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Power System Stability Analysis of SMIB using Artificial Bee Colony Optimization

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ABSTRACT
Due to complexity in the power system there is always a loss of the stability due to the fault. Whenever a fault is intercepted in system, the whole system goes to severe transients. These transients cause oscillation in phase angle which leads poor power quality. The nature of oscillation is increasing instead being sustained, which leads system failure in form of generator damage. To reduce and eliminate the unstable oscillations one needs to use a stabilizer which can generate a perfect compensatory signal in order to minimize the harmonics generated due to instability. This paper presents a Power System stabilizer to reduce oscillations due to small signal disturbance. Additionally, an optimal approach is proposed using the PSS connected SMIB. Artificial Bee Colony (ABC) Algorithm is used for the parameter tuning of the stabilizer.

***Keywords* -** ABC, AVR, PSS, SMIB.

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I. INTRODUCTION

The basic function of an excitation system is to provide direct current to the field winding of a synchronous machine. In addition, the excitation system performs control and protection functions essential for the satisfactory operation of the power system by controlling the field voltage and hence the field current. Control functions include voltage control and reactive power, as well as improved system stability. The protection functions ensure that the capacity limits of the synchronous machine, the excitation system and other equipment are not exceeded. Generator excitation systems maintain the voltage magnitude and control the reactive power flow in the system [1, 2, 3, 4, 5, and 6].

As noted in the previous chapter, a change in the demand for active power essentially affects frequency; while a change in reactive power mainly affects the magnitude of voltage. The interaction between voltage and frequency controls is generally weak, which justifies an independent analysis. Reactive power sources are generators, capacitors and reactors. The reactive power of the generators is controlled by means of the excitation control systems [7].

II. REQUIREMENTS FOR EXCITATION CONTROL SYSTEMS

The operating requirements of the excitation systems are determined by considerations of the synchronous generators as well as the power systems [8].

Considerations of Synchronous Generators: The basic requirement is that the excitation system automatically provides and adjusts the field current of the generator to maintain the voltage at terminals to a given value when the output varies between the continuous capacities of the generator. In addition, the excitation control system must be capable of responding to transient disturbances with field winding efforts consistent with the instantaneous and short-term capacities of the generator. The capacities of the generator are limited by several factors such as insulation and heating of the rotor, heating of the stator, etc. Thermal limits have time-dependent characteristics, and short-term overload capability can take up to sixty seconds. To ensure the best use of the excitation system, it must be capable of overcoming the needs of the system by taking the short-term advantages of the generator, without exceeding the limits [9, 10, and 11].

Power System Considerations: From the point of view of power systems, excitation control systems should contribute to effective voltage control and improved system stability. It must be able to respond fast enough to a disturbance to improve transient stability, and to modulate the generator field in a way that improves small signal stability [12, 13, 14, 15, and 16].

Historically, the role of excitation systems in improving the stability of power systems has continuously increased. Old excitation systems were manually controlled to maintain terminal voltage and reactive power output. When the voltage control was automated for the first time, it was very slow, and only replaced an operator. In the early 1920s, the potential to improve small and large signal stability was recognized through the use of continuous and rapid response regulators. From that point on, great attention is given to the design and development of the excitation systems, so that these systems remain in constant evolution. In the early 1960s, the role of excitation systems was expanded by the sum of auxiliary stabilization signals; in addition to the voltage error signal at terminals, to dampen system oscillations by means of the field voltage control [17]. This part of the excitation control system is referred to as the power system stabilizer (PSS). Modern excitation systems are capable of practically providing an immediate response with high limit voltages. The combination of high field winding effort capacity and the use of auxiliary stabilization signals contribute substantially to the improvement of the overall dynamic response of the systems [18, 19].

In order to satisfy the aforementioned roles satisfactorily, the excitation system must meet the following requirements:

- Meet a specified response criterion.
- Provide limitation and protection functions required to prevent generator and other equipment damage.
- Meet specific requirements of flexibility in operation.
- Satisfying reliability and availability by incorporating internal fault detection and isolation capability.

III. INTRODUCTION TO POWER SYSTEM STABILIZERS - PSS

When it seemed that the action of some voltage regulators could result in negative damping of the electromechanical oscillations, the PSS were introduced as a means of improving the damping of oscillations, through the modulation of the excitation of the generator so that it could be extended the power transfer limit. In some power systems, the frequency oscillations can be as low as 0.1 Hz between areas, and as high as 5 Hz for local mode oscillations.

Nowadays the power system stabilizers or PSS are devices that are widely used to improve the damping of the oscillations in the power system through the excitation system and / or through the turbine and governor system of the generating unit. In addition, the PSS is one of the most economical methods to improve the stability of power systems. This section will deal with the PSS and its applications in an introductory manner.

3.1 General Concepts of the PSS

The addition of supplementary controls to the AVR loop is one of the most common ways of improving small signal stability (also referred to as small angle stability) and large signal stability (also referred to as high angle or transient stability). The addition of extra control loops should be done with much attention since the AVR (without supplementary control loops) can weaken the damping of the field windings and damping.

The reduction of the damping torque is due in principle to the effects of voltage regulation that includes additional currents in the rotor circuits that oppose the currents induced by the rotor speed deviation $\Delta\omega$.

The main idea of the stabilization of power systems is to recognize that in the steady state, which occurs when the speed deviation is zero or almost zero, the voltage controller must be manipulated only by the $V_{err\,1}$ voltage error. However, in the transient state the generator speed is not constant, the oscillations of the rotor, and $V_{err\,1}$ are subjected to oscillations caused by the change in the angle of the rotor. The function of the PSS is to add an additional signal that compensates the oscillations of $V_{err\,1}$ and that provides a damping component that is in phase with $\Delta\omega$. This is illustrated in Fig. 1 where the signal V_S is added to the voltage error signal $V_{err\,1}$. In the stable state V_S must be equal to zero so that it does not distort the normal process of the AVR.

Fig. 2 shows the phasor diagram of the signals involved in Figure 1, during the transient state. Since each signal varies sinusoidally with the rotor frequency oscillations, these can be represented by phasors. The $\bar{V}_S$ phasor directly opposes the $\bar{V}_{err\,1}$ phasor and is much larger than this. The total voltage error phasor $\bar{V}_{err}$ is ahead of the speed deviation $\Delta\bar{\omega}$, if the PSS does not exist it will be delayed with respect to $\Delta\bar{\omega}$.

The phasor of the excitation voltage $\Delta\bar{E}_{FD}$ is delayed with respect to $\bar{V}_{err}$ by an angle introduced by the AVR and the exciter so that the quadrature component (with respect to $\Delta\bar{\delta}$) of the phasor $\Delta\bar{E}_{q(\Delta\delta)}$, introduces a damping torque to the system. However, the magnitude of $\bar{V}_S$ is less than $V_{err\,1}$, then the partial compensation of the negative damping component of the AVR is achieved.

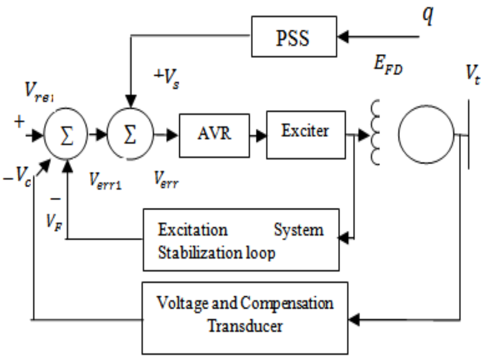

Figure 1 Block diagram of the PSS application [11]

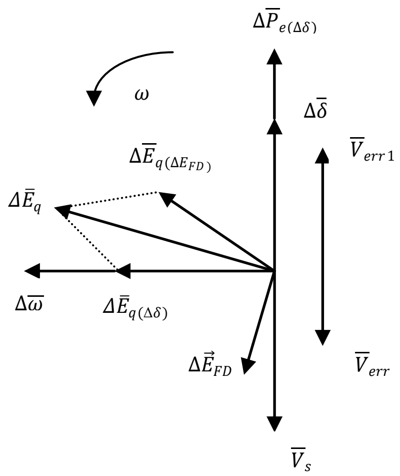

Figure 2 Phasor diagram of the PSS application [11]

IV. PROPOSED METHODOLOGY

4.1 Mathematical Modeling of the PSS

At this point it becomes apparent that PSS is a form of supplementary control that is used to provide additional damping to the oscillations of the power system or to stabilize a generator whose gain in the excitation system is such that it results in negatively damped oscillations. It has also been mentioned that the damping of small oscillations can be improved by means of an appropriate feedback of the stabilization signals to the excitation system of the synchronous machine.

Given that the stabilizers of power systems are being analyzed in an introductory manner and how it is desired to maintain the theoretical rigidity that has been developed in all this research work, the derivation of the mathematical model for the PSS analysis will be carried out through the system of a synchronous machine connected to an infinite bus through a transmission line or SMIB (single-machine infinite bus), which is the simplest case, presented in Fig. 3.

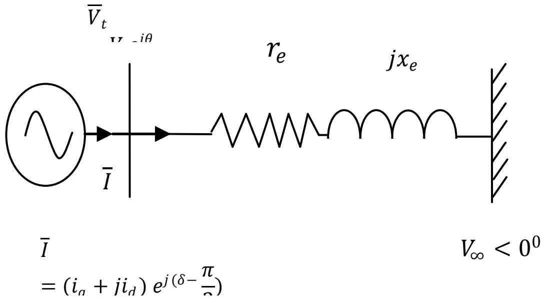

Figure 3 System of a synchronous machine connected to an infinite bus or SMIB [9]

The SMIB model is used to analyze the local oscillation mode of the system in the range of 1 to 3 Hz. This model is linearized with E_{fd} as an input. In addition, it is considered that the excitation system is represented by a model ST1A, which has a fast action between ΔV_t and ΔE_{fd}. In the resulting state-space model, certain constants called $K_1 - K_6$ are identified.

These constants are functions that depend on the point of operation. The derived state-space model can be useful for examining eigenvalues, as well as for designing supplementary controllers that ensure adequate damping of dominant modes of oscillation. The real and imaginary parts of the electromechanical mode are associated with the damping torque and the synchronization torque, respectively. The synchronous machine connected to an infinite bus through an external reactance x_e and a resistance r_e, is a configuration commonly used with the classic model of the synchronous machine, making the stator resistance equal to zero. It is assumed that there is no local load on the generator bus. Fig. 3 shows that system.

The stabilization signals derived from the machine speed deviation signal, the terminal frequency, or the electrical power are processed through the PSS by means of its GPSS (s) transfer function. Fig. 4 shows the model in block diagram of the SMIB system with the implementation of the PSS. From Fig. 4, the contribution of the PSS to the torque-angle loop, assuming $\Delta V_{ref} = 0$ and $\Delta\delta = 0$ (this implies that the speed deviation is very small and therefore the contributions of K_4 and K_5 can be neglected), is expressed by:

$$\frac{\Delta T_{PSS}}{\Delta\omega_r} = \frac{G_{PSS}(S)G_{ex}(S)K_2K_3}{G_{ex}(S)K_3K_6+\left(\frac{T_R}{K_3}+T_{d0}\right)(1+ST_R)} \quad (1)$$

$$\frac{\Delta T_{PSS}}{\Delta\omega_r} = \frac{G_{PSS}(S)G_{ex}(S)K_2}{\left(\frac{1}{K_3}+G_{ex}(S)K_6\right)S\left(\frac{T_R}{K_3}+T'_{d0}\right)+S^2T'_{d0}T_R} \quad (2)$$

$$\frac{\Delta T_{PSS}}{\Delta\omega_r} = G_{PSS}(S)GEP(S) \quad (3)$$

This expression can be approximated, for a common range of constants, as:

$$\frac{\Delta T_{PSS}}{\Delta\omega_r} = \frac{G_{PSS}(S)G_{ex}(S)K_2}{\left(\frac{1}{K_3}+G_{ex}(S)K_6\right)\left(1+S\frac{T'_{d0}}{G_{ex}(S)K_6}\right)(1+ST_R)} \quad (4)$$

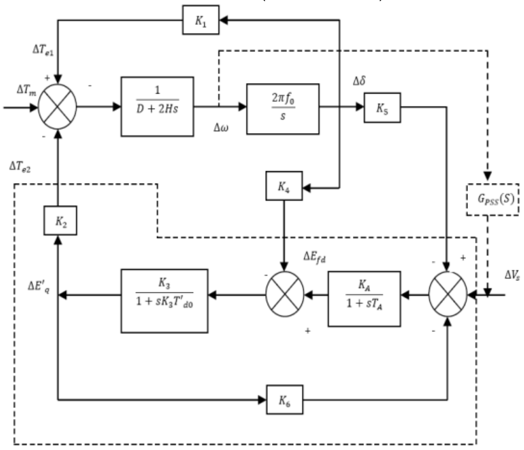

Figure 4 PSS with Heffron-Philips model of a single-machine infinite-bus system

Finally, for exciters with very high gain values, the expression (4) can be approximated by:

$$\frac{\Delta T_{PSS}}{\Delta\omega_r} = \frac{K_2}{K_6}\frac{G_{PSS}(S)}{\left(1+S\frac{T'_{d0}}{G_{ex}(S)K_6}\right)(1+ST_R)} \quad (5)$$

In case of providing pure damping throughout the entire frequency range, GPSS (s) would be a pure phase advance feature with zeros:

$$G_{PSS}(S) = K_{PSS}\left(1+s\frac{T'_{d0}}{G_{ex}(S)K_6}\right)(1+ST_R) \quad (6)$$

Where K_{PSS} is the profit of the PSS. This function is a mathematical detail and cannot be done physically. If the above is taken into account, a phase advance-delay function must be used to provide sufficient phase advance through the desired frequency range. The transfer function of the PSS normally used is given by:

$$G_{PSS}(S) = K_{PSS}\frac{(1+sT_1)}{(1+sT_2)}\frac{(1+sT_3)}{(1+sT_4)}\frac{sT_W}{(1+sT_W)} = K_{PSS}G_1(S) \quad (7)$$

The time constants T_1, T_2, T_3, T_4 must be adjusted to provide damping in the frequency range in which the oscillations normally occur. Through this range, these constants must compensate for the phase lag introduced by the synchronous machine and the regulator. Typical values of these constants are presented in the IEEE Std. 421.5-1992 standard and in computer models for representation of digital-based excitation systems [20].

The gain of the PSS is initially obtained by finding the gain to which the system is made unstable. This can be obtained by a test or by a diagram of the locus of the roots. T_W, the gain of the filter passes high, ensures that there is no steady state error of reference voltage due to the deviation of the speed, it generally adjusts to 10 seconds.K_{PSS} is set to a value of $\frac{1}{3}K^*_{PSS}$, where K^*_{PSS} is the gain under which the system is unstable.

In previous section the linearized equations are derived for proposed Power System Stabilizer (PSS). This section optimizes the parameters of PSS using Artificial Bee Colony Algorithm.

4.2 Fitness Function for PSS

$$f(d_v) = \int_0^t |(d_r - d_v)|\, dt \quad (8)$$

Where,

$d_r = 0$ (Reference speed deviation)

$d_v = f(v)$ (Actual speed deviation due to control variable v)

The control variable v can be given as:

$v = \{K, T_W, T_1, T_2, T_3, T_4\}$

Also v can be given for others like this.

Minimizing $f(d_v)$ will make$d_v = 0$. This is desired.

This fitness function is in terms of Integral time absolute error (ITAE)

4.3 Artificial Bee Colony (ABC) Algorithm

Artificial Bee Colony (ABC) optimization metaheuristic approach that is inspired by the natural model of behaviour of honey bees in the search for their food.

The foraging process in bees is based on a very efficient movement mechanism. It allows them to draw the attention of other bees from the colony to food sources found in order to collect various resources. In fact, bees use a set of wriggling dances as a means of communication between them. These dances allow bees to share information about the direction, distance and quantity of the nectar with its congeners. The collaboration and the collective knowledge of the bees of the same colony are based on the exchange of information on the quantity of the nectar in the food source found by the different members.

In a bee colony optimization algorithm, a source of nectar corresponds to a possible solution to the problem to be treated. The colony of artificial bees is composed of three types of bees: the workers, the spectators and the scouts:

- The worker exploits the food source found. It is based on its memory and tries to make changes to its current position (solution) to discover a new position (i.e. food source).
- The spectator waits for the workers to return to the dance floor to observe their dances and gather information on the sources of nectar they have found.

- The Scout bee exploits the search space by launching a random search of a new food source.

4.1.1 Initialization of the Algorithm

The initial solution population consists of an NFS number of randomly generated food sources in the search space. Assuming that the i^{th} food source of the population is represented by $X_i = [x_{i1}, \dots x_{ij}, \dots, x_{in}]$ where n is the dimension of the problem, then each food source is generated by:

$$x_{ij} = X_{\min j} + rnd(0,1)(X_{\max j} - X_{\min j}), j = 1, \dots n, i = 1, \dots, N_{FS} \quad (9)$$

These food sources are randomly assigned to the worker N_0 of the hive and the values of the corresponding cost functions are evaluated. We will assume here that $N_0 = N_{FS}$.

Similarly we will assume that the number of bees spectators N_S is equal to N_0. Finally each food source has an abandon counter initialized to 0. The k^{th} iteration consists of successively performing the three phases described below.

Worker Phase: In this phase, each employed bee generates a new food source x_{new} chosen near the position currently found:

$$x_{new_{ij}} = x_{ij} + rnd(-1,1)(x_{ij} - x_{kj}), \; i = 1, \dots, N_0 \quad (10)$$

Where $k \in \{1,2,3, \dots N_{FS}\}$ such that $k \neq i$and $j \in \{1,2,3, \dots n\}$, are randomly chosen.
We then proceed to a selection after evaluation of the cost function for this new solution. X_{new} replaces X_i in the population if
$f(X_{new}) \leq f(X_i)$ (and its abort counter is reset) otherwise X_i is retained and its abort counter is incremented.

Spectator Phase: In this stage the spectators recover from the workers of the information on the quantity of nectar of the source X_i. The probability p_i that spectators choose the source X_i is determined as follows:

$$p_i = \frac{fit_i}{\sum_{k=1}^{N_{FS}} fit_k} \quad (11)$$

Where fit_i is the quantity of nectar of the i^{th} food source X_i.
The following expression is also found in the literature [21]:

$$p_i = 0.1 + \frac{0.9 fit_i}{\max_k (fit_k)} \quad (12)$$

The quantity of nectar associated with the source X_i is determined by:

$$fit_i = \begin{cases} \frac{1}{1+f(X_i)}, & if\ f(X_i) \geq 0 \\ 1 + |f(X_i)|, & if\ f(X_i) < 0 \end{cases} \quad (13)$$

According to equations (11) and (13), it is clear that the higher the fit_i, the greater the probability of selecting the corresponding source X_i.

Once the i^{th} source is selected by the spectators, they make a modification using equation (10).
If the source thus modified is better than X_i then the modified source replaces X_i in the population (its abort counter is then reset), otherwise X_i is kept and its abort counter is incremented.

Scout Phase: The i^{th} food source is abandoned if it cannot be improved after a predetermined number of T_{limit} tests (i.e. if its abandon counter exceedsT_{limit}) and the corresponding worker bee becomes a scout bee. The scout bee then generates its food source randomly:

$$x_{ij} = X_{\min j} + rnd(0,1)(X_{\max j} - X_{\min j}), \; j = 1, \dots, n \quad (14)$$

4.1.2 Pseudo-code for the ABC Algorithm

For each worker
Generate an initial solution X_i for each worker with (9),
Evaluate the function of cost $f(X_i)$
Evaluate the amount of nectar (fit_i) associated using (13),
Initialize an abort counter $C_i = 0$.
As long as the stopping criterion is not satisfied, repeat:
  Work phase
    For each worker
      Generate a new X_{new} position with (10),
      Evaluate the corresponding cost function f(X_{new}),
      Evaluate the amount of nectar (fit_{new}) using (13),
      if $f(X_{new}) \leq f(X_i)$, then
        $X_i \leftarrow X_{new}$
        $C_i = 0$
      else
        $C_i = C_i + 1$
      end if
end for
Evaluate the probability of information transmission associated with each source p_i using (11),
Spectator phase
For each spectator
      if$rnd(0,1) < p_i$
        Generate a new X_{new} position with (10),

Evaluate the corresponding cost function $f(X_{new})$,
Evaluate the amount of nectar (fit_{new}) using (13)

if $f(X_{new}) \leq f(X_i)$, then

$$X_i \leftarrow X_{new}$$
$$C_i = 0$$

else

$$C_i = C_i + 1$$

end if
Scout phase
For each scout
if $C_i \geq T_{limit}$
Generate a new position with (14),
Evaluate the corresponding cost function
Evaluate the amount of nectar (fit_i) using (13),

$$C_i = 0$$

Remember the best solution X_{best}
End as long as

4.1.3 Stopping Criterion

Several stop criteria can be used. We will remember:

- The number of iterations maximum, knowing that at each iteration, the cost function must be evaluated P times
- A maximum number of evaluations of the cost function
- The premature convergence of the algorithm that is detected when all the particles tend to be identical, that is to say when the following relation is satisfied:

$$\exists X_{best} : \frac{max_{\,i=1,\ldots,P} \left\| X_i^{(k)} - X_{best} \right\|}{\| X_{max} - X_{min} \|} < \varepsilon \qquad (15)$$

We will choose in most cases $\varepsilon = 10^{-5}$.

4.1.4 Variants of the Algorithm

The basic parameters of the algorithm are the number of N_{FS} food sources, the number of N_0workers, the number of N_S spectators, and thelimit (T_{limit}) from which the food source is to be abandoned.
The standard version of the algorithm is to take:

$$N_{FS} = N_0 = N_S \qquad (16)$$

There are only two parameters left to adjust.

Although an N_{FS} population size of the order 10n is generally recommended, the algorithm gave its best results using:

$$N_{FS} = floor(10 + \sqrt{n}) \qquad (17)$$

Finally in the literature, it is recommended to choose [22]:

$$T_{limit} = n \times N_{FS} \qquad (18)$$

V. EXPERIMENTAL SETUP

5.1.1 Simulation Parameters

1. Generator:H = 3.5, M = 2H, TdO‘ = 7.76, D = 0, Xd = 0.973, Xd = 0.19, Xq = 0.55, Xe = 1.08.
2. Excitation system: KA = 200, TA = 0.
3. Transmission line and Transformer: =0.0 + j0.8 (XL = j0.7, XT = 0.1)
4. Field circuit: K3 = 0.4494, T3 = 3.9336.
5. SMIB K constants: K1 = 0.5320, K2 = 0.7858, K4 = 1.0184, K5 = −0.0597, K6 = 0.5746.
6. Operating points:

- P = 1.0, Q = 0.6, D = 0, Et = 1.1, Frequency = 60 Hz.
- P = 1.1, Q = 0.8, D = 0, Et = 1.1, Frequency = 60 Hz.
- P = 1.2, Q = 0.9, D = 0, Et = 1.1, Frequency = 60 Hz.

The optimization was held by bounded search. Various parameters used for proposed strategy are listed in Table-1. Certain parameters are utilized for tuning purpose are; KP, T1P, T2P, T3P and T4P. The parameter with subscript P shows they have a place with PSS Control.

Table 5.1: Max. / Min. values measured for parameters

Parameter	Range
Kp	30-80
T1p	0.1-0.6
T2p	0.02-0.4
T3p	0.1-0.6
T4p	0.02-0.4

Table 5.2: Parameter utilized in ABC algorithm

Parameter	Value
Colony size	40
Iteration	200
Food number	20
Round	1

5.1.2 Results

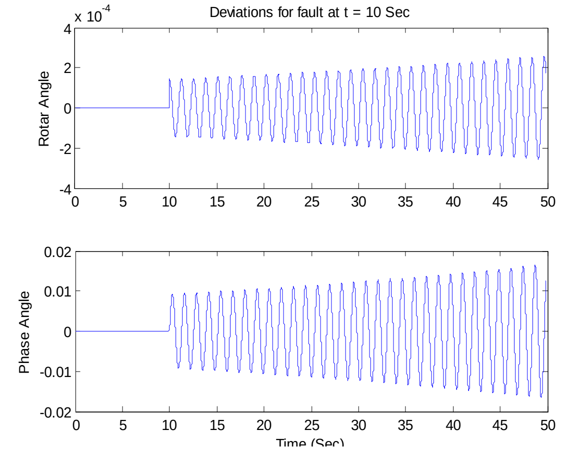

Figure 5 Rotor angle and phase angle deviations in SMIB-PSS without optimization

When a fault occurs in the SMIB system at t=10 Sec, rotor and phase start deviation and if no control is there than oscillation become higher as shown above.

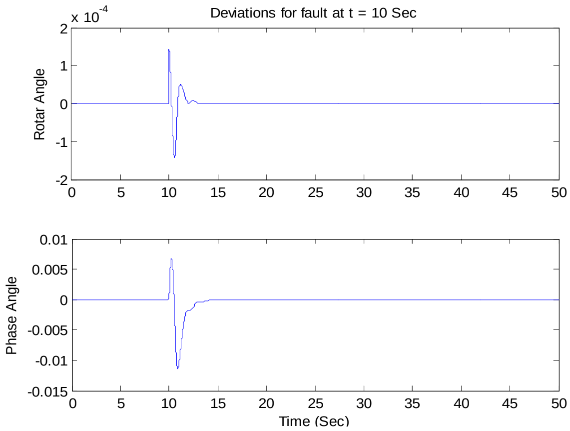

Figure 6 Rotor angle and phase angle deviations in SMIB-PSS optimized with ABC Algorithm

When a fault occurs in the SMIB system at t=10 Sec, rotor and phase start but with ABC-Optimized PSS it stables very fast (within 14 Sec) as shown above.

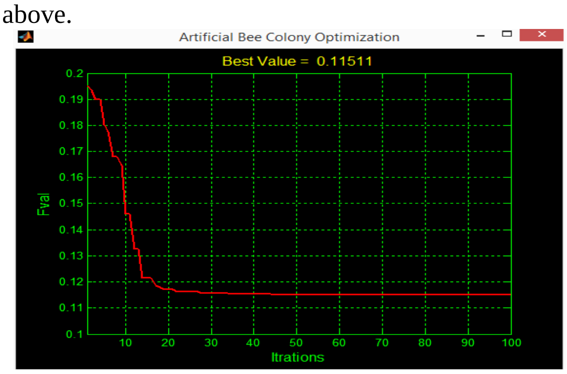

Figure 7 Convergence plot of Artificial Bee Colony Algorithm

Fig. above show the convergence of solution by ABC toward the optimal solution. This shows that ABC got its solution very fast and it is also not premature convergence.

VI. CONCLUSION

This paper considered linearize Haffron-Philips model of single machine infinite bus system to investigate the instability generate in power system due to small signal disturbance and the elimination of this disturbance. Excitation controllers are capable of maintaining better dynamic performances and of guaranteeing the robustness of stability of the system studied in the face of disturbances including system uncertainties under different operating modes. The study presented in this paper deals with the application of Artificial Bee Colony (ABC) Algorithm in the optimization of the PSS parameters of the stabilizing device of the power system. The aim of the paper is to provide the necessary damping to the electromechanical oscillations of the generators, when the system undergoes perturbations around its operating point. A fitness function is derived which is aimed to minimize rotor speed deviation as a function of stabilizers parameter. It is found that with the proposed tuning method the stabilizer gives stable study state.

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