Australian Journal of Basic and Applied Sciences, 10(12) July 2016, Pages: 102-109

AUSTRALIAN JOURNAL OF BASIC AND APPLIED SCIENCES

ISSN:1991-8178 EISSN: 2309-8414
Journal home page: www.ajbasweb.com

Design of Coordinated Controller using BBO Algorithm for Synchronous Machine Speed Control

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ARTICLE INFO

Article history:
Received 26 April 2016
Accepted 21 July 2016
Published 30 July 2016

Keywords:
SMIB; PID controller; PSS design; BBO algorithm;

ABSTRACT

Stabilization of low frequency oscillations (LFO) is one of the most important phenomena in power system operation. Basically the automatic voltage regulator (AVR) and generator field coil will produce damping torque to suppress these oscillations automatically. If LFO are not properly controlled, it will damage the system and the relay pick will block out the generator from the system. To overcome this drawback, Conventional Power System Stabilizer (CPSS) is applied to the electrical machines in power system. Despite its popularity, CPSS faces a significant drawback, which is the parameters were tuned and fixed for certain operating conditions. Since power system in non-linear, it is necessary to provide adaptive based PSS. This study proposes a new meta-heuristic Biogeography based optimization (BBO) algorithm to design the coordinated controller (PID controller & Power system stabilizer (PSS)) for stability enhancement in power system. The design of BBO PID-PSS is considered as an optimization problem to damp out the low frequency oscillations (LFO) in the rotor of synchronous machine. This objective can be achieved by minimizing the performance index (PI) such as Integral square error (ISE) using BBO algorithm for wide range of operating conditions. To examine the robustness of BBO PID-PSS, it has been tested on a single machine infinite bus (SMIB) power system under different disturbances and operating conditions. Further, the simulation results obtained using BBO based PID-PSS are compared with Particle Swarm Optimization (PSO) based PID-PSS, Adaptation law (AL) based PID-PSS and Conventional PSS in MATLAB environment. Analysis of results shows that BBO based PID-PSS yield faster convergence rate and superior robust performance for enhancement of power system stability compared to other methods.

INTRODUCTION

Power system stability is defined as the ability of power system to converge or stay closer to equilibrium state when subjected to disturbances such as change in load, fault conditions etc. Generally, the power systems are non-linear, complex and exhibits low frequency oscillations due to insufficient damping torque. These oscillations are in the range of 0.1 – 2.5 Hz with small magnitude and persist for long period of time and present limitations on power transfer capability. The LFO oscillations should be controlled properly otherwise this will damage the system and relay pick will block out the generator from the system. To overcome this drawback, PSS is widely used to damp out the LFO and to enhance the stability of the electrical machines in power system. A PSS acts as a feedback controller that is connected to the excitation system of electrical machine through automatic voltage regulator (AVR). The conventional PSS (CPSS) parameters were designed based on linear control theory and can be operated for certain operating conditions. And it has drawbacks such as time consuming tuning and non-optimal damping for other operating conditions (Kundur, 1993). Since the power

To Cite This Article: Gowrishankar Kasilingam and Jagadeesh Pasupuleti., Design of Coordinated Controller using BBO Algorithm for Synchronous Machine Speed Control. ***Aust. J. Basic & Appl. Sci.,*** *10(12):102-109, 2016*

systems are almost nonlinear, the conventional PSS does not assure optimal damping in the operating process and even the system may become unstable. This is because the parameters of PSS were fixed for certain operating conditions will not be satisfactory for other operating conditions. Later artificial intelligence techniques have been used to reduce this drawback to a great extent, but these methods are complex and costlier, even sometimes these methods do not provide good optimization and tend to produce surges and overshoots (El-Metwally, 2010; Segal *et al*., 2004). Then researcher's attention turns towards the random search algorithms such as Genetic Algorithm (GA), Evolutionary programming, Differential Evolution etc. to enhance the conventional PSS tuning techniques (Duman and Oztruk, 2010; Abido and Abdel, 2002; Zhe sun *et al*., 2014). Even though, these methods were suitable for solving complex problems, it has some drawbacks on applying to real time systems such as poor premature convergence, optimization response time (computational complexity) and no assurance of finding global optimum solution.

Then, research interests are more concentrated on swarm intelligence (SI) techniques due to their ability to produce accurate results within a reasonable time and adaptation to wide range of operating conditions while tuning the parameters of PSS (Sheeba *et al*., 2014; Al Habri, 2009). Many research papers have been published using SI techniques to tune the parameters of PSS, which includes Artificial Bee Colony (ABC Algorithm, Ant colony optimization (ACO), Particle swarm optimization (PSO) etc.

On analyzing the drawbacks from the existing optimization techniques, this paper proposes a new meta-heuristic Biogeography based optimization (BBO) algorithm to design the coordinated controller (PID controller & Power system stabilizer (PSS)) for stability enhancement in power system. An attempt has been made of combining PID controller and power system stabilizer to increase the efficiency of synchronous machine. The parameters of coordinated controller have been optimized using BBO algorithm. Roy *et al*. (2010) approached BBO algorithm for power flow problem considering valve loading effects. Then, Tissa and Rinku (2013) proposed BBO algorithm for active and reactive power compensation in distribution system. Further, Lakshmi and Karthikeyan (2012) investigated PID controller design to improve rotor angle stability using BBO algorithm.

From the literature survey, the proposed BBO algorithm reveals better solution quality and computation efficiency over the other optimization methods. Therefore an attempt is made in this paper by proposing the BBO algorithm to optimize coordinated controller in order to enhance the stability of the power system subjected to different operating conditions. The simulation results are tested with other optimization techniques such as PSO algorithm and adaptation law.

Background:

Power system stabilizer (PSS):

Power system stabilizer is a feedback controller connected to the excitation system through AVR to generate supplementary feedback stabilizing signals to suppress the low frequency oscillations. Conventional power system stabilizer (CPSS) is designed based on stabilizer gain (K_{stab}), washout time (T_w) and lead - lag compensator (T_1 & T_2). The input signal given to the PSS is the speed deviation signal ($\Delta\omega$) and output is the stabilizing signal (ΔV_{PSS}). The parameters to be optimized in PSS are K_{PSS}, T_1 and T_2.

$$V_{PSS} = K_{PSS} \frac{sT_W}{1+sT_W} \frac{sT_1+1}{sT_2+1} \qquad (1)$$

Proportional Integral Derivative (PID) controller:

Proportional Integral Derivative (PID) controller is one of the earliest control technique widely used in industrial control system, because of its robust performance and easy implementation. The PID calculation involves three parameters: Proportional (K_P), Integral (K_I) and Derivative (K_D) gains.

$$V_{PID} = K_P + \frac{K_I}{s} + K_D s \qquad (2)$$

PID – PSS Structure:

In view of the advantage of a PID controller, this paper proposed a method of combining the PID controller and PSS in parallel to enhance the stability of a synchronous machine connected to a linear-load. The robust performance of the PID controller involves choosing the parameters: K_P, K_I and K_D, which provide satisfactory closed loop performance. The block diagram of PID – PSS structure is shown in Fig. 1.

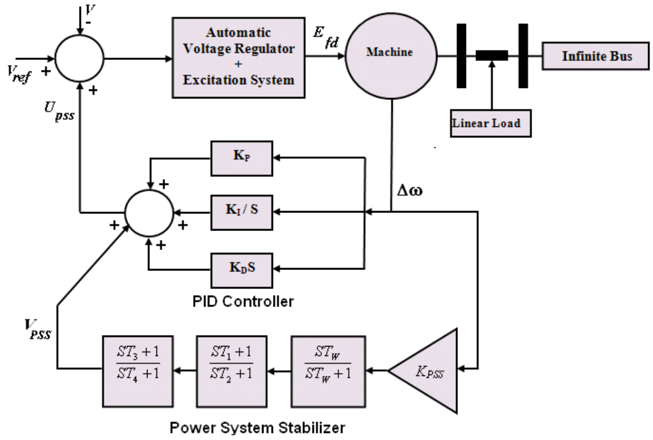

Fig. 1: PID - PSS Structure

From Fig. 1 the U_{PSS} can be written as:

$$U_{PSS} = \left[K_P + \frac{K_I}{s} + K_D s \right] \Delta\omega(s) + V_{PSS} \tag{3}$$

Methodology:

Particle Swarm Optimization (PSO) Algorithm:

PSO algorithm is an optimization technique used to find the optimal solution for the different parameters needed. This technique is inspired by the intelligence of birds flocking and fish schooling. The concept of PSO consists in moving a pre-defined number of particles throughout the searching space in order to find the local best and global best solutions. The movement of particles is defined by the social interaction between the individuals from population. PSO is a method to improve the speed of convergence and find the optimum value of fitness function (Gowrishankar and Jagadeesh, 2014).

PSO parameters and the values are: Iteration K_{max} = 50; Generation N = 20; w_{min} = 0.4; w_{max} = 0.9; C_1 & C_2 = 2. The PSO algorithm used to solve the optimization problem and search the optimal set of PSS parameters. The range of PID and PSS parameters using PSO algorithm are: $0 \le K_P \le 9$, $0 \le K_I \le 1.2$ and $0 \le K_D \le 1.9$, $0 \le K_{PSS} \le 110$, $0 \le T_1 \le 3$ and $0 \le T_2 \le 0.2$.

Adaptation Law Technique:

Adaptation law is used to identify system parameters and optimize the gain of PID stabilizer to bring the system to stable state. The tuning of PID gains is based on eigen value placement method. The self-tuning gains of the PID controller (Gowrishankar and Jagadeesh, 2014)

$$K_P = (s_1 + 2s_2)/(1 + r_1) \tag{4}$$

$$K_I = -(s_0 + s_1 + s_2)/T_S \tag{5}$$

$$K_D = ([r_1 s_1 - (1 - r_1)s_2]/(1 + r_1))T_S \tag{6}$$

The gains, K_P, K_I and K_D, are computed at each sampling instant using the present estimated values of the four coefficients a_1, a_2, b_l and b_2, characterizing the dynamic behavior of the generator at that instant.

The gain settings of PID controller are computed at each sampling instant using the present values of estimated coefficients. The optimized PID controller combined with PSS for the excitation control of synchronous generator. The values of PSS parameters are: K_{PSS} = 125; T_w = 2; Lead–lag time constants, T_1 = 5000 and T_2 = 2000.

Biogeography Based Optimization (BBO) Algorithm:

Biogeography based optimization (BBO) is first introduced by Dan Simon (2008). BBO technique is a new population-based technique of Evolutionary Algorithm (EA) has been developed based on the concept of Migration and Mutation. The concept and mathematical formulation of migration and mutation for optimization of parameters were explained below.

Migration:

Each value of K_P, K_I, K_D, K_{PSS}, T_1 and T_2 in the solution vector is considered as Suitable Index Value (SIV). In order to know how good or bad the habitat (solution), computation made on the habitat suitability index (HSI). To optimize the PID and PSS parameters, HSI would be considered as the objective function. In this paper, integral square error (ISE) of the speed deviation (Δω) is considered as the objective function. The parameters of the PID and PSS were tuned using performance index (ISE) (James *et al*., 2009)

The fitness function is as following:

$$ISE : J = \int_{0}^{\infty} \Delta\omega^2(t)dt\,, \quad \infty = t_{sim} \tag{7}$$

The speed deviation (Δω) is the parameter chosen to evaluate the performance of the design system. In BBO we say that habitat with high HSI has a lot of species whereas habitat with low HSI has a few species. Eventually the number of species will help us to decide the immigration rate and emigration rate of each habitat.

Mutation:

Mutation in BBO considered as SIV mutation, which is K_P, K_I, K_D, K_{PSS}, T_1 and T_2 values in a habitat. The species count probability is used to determine the mutation rate. A very low HSI and a very High HSI has less chance to mutate as compare to a habitat that has medium HSI. The reason is, the habitat which has a very high HSI and very low HSI are given a chance to further improve their performance, whereas, medium HSI unlikely to mutate due to the habitat might have a solution. The following flow chart explains the BBO algorithm for tuning the PID parameters shown in Fig.2 (Gowrishankar and Jagadeesh, 2015).

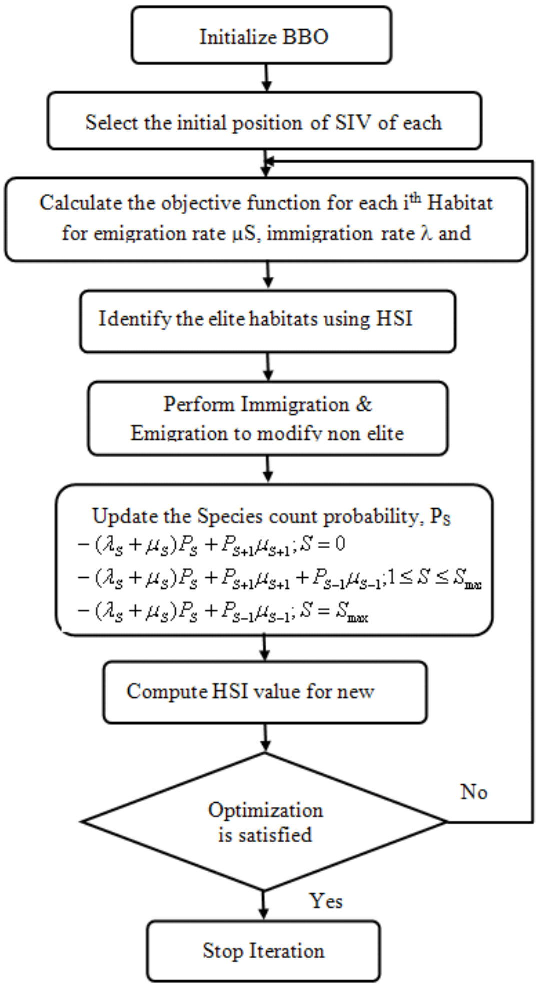

Fig. 2: BBO algorithm for optimization

The ranges of optimized parameters of the PID controller and PSS are:

$K_P^{\min} \le K_P \le K_P^{\max} = 0.5 \le K_P \le 80$;;

$K_I^{\min} \le K_I \le K_I^{\max} = 0.2 \le K_I \le 30$;

$K_D^{\min} \le K_D \le K_D^{\max} = 0.1 \le K_D \le 15$;

$K_{PSS}^{\min} \le K_{PSS} \le K_{PSS}^{\max} = 1 \le K_{PSS} \le 60$;

$T_1^{\min} \le T_1 \le T_1^{\max} = 0.2 \le T_1 \le 2$;

$T_2^{\min} \le T_2 \le T_2^{\max} = 0.2 \le T_2 \le 2$.

BBO parameters and the values are: Habitat modification probability = 1; Population number = 50, Mutation rate = 0.5, iteration count = 50, No. of elite habitat = 3, Max. Emigration & immigration rate = 1.

Model Of Proposed System:

The proposed system combines a PID controller with a PSS to provide better performance for a different range of operating conditions. The simulink model of the proposed system is shown in Fig. 3. In the proposed system, BBO algorithm is used to optimize the PID gains and PSS parameters of coordinated controller to enhance the stability of the synchronous machine for the wide range of operating conditions. The speed deviation ($\Delta\omega$) from the generator, is given as the input to the proposed coordinated controller. The Output of the coordinated controller provides the electrical damping torque in phase with the speed deviation. The controller output is given to the excitation system through AVR. The aim is to control the phase difference between the generator and load.

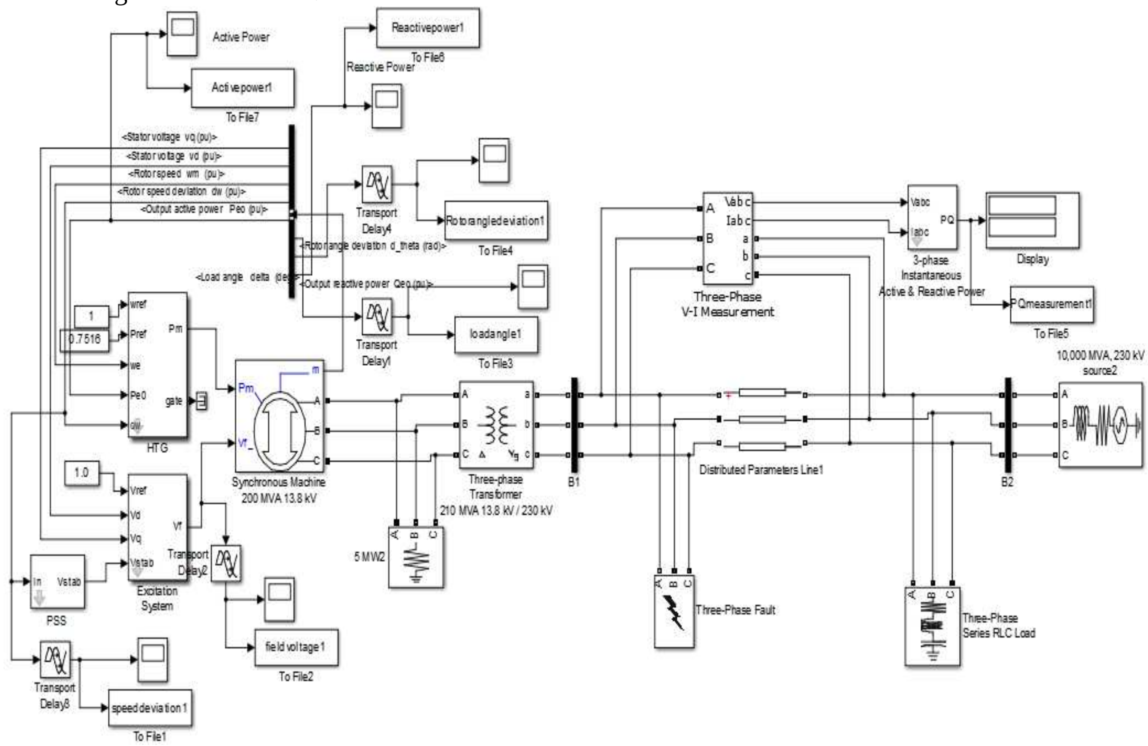

Fig. 3: Simulink model of SMIB system

Simulation Results:

To analyze the performance of coordinated controller, a model of SMIB system was developed in MATLAB Simulink environment and investigated over different operating conditions. The effectiveness of proposed BBO algorithm and other conventional techniques such as PSO algorithm and adaptation law method was thoroughly investigated under different case studies.

Iteration comparison graph for BBO PIDPSS and PSO PID PSS is given in Fig.4. From the plot, observation shows that BBO algorithm is having better convergence than PSO algorithm.

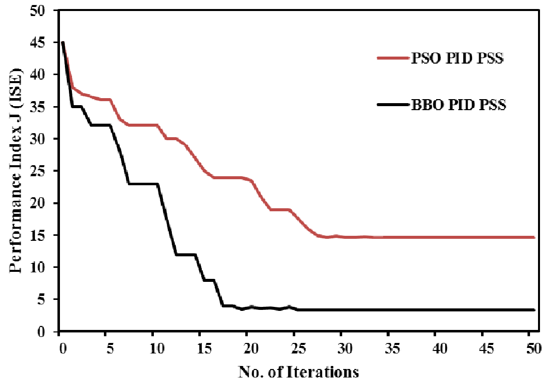

Fig. 4: Comparison of fitness function

The statistical indices mean (M) and standard deviation (σ) of algorithms are given by,

$$M = \frac{\sum_{i=1}^{n} f(K_i)}{n} \tag{8}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f(K_i) - M)^2} \tag{9}$$

Where $f(K_i)$ the fitness value of individual K_i and n is the population size.

The comparison of BBO algorithm and PSO algorithm with respect to statistical data analysis is shown in Table I.

Table I: Comparison of Computation Efficiency

Optimization Methods	Max.	Min.	Range	Mean (M)	Standard. Deviation (σ)
PSO	45	14.6	30.4	21.90	8.6291
BBO	45	3.4	41.6	10.376	11.356

The performance of BBO PID-PSS, PSO PID-PSS, AL PID-PSS and CPSS were simulated and analyzed in the Matlab Simulink environment for different operating conditions and the following test cases was considered for simulations.

Base load condition:

Under base load condition the synchronous machine is subjected to 100MW load (Active Power P = 200MVA; Inductive reactive power Q_L = 80MVA; Capacitive reactive power Q_C = 80 MVA) with ground fault condition in the transmission line. The performance of coordinated controller was analysed in simulink environment. The parameters of PID ans PSS were tuned based on BBO, PSO and Adaptation law in Matlab Simulink. Fig. 5 shows the response of speed deviation for case 1.

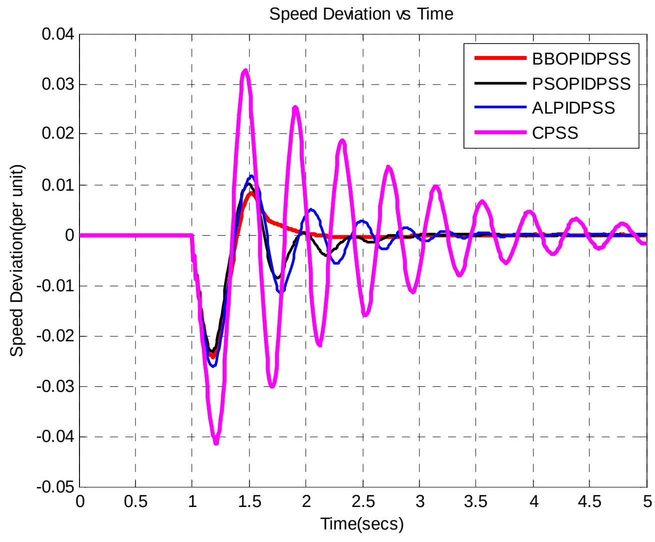

Fig. 5: Speed deviation for base load condition

Increasing in load with fault condition:

In this case, the synchronous machine subjected to increasing in load (3 times × normal load) of Active Power P = 600MVA; Inductive reactive power Q_L = 480MVA; Capacitive reactive power Q_C = 480 MVA) with 3ϕ fault condition in the transmission line. In 3ϕ fault condition, the fault switching of phase A, phase B and phase C are activated. The initial status of the fault breaker is usually 0 (open). In 3ϕ fault condition, the transition time is applied at t = 0.6/60 secs and closed at t = 6/60 secs in the transmission line similar to the ground fault i.e. the fault persists in the system for 0.01 sec and it is cleared after 0.1 sec. The performance analyses of the system during fault condition are illustrated in Fig. 6.

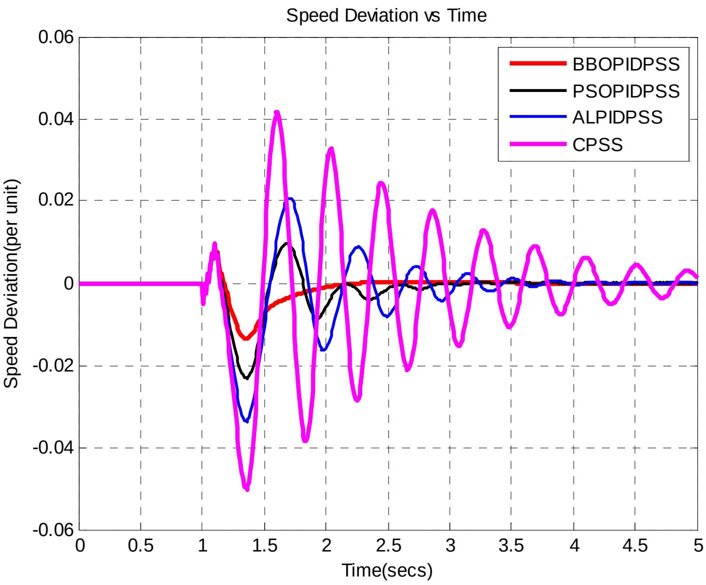

Fig. 6: Speed deviation for increasing in load with fault condition

Fig. 5 and 6 confirms the robustness of the BBO algorithm over PSO algorithm, adaptation law and CPSS. The values of the PID gains and PSS parameters of coordinated controller obtained using three methods are presented in Table II.

Table II: Parameters of Coordinated Controller

Tuning – method		PID gains			PSS Parameters		
		K_P	K_I	K_D	K_{PSS}	T_1	T_2
BBO Algorithm		52.6	20.2	9.73	31.7	0.8	0.38
PSO Algorithm		5.14	0.9	1.63	74.6	1.87	0.074
Adaptation law	Normal load with ground fault	- 0.26	- 1.5	1.24	125	5000	2000
	Heavy load with 3ϕ fault	-0.25	-1.4	1.12			

Conclusion:

This paper proposes a novel BBO algorithm to determine the optimal parameters of PID controller and PSS. The design problem of tuning the PID gains and PSS parameters is converted into an optimization problem which is solved by BBO algorithm and conventional methods. The proposed method was used with a typical SMIB power system is compared with PSO algorithm and AL method for various cases such as base load and increasing in load with fault condition. We conclude from simulations that the PSO and adaptation law methods are not effective because the settling time is long and there are oscillations, even though they stabilize the system. It is observed from simulation results that the proposed method successfully suppressed the low frequency oscillations of the rotor speed and enhance the stability of the power system compared to other methods.

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