Design of PID Controller Based Power System Stabilizer Using Modified Philip-Heffron's Model: An Artificial Bee Colony Approach

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***Abstract*— In this paper an optimally designed PID controller equipped with Power System Stabilizer (PSS) for a Single Machine Infinite Bus (SMIB) system using linearized Modified Philip-Heffron's model is presented. The PSS design based on this model utilizes signals available within the generating station and doesn't require the knowledge about external system parameters like line impedance and infinite bus voltage. A new swarm intelligent Artificial Bee Colony (ABC) algorithm has been used to tune the PSS-PID parameters to enhance the small signal stability due to small variations in generation and loads. Various simulation results and comparisons over different loading conditions on a single machine infinite bus power system using ABC tuned PID-PSS show the superiority of ABC in designing the power system stabilizer for the model considered.**

Keywords—Artificial Bee Colony; PSS; Modified Philip-heffron's model; SMIB; AVR.

I. Introduction

To supply the load demand in earlier days, power was generated beside the load center locally. Due to the rapid growth of power demand in recent years accompanied with scarcity of resources resulted in the increased complexity and remoteness of power systems. As a result heavy loads are being imposed on the existing power system [1]. Finally this leads to power system to operate near its transient stability limits. For reliable power supply, the modern day power systems require continuous balance between electrical power generation and varying load demand [2].

Power system is dynamic and nonlinear system, often experience changes in generation, transmission and loading conditions. As the distantly located interconnected power systems need to be maintained at constant operating voltage, fast acting high gain Automatic Voltage Regulators (AVR) are being used for synchronous generators. Though AVRs are used to maintain constant voltage, they are responsible for low frequency oscillations (0.1-3 Hz) and causes negative damping on the rotor by producing a component of electric torque out of phase with speed deviation ($\Delta\omega$) [3]. These oscillations may affect the small signal stability. Small signal stability is the ability of a system to sustain synchronism under small disturbances which are generally caused due to small variations in generation and loads [4]. To compensate the unwanted effect of these AVR's, additional supplementary signals (which are derived from the speed deviation signal $\Delta\omega$) are introduced in the feedback loop of voltage regulator. So, Power System Stabilizer (PSS) are used to produce positive damping on rotor oscillations [5].

Since 1960's conventional lead-lag PSS were in usage to damp out low frequency oscillations on rotor [6]. To carry small signal stability studies of Single Machine Infinite Bus system (SMIB), Philip-Heffron's model with conventional lead-lag PSS is used extensively [3]. Recently Gurrala and Sen [7] proposed a modified Philip-Heffron model with PSS which judges system disturbances like change in system configuration and load changes based on deviation of power flow, voltage and rotor angle at secondary of step-up transformer. The main advantage with this system is that it doesn't require knowledge of system parameters external to generating station which may vary during normal operation.

To further enhance the performance of this system in terms of stability the PID controller had been incorporated in the modified Philip-Heffron model. As the present model consists of both PSS and PID parameters, trial and error methods are not suitable to design the required system and hence to find optimum parameters with reduced computational complexity we used a new swarm intelligent based Artificial Bee Colony (ABC) algorithm based on the foraging of bees. ABC was proposed by Karaboga and Basturk for numerical function optimization [12, 13, 16]. Due to its simplicity in structure along with good global and local exploration skills it has been used in designing the solutions for many real world practical problems [14].

The rest of paper is organized as follows; Section II deals with the mathematical modeling of power system for single machine. In Section III the problem is formulated followed by the objective function considered. Section IV briefs the Artificial Bee Colony algorithm and design scheme is been provided in Section V. The simulations and results are put forth in Section VI and at end we wind up with few conclusions in Section VII.

II. Power System Modeling

The dynamic modeling [15] of components in the power system like synchronous generator, excitation system, AVR etc. is needed for small signal stability studies. A SMIB power system model shown in Fig.1 is used to obtain Modified Philip-Heffron's model parameters.

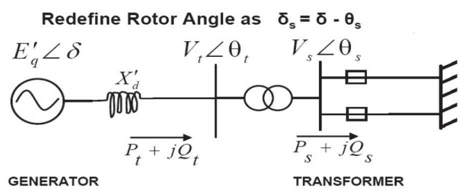

Fig.1 Single machine power system model [7]

A. Generator Modeling

This is a simplified representation of a generator connected to the load through a transmission line. IEEE Model 1.0 is used to model the synchronous generator. The dynamic equations corresponding to this SMIB Model 1.0 are given below.

$$\delta^{\bullet} = \omega_B \omega \tag{1}$$

$$\omega^{\bullet} = \frac{1}{2H}\left(T_{mech} - T_{elec} - D\omega\right) \tag{2}$$

$$E_q^{'\bullet} = \frac{1}{T_{do}^{'}}(-E_q^{'} + (X_d - X_d^{'})i_d + E_{fd}) \tag{3}$$

$$E_{fd}^{'\bullet} = \frac{1}{T_e}\{-E_{fd} + K_E(V_{ref} + V_{pss} - V_t)\} \tag{4}$$

$$T_{elec} = E_q^{'} i_q + (X_d^{'} - X_q^{'}) i_d i_q \tag{5}$$

The above equations are based on rotor angle δ measured with respect to the remote bus V_B. To get the dynamic equations with respect to the secondary bus voltage $V_s\angle\theta_s$ of the step up transformer, all the expressions involving the rotor angle δ have to be expressed in terms of δ_s, where $\delta_s = \delta - \theta_s$. The expressions for δ_s and $E_q^{'}$ are as under

$$\delta_s = Tan^{-1}\left(\frac{P_s(X_t + X_q) - Q_s R_a}{P_s R_a + Q_s(X_t + X_q) + V_s^2}\right) \tag{6}$$

$$\text{If } \delta_s < 0,\ then\ \delta_s = \pi - |\delta_s|$$

$$E_q^{'} = \left(\frac{X_t + X_d^{'}}{X_t}\right)\sqrt{V_t^2 - \left(\frac{X_q}{(X_t + X_q)} V_s \sin\delta_s\right)^2} - \frac{X_d^{'}}{X_t} V_s \cos\delta_s \tag{7}$$

B. Modified Philip-Heffron's model

The standard Heffron-Phillips model can be obtained by linearizing the system equations around an operating condition. Following equations can be obtained from above model.

$$E_q^{'} + X_d^{'} i_d - R_a i_q = V_q \tag{8}$$

$$-X_q^{'} i_q - R_a i_d = V_d \tag{9}$$

The q and d subscripts refers to *q-axis* and *d-axis* respectively. The machine terminal voltage in terms of the transformer secondary is given by

$$V_q = R_t i_q - X_t i_d + V_s \cos\delta_s \tag{10}$$

$$V_d = R_t i_d + X_t i_q - V_s \sin\delta_s \tag{11}$$

Substitution of Eqn (8), Eqn (9) in Eqn (10) and Eqn (11), and there by rearranging gives the following matrix

$$\begin{bmatrix} X_d^{'} + X_t & -R_t \\ -R_t & X_q + X_t \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} V_s\cos\delta_s - E_q^{'} \\ -V_s \sin\delta_s \end{bmatrix} \tag{12}$$

The system mechanical, electrical equations and (12) are linearized to obtain K constants as follows

$$K_1 = \frac{V_{so}E_{qo}\cos\delta_{so}}{X_t + X_q} + \left(\frac{X_q - X_d^{'}}{X_t + X_q}\right)V_{so}\sin\delta_{so}$$

$$K_2 = \frac{X_q + X_t}{X_d^{'} + X_t} i_{qo};\ K_3 = \frac{X_t + X_d^{'}}{X_d + X_t};\ K_4 = \frac{X_d - X_d^{'}}{X_t + X_d^{'}} V_{so}\sin\delta_{so};$$

$$K_6 = \frac{X_t}{X_t + X_d^{'}}\,\mathrm{x}\,\frac{V_{qo}}{V_{to}};\quad K_{v2} = -\left(\frac{X_d - X_d^{'}}{X_d^{'} + X_t}\right)\cos\delta_{so}$$

$$K_5 = -\frac{X_q V_{do} V_{so}\cos\delta_{so}}{(X_q + X_t)V_{to}} - \frac{X_d^{'} V_{qo} V_{so}\sin\delta_{so}}{(X_t + X_d^{'})V_{to}}$$

$$K_{v1} = \frac{E_{qo}\sin\delta_{so}}{X_t + X_q} - \left(\frac{X_q - X_d^{'}}{X_d^{'} + X_t}\right)\cos\delta_{so} i_{qo}$$

$$K_{v3} = \frac{-X_q V_{do}\sin\delta_{so}}{(X_q + X_t)V_{to}} + \frac{X_d^{'} V_{qo}\cos\delta_{so}}{(X_t + X_d^{'})V_{to}}$$

where $E_{q0} = E^{'}_{q0} - (X_q - X^{'}_d) i_{d0}$ and here the modified Heffron-Phillip's model comprises six constants K_1 to K_6 whose definitions remain unchanged but they are not with reference to δ and E_B. It can be observed that the modified K-constants are also no longer the functions of the equivalent reactance X_e. They are functions of V_s, δ_s, V_t and machine currents. Therefore the modified K constants can be now computed based on local measurements only.

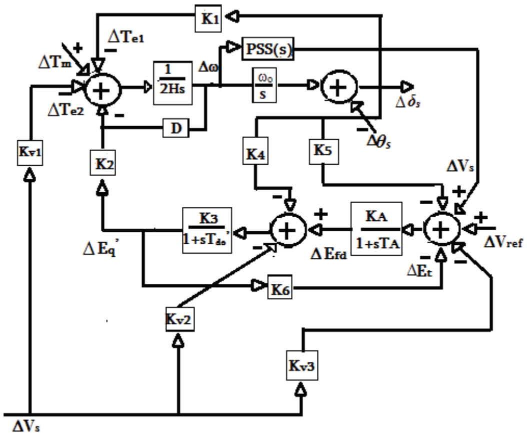

Fig.2 Modified Philip-Heffron's model, $\Delta\delta_s$ is rotor angle

In this model, as V_s is not a constant, during linearization, three additional constants K_{v1} to K_{v3} are introduced at the torque, field voltage and terminal voltage junction points.

For the Modified Philip-Heffron's model the action of PSS is effective through the transfer function block $G(s)$ between the electric torque and the reference voltage input with variation in the machine speed assumed to be zero.

$$G(s) = \frac{(K_2 K_3 K_{v1} K_E)}{(G_3)s^2 + (G_2)s + (G_1)} \tag{13}$$

$$G_1 = K_6 K_3 K_E + K_2 K_3 K_{v1} K_{v2} + K_2 K_3 K_{v1} K_{v2} T_E + 1; \quad G_3 = K_3 T'_{do} T_E$$

$$G_2 = K_3 T'_{do} + T_E + K_2 K_3 K_{v1} K_{v2} T_E$$

C. PSS and Excitation system

A conventional two stage lead-lag Power System Stabilizer along with IEEE Type-ST1A excitation system is considered. The inputs to excitation system are terminal voltage (V_T), supplementary signal (V_s) from PSS and reference voltage (V_{ref}). K_A and T_A are the gain and time constant of excitation system respectively.

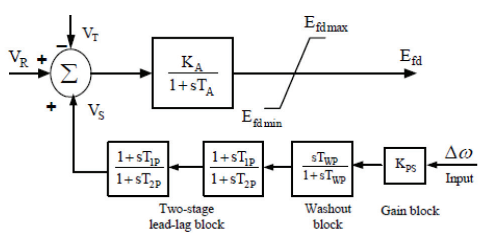

Fig.3 Structure of PSS and IEEE- ST1A

The PSS takes the speed deviation signal (Δω) as input to produce a component of electrical torque in the direction of Δω and gives a supplementary control signal (ΔV_s) to excitation system as output. A schematic representation of PSS along with excitation is presented in Fig 3.

III. Problem Formulation

A. Structure of PSS

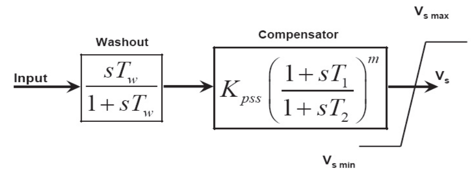

Fig.4 Structure of Lead-lag PSS [7]

The conventional lead–lag structure is chosen in this study. It consists of a gain block with gain K_{PSS}, a signal washout block and two-stage phase compensation block as shown in fig. 4 (m = 2). The phase compensation block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The signal washout block serves as a high-pass filter, with the time constant T_W (1-10 sec), high enough to allow signals associated with oscillations in input signal to pass unchanged. Transfer function of PSS is given by

$$V_s = K_{PSS}\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right) \tag{14}$$

In this design T_W is usually pre-specified. The gains K_{PSS} and T_1, T_2, T_3, T_4 are to be determined. The input signal of the proposed PSS is the speed deviation (Δω) and the output is supplementary signal (ΔVs).

B. PID-PSS controller

Transfer function of PID-PSS is given by

$$V_s = K_{PSS}\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)G_c(s) \tag{15}$$

where

$$G_c(s) = (K_p + \frac{K_i}{s} + K_d s) \tag{16}$$

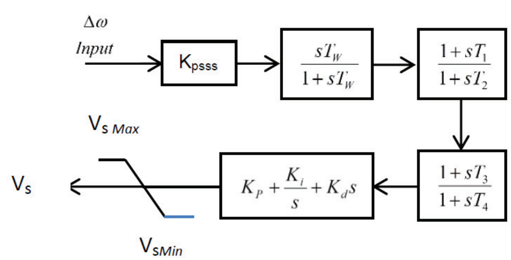

Fig.5 Structure of Lead-lag PSS with PID controller

The proportional gain K_p provides a control action proportional to the error and reduces the rise time. The integral gain K_i reduces the steady state error by performing an integral control action and eliminates the steady state error. The derivative term K_d improves the stability of the system and reduces the overshoot by improving the transient response. Hence, ABC is used to determine optimal Kp, K_i, K_d values.

C. Objective function

The performance of the system considered depends on the controller parameters, which in turn depends on the objective function to be minimized. The design of PSS is done based on minimizing the objective function considered in order to reduce the power system oscillations after a disturbance in loading condition so as to improve the stability of power system. In this paper the objective function is formulated in such a way that rotor speed deviation is minimized and is mathematically formulated as follows

$$J = \sum \int_0^t t[\Delta\omega(t, X)]^2 \, dt \quad (17)$$

In the Eqn (17), $\Delta\omega(t, X)$ denotes the rotor speed deviation for a set of controller parameters X. Here X represents the parameters to be optimized. The optimization is carried in two phases, initially the 5 parameters corresponding to PSS controller are been tuned and in second phase by fixing the obtained parameters of PSS controller, the PID parameters K_p, K_i and K_d are tuned to obtain optimum system response.

IV. ARTIFICIAL BEE COLONY ALGORITHM

Artificial Bee Colony (ABC) algorithm classifies the foraging artificial bees into three groups; the *employed bees, the onlooker bees* and the *scouts* [12, 13]. The first half of the colony consists of the employed bees and second half consist of the onlooker bees. A bee that is currently searching for food or exploiting a food source is called an *employed bee* and a bee waiting in the hive for making decision to choose a food source is called an *onlooker bee*. For every food source, there is only one employed bee. The employed bee of abandoned food source becomes a *Scout*. In ABC algorithm each solution to the problem is considered as food source and is represented by a *D*-dimensional real-valued vector, where the fitness of the solution corresponds to the nectar amount of associated food source.

The algorithm starts by initializing all the employed bees with randomly generated food sources (solutions). In each generation every employed bee finds a food source in the neighborhood of its current food source and evaluates its *nectar* amount i.e., (*fitness*). In general the position of i_{th} food source, for a D dimensional search space, is represented as $X_i=\{x_{i1}, x_{i2}, \ldots, x_{iD}\}$. After the information is shared by the employed bees; onlooker bees go to the region of food source at X_i based on the probability P_i defined as

$$P_i = \frac{fit_i}{\sum_{k=1}^{FS} fit_k} \quad (18)$$

FS is total number of food sources. Fitness value fit_i is calculated by using following equation.

$$fit_i = \frac{1}{1 + f(X_i)} \quad (19)$$

Here $f(X_i)$ is the objective function to be minimized. The onlooker finds its *food source* in the region X_i, by making use of following equation.

$$x_{new} = x_{ij} + r*(x_{ij} - x_{kj}) \quad (20)$$

Where $k \in (1,2,3,\ldots,FS)$ such that $k \notin i$ and $j \in (1,2,3,\ldots,D)$ are randomly chosen indexes, r is a uniformly distributed random number in the range [-1, 1]. If the obtained new fitness value is better than the fitness value achieved so far, than the bee moves to this new food source leaving this old one otherwise it retains the old food source. Each bee will search for a better food source for a certain number of cycles (*limit*), and if the fitness value doesn't improve then that particular bee becomes a *Scout* bee. A food source is initialized to that *scout bee* randomly and the search process continues. In this approach we used basic version which involve only one scout bee.

Pseudo Code of ABC

1. Initialize the food sources.
2. Move the employed bees onto their food sources and appraise their nectar amounts.
3. Place the onlookers, depending upon the nectar amounts obtained by employed bees.
4. Send the scouts for exploring new food sources.
5. Memorize the best food sources obtained so far.
6. If a termination criterion is not satisfied, go to step 2; otherwise stop the procedure and display the best food source obtained so far.

V. DESIGN OF POWER SYSTEM STABILIZER (PSS)

A. Parameters of the power system considered

For the small signal stability analysis of SMIB the design of the system and system data is taken from [1].

1. System data: All data are in p.u unless specified otherwise

2. Generator: H = 5 s, D = 0, X_d = 1.6, X_q = 1.55, X_d' =0.32, T_{d0}=6, machine

3. Exciter: (IEEE type ST1) K_A=200, T_A=0.05s, $E_{fd\,max}$=6 p.u & $E_{fd\,min}$= -6 p.u

4. Transformer: = X_T=0.1

5. CPSS data : T_1=0.078, T_2=0.026, K_{PSS}=16, T_W=2, *PSS output limits* $\pm$ 0.05

6. Mod HP-CPSS: T_1=0.0952, T_2=0.0217, K_{PSS}=13, T_W=2, *PSS output limits* $\pm$ 0.05

As the optimization is carried out within bounds the following ranges are considered for the parameters to be tuned. The parameters being considered for tuning were K_{PSS}, T_1, T_2, T_3, T_4 and K_p, K_i and K_d. Maximum and minimum parameters considered are as follows.

$10<K_{ps}<80$; $0.05<T_1,T_3<0.6$; $0.02<T_2$, $T_4<0.4$; $0<K_P,K_I<50$; $0<K_d<10$.

B. Parameters of Artificial Bee Colony Algorithm

Various parameters involved in the ABC algorithm are as follows, number of bees (*NB*)=20, Food sources (*FS*)=*NB/2*, Employed and Onlooker are assigned value equal to half total number of bees and the last parameter *limit* is initialized to n_e*D. A termination criterion of 4000 Number of function evaluations are used for the tuning procedure.

VI. SIMULATIONS AND RESULTS

In this section we had summarized the loading conditions considered in the following tables.

Table 1: Loading conditions considered (p.u)

Nominal Loading or Nominal system	P_s=1.0, Q_s=0.2
Heavy Loading or strong system	P_s=0.8,Q_s=0.37
Light Loading or weak system	P_s=1.0 ,Q_s=0.5

Table 2: Parametric Values Obtained for PSS Using ABC

Parameter	Nominal System	Strong System	Weak System
K_{PSS}	40.7576	19.5975	19.8468
T_1	0.1084	0.4227	0.1991
T_2	0.0200	0.0200	0.0200
T_3	0.6000	0.1818	0.2020
T_4	0.3411	0.3792	0.4000

Table 3: Parametric Values Obtained for PID Using ABC

Parameter	Nominal System	Strong System	Weak System
K_P	26.0326	21.0599	9.9071
K_i	14.7003	9.5978	4.1251
K_d	0.8354	0.4256	0.3348

Table 4: Mean and Standard Deviation (std) without PID controller

Loading Condition	without PID controller	With PID controller
Nominal system	8.268e-04 (2.359e-06)	8.02e-04 (1.9525e-06)
Strong system	2.494e-03 (4.0518e-06)	2.3801e-03 (3.8243e-06)
Weak system	2.0196-03 (2.3082e-06)	1.9707e-03 (1.973e-06)

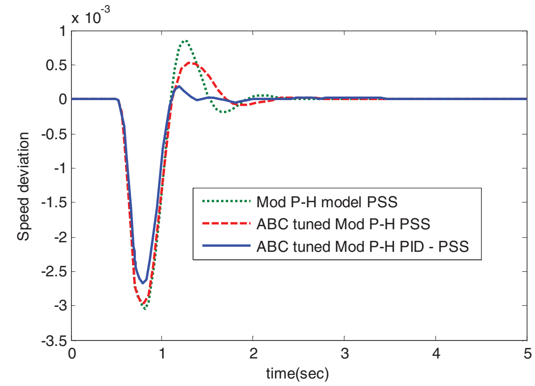

Fig 6. Speed dev. for a step change of 10% in V_{ref} for nominal system

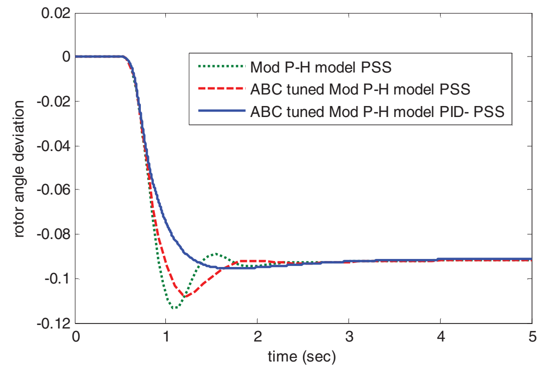

Fig 7. Rotor angle dev. for a step change of 10% in V_{ref} for nominal system

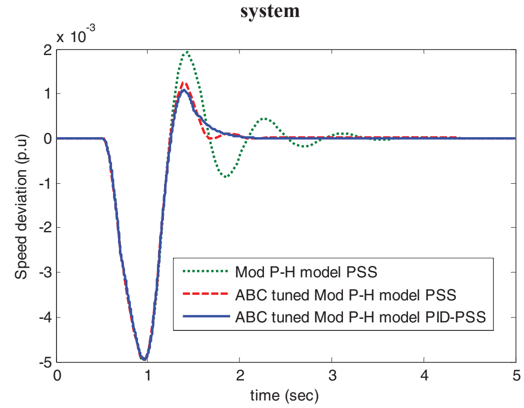

Fig 8. Speed deviation for a step change of 10% in Vref for strong system

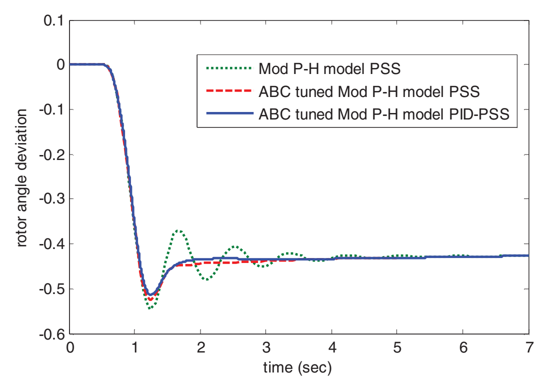

Fig 9. Rotor angle deviation for a step change of 10% in Vref for strong system

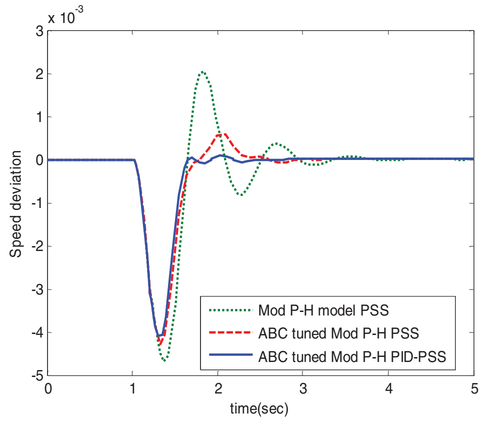

Fig 10. Speed dev. for a step change of 10% in V_{ref} for weak system

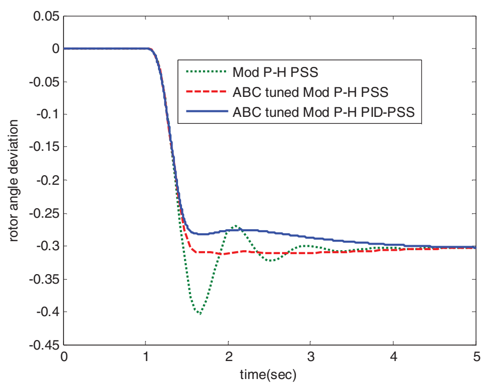

Fig 11. Rotor angle dev. for a step change of 10% in V_{ref} for weak system

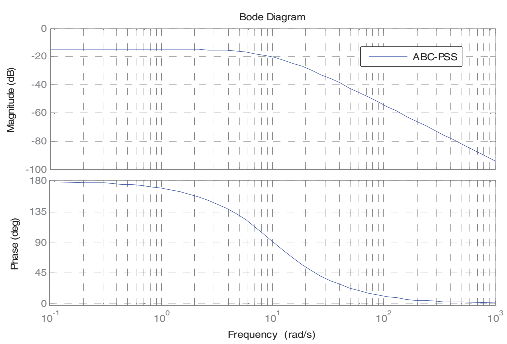

Fig 12. Bode plot stability analysis for nominal system

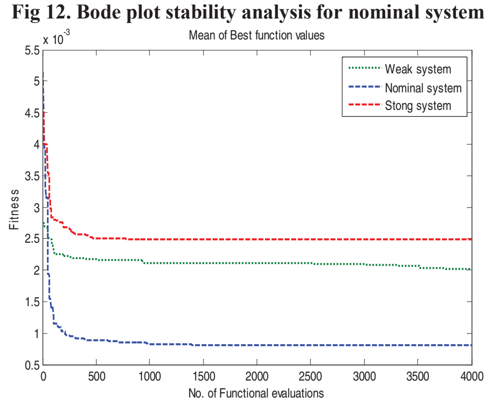

Fig 13. Convergence Characteristics of ABC towards optimum for different loading conditions without PID

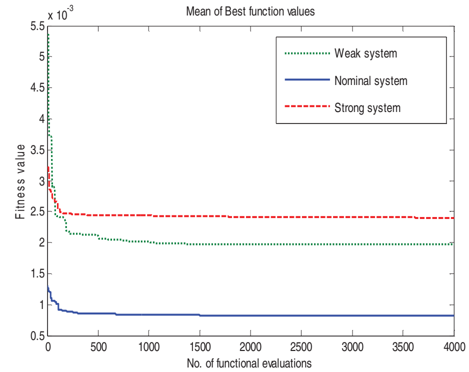

Fig 14. Convergence Characteristics of ABC towards optimum for different loading conditions with PID

For a given 10% step change in input ΔT_m, the responses obtained for nominal, strong and weak systems are depicted in terms of speed deviation and rotor angle deviations. Fig 6, 8 and 10 show speed deviations, and Fig 7, 9 and 11 show rotor angle deviations of the systems considered (in the order mentioned above). Table 5 shows the time domain indices values for different loading conditions in terms of peak value and settling time. From the figures and Table 5 it is evident that ABC tuned PID-PSS outperformed the ABC tuned PSS without PID and also the un-tuned PSS in terms of transient stability. To further validate the stability we also conducted bode tests for the normal system which was shown in the Fig12. Finally Fig 13 and 14 show the convergence characteristics of ABC progressing towards optimum values without and with PID respectively.

VII. Conclusion

This paper presents a novel method of desiging PID controller for the power system considered using modfied Philip-Heffron's Model. A new intelligent Artificial Bee Colony algorithm has been employed for obtaining the controller paraemters based on time domain based objective function minimization. Different loading conditions are considered and correspoding speed and rotor angle deviations are recorded. From the experimental values obtained it was evident that proposed method has performed superiorly well.

Our future research will include implementation of fractional order controllers for single machine and also for three machine power systems.

References

[1] M. A. Abido and Y. L. Abdel-Magid, "Power system stability enhancement via coordinated design of a PSS and an SVC-based controller", Proceedings of the 10th *IEEE International Conference on Electronics, Circuits and Systems*, pp. 850 – 853, Dec. 2003.

[2] I. Manuaba, M. Abdillah, A. Soeprijanto, M. P. Hery, "Coordination of PID based power system stabilizer and AVR using combination of bacterial foraging technique – particle swarm optimization," *4th International Confernce on Modeling, Simulation and Applied Optimization (ICMSAO)*, pp. 1-7, April 2011.

[3] Y. L. Abdel-Magid, M. Bettayeb, M. M. Dawoud, "Simultaneous stabilization of power systems using genetic algorithms" in *IEE Proceedings Generation Transmission Distribution*, vol. 144, No. 1, pp. 39-44, Jan. 1997.

[4] R. Vikal and G. Goyal, "TCSC controller design using global optimization for stability analysis of single machine infinite-bus power system," *15th International Conference on Intelligent System Applications to Power Systems, 2009. ISAP '09,* pp.1-7, 2009.

[5] E. V. Larsen and D. A. Swann, "Applying power system stabilizers part ii: performance objectives and tuning concepts", *IEEE Transactions on Power Apparatus and Systems,* , vol.PAS-100, no.6, pp.3025-3033, June 1981.

[6] P. Hoang and K. Tomsovic, "Design and analysis of an adaptive fuzzy power system stabilizer", *IEEE Trans on Energy conversion*, Vol. 11, No. 2, pp. 455 – 461, June 1996.

[7] G. Gurrala and I. Sen, "A modified Heffron-Phillip's model for the design of power system stabilizers," *Joint International Conference on Power System Technology and IEEE Power India Conference, 2008. POWERCON 2008,* pp.1-6, Oct. 2008.

[8] B. Selvabala and D. Devaraj, "Co-ordinated tuning of AVR-PSS using differential evolution algorithm," In Proceedings: *IPEC, 2010,* pp.439-444, Oct. 2010.

[9] P. W. Sauer and M. A. Pai, *Power System Dynamics and Stability*, Prentice Hall, 1997.

[10] M. Dubayand P. Gupta. "Design of genetic-algorithm based robust power system stabilizer", *International Journal of Computational Intelligence*, 2006.

[11] A. D Del Rosso, C. A Canizares and V. M. Dona, "A study of TCSC controller design for power system stability improvement," *IEEE Trans. Power Systs.*, vol-18, pp. 1487-1496, 2003.

[12] D. Karaboga and B. Basturk, "A powerful and efficient algorithm for numerical optimization: artificial bee colony algorithm", *Journal of Global Optim*., 2007, **3**(39):159-172.

[13] D. Karaboga and B. Basturk, "On the performance of artificial bee colony algorithm", *Applied Soft Comp.*, 2008, **8**(1): 697-697.

[14] D. Karaboga, B. Gorkemli, C. Ozturk, and N. Karaboga, "A comprehensive survey: artificial bee colony algoirhtm and applications", *Artificial Intelligence Review*, Springer Verlag, DOI: 10.1007/s10462-012-9328-0, March 2012.

[15] D. P. Kothari and I. J. Nagarath, *Modern Power System analysis*, 4thed. TMH, New Delhi, 2011.

[16] D. P. Kothari and J. S. Dhillon, *Power System Optimization*, 2nd Ed., PHI, New Delhi, 2011.

Table 5 Settling times[1] and peak values for various loading conditions

Loading condition	Response	Settling time T_s(sec)			Peak value (For speed deviation 1st max peak value) (For Rotor angle deviation 1st under shoot)		
		Un tuned PSS	ABC tuned PSS	ABC tuned PID-PSS	Un tuned PSS	ABC tuned PSS	ABC tuned PID-PSS
Nominal system	Speed deviation	3.331	**3.182**	3.203	8.55e-04	5.36e-04	**1.84e-04**
	Rotor angle deviation	3.462	2.831	**2.314**	-0.1181	-0.1123	**-1.076**
Strong system	Speed deviation	3.714	3.367	**2.382**	1.95e-03	1.25e-03	**1.08e-03**
	Rotor angle deviation	6.138	4.252	**3.964**	-0.542	-0.525	**-0.513**
Weak system	Speed deviation	4.413	3.906	**3.534**	2.1e-03	5.8e-04	**0.85e-04**
	Rotor angle deviation	3.612	**3.504**	3.512	-0.403	-0.312	**-0.285**

[1]Considered from the instant at which step change in input and V_{ref} are given