range} \cdot e \tag{8}$$

where x_{old} is the existing pitch or solution from the harmony memory, and x_{new} is the new pitch after the pitch adjusting action. This essentially produces a new solution around the existing quality solution by varying the pitch slightly by a small random amount $[1, 2]$. Here e is a random number generated in the range of $[-1, 1]$. Pitch adjustment is similar to the mutation operator in genetic algorithms. We can assign a pitch-adjusting rate (*rpa*) to control the degree of the adjustment. A low pitch adjusting rate with a narrow bandwidth can slow down the convergence of HS because of the limitation in the exploration of only a small subspace of the whole search space. On the other hand, a very high pitch-adjusting rate with a wide bandwidth may cause the solution to scatter around some potential optima as in a random search. Thus, we use *rpa* $= 0.1 \sim 0.5$ in most applications.

The third component is the randomization, which is to increase the diversity of the solutions. Although adjusting pitch has a similar role, but it is limited to certain local pitch adjustment and thus corresponds to a local search. The use of randomization can drive the system further to explore various diverse solutions so as to find the global optimality.

The three components in harmony search can be summarized as the pseudo code shown below.

Algorithm 1 Harmony Search

```
Input: Objective function $f(\mathbf{x})$, $\mathbf{x} = (x_1, x_2, \dots, x_d)^T$
Output: Best solutions found
Generate initial harmonics (real number arrays)
Define pitch adjusting rate (rpa), pitch limits and bandwidth
Define harmony memory accepting rate (raccept)
while $t <$ Max. number of iterations do
    Generate new harmonics by accepting best harmonics
    Adjust pitch to get new harmonics (solutions)
    if rand > raccept then
        Choose an existing harmonic randomly
    else if rand > rpa then
        Adjust the pitch randomly within limits
    else
        Generate new harmonics via randomization
    end if
end while
Find the current best solutions
```

By using the above pseudo code, dedicated software is developed in the MATLAB programming language for the above mentioned problem. The various parameters used in the software implementation of HSA in the present work are listed in section V.

V.HSA 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 minimum plant information than a complete mathematical model. In the proposed design approach, the PID control structure shown in Fig. 3 is used as the power system stabilizer as opposed to the traditional lead-lag controller.

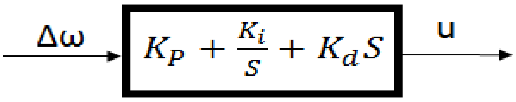

Fig. 3. The PID power system stabilizer

In Fig. 3 the speed deviation ($\Delta\omega$) is the input to the controller and u is the supplementary stabilizing signal. The PID parameters K_p, K_i, and K_d are tuned using the HSA technique discussed in section IV. To compute the optimum parameter values, a 0.1 step change in reference mechanical torque (T_m) is assumed and the performance index

$$F = \frac{1}{(1 + \Delta\omega_p)(1 + ts)} \tag{9}$$

is minimized using Harmony Search algorithm. The settling time (t_s) 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:

$$\left[\begin{array}{c|c|c|c|c} 0 & 314 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & 0 \\ -\frac{K_4}{T'_{d_0}} & 0 & -\frac{1}{K_3 T'_{d_0}} & -\frac{1}{T'_{d_0}} & 0 \\ \frac{MK_e(-K_5 \dots}{MT_e} & \frac{K_e K_p}{T_e} & -MK_6K_e \dots & \frac{1}{T_e} & \frac{K_e}{T_e} \\ \frac{\dots + MK_i/314 - K_d K_1)}{MT_e} & & \dots - \frac{K_2 K_e K_d}{MT_e} & & \\ \frac{MK_i}{314} - \frac{K_d K_1}{MT_w} & \frac{K_p}{T_w} & -\frac{K_2 K_d}{MT_w} & 0 & -\frac{1}{T_w} \end{array}\right] \tag{10}$$

The following machine parameters are chosen for study: $xd = 1.6$, $x'_d = 0.32$, $x_q = 1.55$, $v_{t_0} = 1.05$, $w = 100\pi$ [rad/s], $T'_{d0} = 6.0$ $[s]$, $D = 0.0$, $M = 10.0$, $r_e = 0$, $x_e = 0.4$, $K_e = 50$, $T_e = 0.05$ [s], $T_w = 5$ [s].

The parameters for HSA used in this study are as follows:

- Number of decision variables (N): 3,
- Harmony memory size (HMS): 48,
- Number of improvisations (NI): 500,
- Harmony Memory Consideration Rate (HMCR): 0.9.

5 TUNING RESULTS AND DISCUSSION

Simulation tests were made using a computational program that represents the single machine connected to infinite bus bar system. The machine with PID-PSS is represented as 5^{th} 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 Harmony Search Algorithm (HSA) is carried out for a step disturbance of 0.1 p.u mechanical torque (ΔT_m). Simulation study is also carried out for the mentioned operating conditions for the PSS designed using conventional and genetic algorithm

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

(GA).The conventional PSS parameters are calculated using frequency response method. The PSS parameters obtained by the application of conventional, GA and HSA 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 HSAPSS 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.

From Fig. 4-6 and Table 3, it is observed that the performance of the PSS designed using HSA is far superior compared to the PSS designed using conventional as well as genetic algorithm (GA).

Figure 7 illustrates the convergence of the objective function with genetic algorithm (GA) and HSA. From the convergence characteristics it is clear that HSA offers superior performance than GA.

Figure 8 shows the speed deviation for different operating conditions 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 HSAPSS do not change appreciably when the operating condition changes which suggests the robustness of the PSS. It is therefore possible to choose the PSS parameters obtained by HSA 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 HSA and GA for light load condition is chosen. With these PSS parameters fixed at all operating conditions the dynamic response of the system for 0.1 p.u mechanical disturbance (ΔT_m) for light, normal and heavy operating conditions are obtained and plotted as shown in Fig. 9 and Fig. 10. From Figures 9 and 10 it is evident that the oscillations due to disturbances are completely suppressed and the system rejects external disturbances at all operating conditions. In addition, the system performance

Table 2. Eigen value analysis

Operating condition	CPSS	GAPSS	HSAPSS
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=26.758 Ki=3.1202 Kd=15.479
Eigen values	-21.2515 ± 4.9661i -0.7438 ±6.6601i -5.6514	-14.712 ± 15.301i - 10.6116 -3.3594 -0.3235	-14.388± 20.379i - 12.8423 -4.9454 -0.3266
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=49.905 Ki=3.7074 Kd=19.365
Eigen values	-21.3386 ± 4.1240i -0.6869 ± 6.5345i -5.3633	-14.9530± 14.300i - 9.5003 -2.7187 -0.3125	-14.1482± 22.9699i - 13.8372 -5.4619 -0.3283
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=3.3509 Ki=3.2308 Kd=17.077
Eigen values	-21.3488 ± 3.3392i - 0.6133 ± 6.2708i -5.1956	-15.1088± 15.2737i - 9.3967 -2.8915 -0.2773	-15.1315± 21.926i - 11.7811 -5.3698 -0.3256

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

Operating Point	GAPSS		HSAPSS	
	t_s in Sec	ωp	ts in Sec	ωp
P=1.2 Q=0.2	2.1	1.1 x10^{-4}	1.1	0.5 x10^{-4}
P=0.9 Q=0.3	3.2	1.15 x10^{-4}	1.3	0.6 x10^{-4}
P=0.7 Q=0.2	2.9	1.1 x10^{-4}	1.2	0.55x10^{-4}

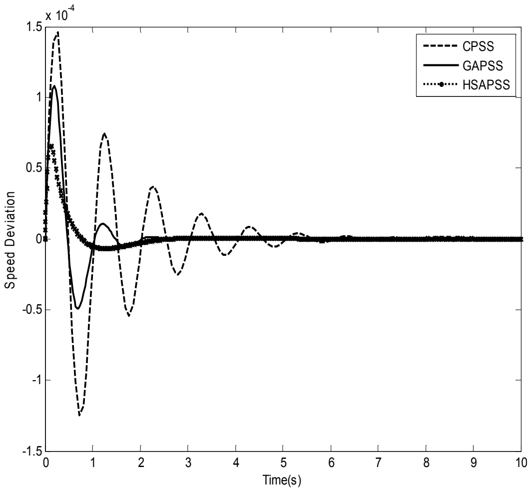

Fig. 4. Speed deviation for Operating condition ($P = 1.2$, $Q = 0.2$)

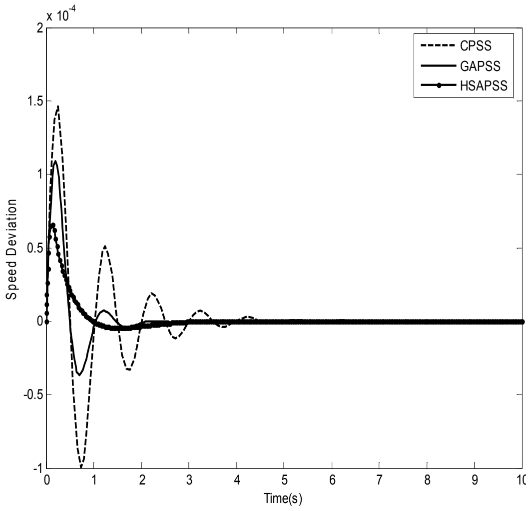

Fig. 5. Speed deviation for Operating condition ($P = 0.9$, $Q = 0.3$)

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.

6 CONCLUSION

In this study, optimal design of robust power system stabilizer (PSS) for single machine system connected to infinite bus is presented. 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 Harmony Search 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 without the need of tuning the controller parameters according to the change in operating conditions which is very difficult to accomplish on line. This shows the robustness of the controller designed using HSA. Furthermore, the simulation results also show that the proposed method in this paper gives much improved dynamic response when the system is subjected to disturbances when compared to the performance obtained using conventional and GA based design of controller for PSS. Further, the convergence of the objective function of HSA is much faster when compared to GA.

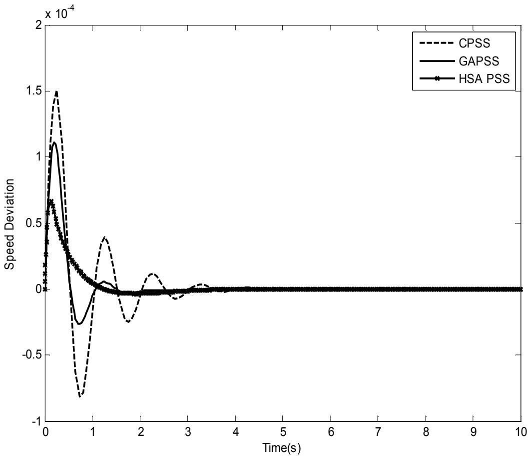

Fig. 6. Speed deviation for Operating condition ($P = 0.7$, $Q = 0.2$)

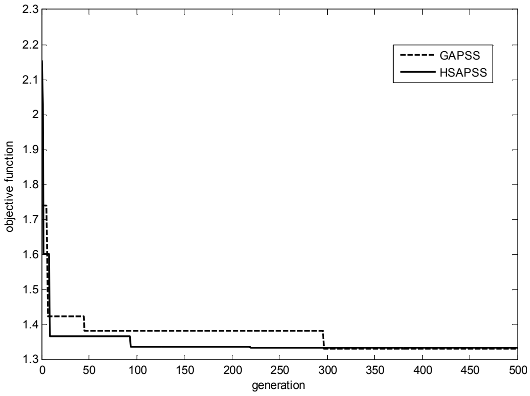

Fig. 7. Convergence comparison of GA and HSA

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

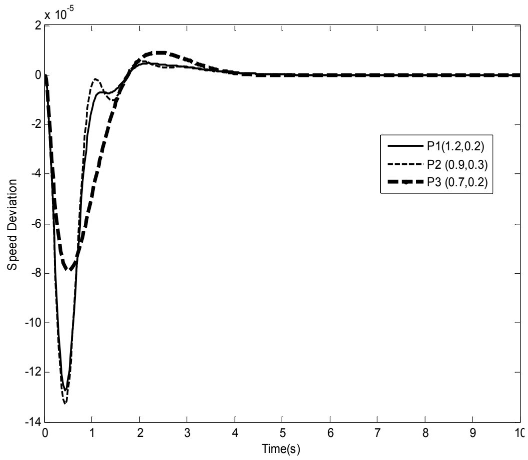

Fig. 8. Speed Deviation for different operating conditions for a 0.1 p.u step change in reference input voltage (ΔVref) with HSAPSS

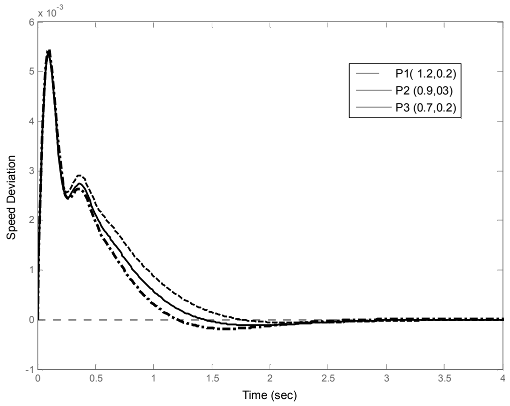

Fig. 9. Speed deviation for different operating conditions using

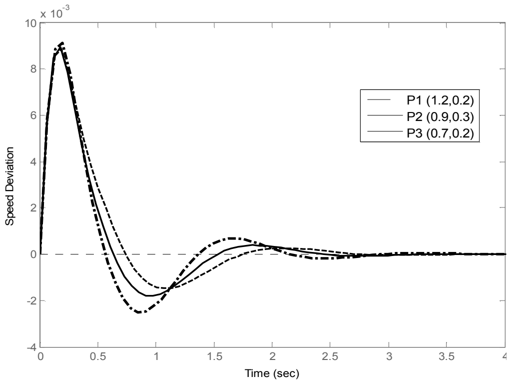

Fig. 10. Speed deviation for different operating conditions with GAPSS $K_p = 8.352$, $K_i = 2.941$ and K_d=7.294

system is highly non-linear one and therefore it becomes necessary to validate the results obtained here by laboratory test which has been taken for future work. The Harmony Search Algorithm remains to be tried out for designing controllers in the capacitive area and also for multi-machine complex power system.

APPENDIX A LIST OF SYMBOLS

x_e	Transmission Line Reactance
$K_1 - K_6$	Synchronous machine parameters
$T'd0$	d-axis open circuit field time
constant	Inertia coefficient (M=2H)
M, H	
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
K_e, T_e	Exciter gain and time
constant	Terminal Voltage
V_{t_0}	
T_w	Washout Time constant

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