Comparative Performance Analysis of PSO based FOPID plus Second Order Derivative Controller for AVR system in a Synchronous Generator

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Abstract: *In any power plant or grid, the controller increases the production capacity and the energy savings. However, in the conventional Proportional, Integral and Derivative controller the uncertain parameters and the load disturbances will result in reducing the system robustness. Instead of integer order controller, Fractional order controller gives the better robustness. This paper proposes a novel Fractional Order Proportional, Integral, Derivative plus second order derivative controller for Single Machine connected to an Infinite Bus with Automatic Voltage Regulator on the synchronous generator. The controller objective is to minimise the Integral Absolute Error through optimum gain values in order to minimize the effect of external disturbances and measurement noise present in the system. Particle Swarm Optimisation algorithm is used to obtain the best possible gain values. Saturation and damping elements are used to improve the system dynamic performance. The proposed controller performance is compared with the controllers such as PID, PIDD^2 and FOPID controllers. The robustness of the AVR system is improved with respect to model uncertainties like non-linearity and external disturbances using this proposed controller.*

Key words: *Automatic Voltage Regulator, Fractional Order controller, IAE, PSO algorithm.*

Nomenclature:

AVR   - Automatic Voltage Regulator
PID   - Proportional, Integral and Derivative Controller
$PI^\lambda D^\mu$/FOPID - Fractional Order Proportional, Integral and Derivative Controller
PIDD^2 - Proportional, Integral, Derivative plus Second Order Derivative Controller
$PI^\lambda D_1^\mu D_2^{(\mu_1+\mu_2)}$ - Fractional Order Proportional, Integral, Derivative plus Second Order Derivative Controller
PSO   - Particle Swarm Optimization
IAE   - Integral Absolute Error
k_p - Proportional gain
k_i - Integral gain
k_{d1} - Derivative gain
k_{d2} - Second order derivative gain
λ - Integral order
μ - Derivative order
$\mu1$ and $\mu2$ - Second order derivative orders

1. Introduction

The electric utility is responsible for voltage control of the utility system and the Automatic Voltage Regulator (AVR) is used for voltage control in synchronous generator. The conditions to be maintained in the utility system are: voltage regulation, thermal ratings of equipment are being not exceeded, fault ratings of switchgear and cables being not exceeded. The voltage disturbance affected in terms of step changes, flicker and harmonics and they are kept in minimum and within allowable limits. For large generators, it may be necessary to perform some degree of automatic voltage control to maintain the feeder voltage. In distributed wind power generation applications, the turbines are to be sited in some distance from the substation. These places require special challenges on feeder voltage regulation. AVR is used to regulate the voltage in any of the generating unit using the synchronous generator. It is essential to enhance the AVR overall performance and ensure robust response to transient changes in terminal voltage.

Different control structures have been proposed for the AVR system. Proportional, Integral plus Derivative controller (PID) is the most preferable controller for all industrial applications. Now-a-days, power plants also use these types of controllers for getting reliable performance. On the other hand, Fractional Order (FO) PID controllers are also used in industries to enhance the plant performance. Applications of FO controllers for electrical power and energy systems are still largely unexplored. Few literatures are available on $PI^\lambda D^\mu$ controller for AVR system [1]. Fractional-order controllers demonstrated by many researchers, such as Podlubny [2] and El-Khazali [3]. FOPID is a generalisation of the PID in which the orders of derivative (μ) and integrals λ are non-integer. In earlier mechanical systems described by fractional-order state equations [4, 5] and recently electrical system employs these controllers. Fabrizio Padula et al. discuss the tuning rules for PID and FOPID [6] controllers. S. Das et al [7] proposed time domain FO fuzzy PID controller and the results are compared with PID, FOPID,

fuzzy PID and fuzzy FOPID with various performance indices. Pan and Das [8] proposed FOPID controller for AVR system using Chaotic Multi-objective optimization algorithm. The relative merits and demerits of conventional PID and FOPID are discussed with the results in frequency domain. Majid Zamani et al. designed FOPID controller for AVR using PSO algorithm and comparisons were made with the conventional PID controller. Results showed that FOPID highly improves the system robustness with respect to model uncertainties [9]. Four terms structure PID plus second order derivative (PIDD^2) controller are implemented by M. A. Sahib [10]. The results are compared with the MOL, GA, ABC, DEA and LUS algorithms.

There are many powerful intelligent searching algorithms which are used in industries. Such algorithms include Particle Swarm Optimization (PSO), Craziness based Particle Swarm Optimisation algorithm (CRPSO), Differential Evolution Algorithm (DEA), and Chaotic Ant Swarm (CAS) algorithm. PSO is easy to implement efficient algorithm, flexible and well-balanced mechanism to enhance global and local best values, and it has more efficiency than GA [11]. V.Mukherjee et al. [12] have proposed Craziness based particle swarm optimized fuzzy PID control (CRPSO) algorithm and the results are compared with the Genetic Algorithm PID controller algorithm (GA PID). Hui Zhu et al. have worked with Chaotic Ant Swarm PID (CAS-PID) algorithm for AVR and the results are compared with the GA-PID controller [14]. S.Panda et al. have proposed a Many Optimizing Liaisons PID (MOL) algorithm for AVR system and the results are compared with Artificial Bee Colony (ABC) algorithm [15]. AGPSO algorithm is used for the power loss minimisation in distribution network [23].

From the literatures, it is observed that, the conventional PID controller strength will lost if any load disturbances and external noise in the system. Whereas, Fractional order controller is used to resist the system with unexpected changes in the system. This paper proposes a new Fractional Order Proportional, Integral, and Derivative plus second order Derivative (FOPIDD^2 /$PI^\lambda D_1^\mu D_2^{(\mu_1+\mu_2)}$) controller design for AVR system. The proposed controller performance is analysed with the three cases. They are: a) without saturation and damping b) with saturation and damping and c) with noise and disturbances. The PSO optimisation algorithm is used to tune the eight unknown parameters, namely proportional gain (k_p), Integral gain (k_i,), Derivative gain (k_{d1}), second order derivative gain (k_{d2}), integral order (λ),

derivative order (μ) and second order derivative orders ($\mu1, \mu2$) in the proposed controller. The performance of the proposed controller is validated with other controllers such as PID, PIDD^2 and FOPID controllers. Based on the IAE value and transient response the controller performance is investigated in this work.

2. AVR system Model

In a power generating unit, the synchronous generator is one of the most important elements to improve the power system stability and quality of electrical power. Automatic Voltage Regulator is used to maintain the terminal voltage at a constant specified value in such synchronous generator. It consists of four main parts, namely amplifier, exciter, generator and sensor. Each component is modelled by a first order system defined by a gain and time constant. For mathematical modelling, the synchronous generator parts are supposed to be linear. The transfer function, gain and time constant of the components is given below in the Table 1.

Table 1. AVR system Components

Components	Transfer Function	Gain values	Time constant
Amplifier	$G_a = \dfrac{k_a}{\tau_a s + 1}$	10 - 40	0.02 – 0.1
Exciter	$G_e = \dfrac{k_e}{\tau_e s + 1}$	1 – 10	0.4 - 1
Generator	$G_g = \dfrac{k_g}{\tau_g s + 1}$	0.7 – 1	1.0 - 2.0
Sensor	$H_s = \dfrac{k_s}{\tau_s s + 1}$	0.9 – 1.1	0.001–0.06

From the literatures [11, 15, 19, 20, 21], the AVR system parameters considered in this work are:
$k_a = 10.0, \tau_{a=0.1}, k_e = 1.0, \tau_e = 0.4,$
$k_g = 1.0, \tau_g = 1.0, k_s = 1.0, \tau_s = 0.01$.
The schematic diagram of the AVR system is shown in Figure 1.
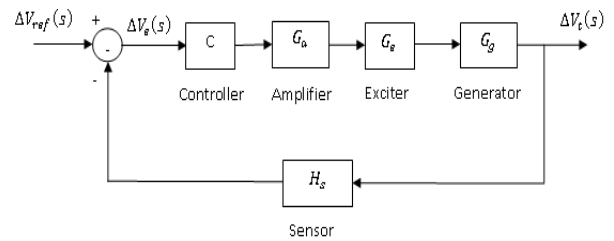

Fig.1. Block diagram of AVR system

The difference between the

reference input voltage and the sensor output signal gives the error signal. Controller minimizes this error signal based on the optimised controller gain parameters and the controlled output is drive the AVR system i.e., the exciter output is used to regulate the terminal voltage of the generator. The closed loop transfer function of the AVR system is given by

$$G_{clavr} = \frac{G_a G_e G_g}{1 + G_a G_e G_g H_s} \quad (1)$$

Where,

G_{clavr} — Closed loop transfer function for AVR system

$G_a G_e G_g$ - Amplifier, Exciter and Generator transfer function

H_s — Sensor transfer function

3. Controller design

3.1 Particle Swarm Optimization Algorithm

The PSO algorithm is considered to be one of the most optimization methods due to its simplicity, robustness, fast convergence and ease of implementation [18]. Flowchart of a PSO algorithm is shown in figure 2. PSO is based on the concept of evolutionary computational model, a stochastic search approach based on swarm intelligence. Social behavioural pattern of organisms such as hen flocking and fish training inspired them to seem into the effect of collaboration of species when achieving their goals as a group. PSO is primarily a population based optimization technique, where the population is referred to as 'swarm'. In a PSO system, more than one candidate solution coexists and collaborates simultaneously. Each answer candidate, known as a 'particle', flies in the problem house (similar to the search system for food of a chicken swarm) looking for the top of the line position. A 'particle' with time adjusts its position to its personal 'experience', while adjusting to the 'experience' of neighbouring particles. The new function of particles is calculated by adding their preceding function to their corresponding updated pace values. This updating speed of an every particle is an important step in PSO. The speed is updated the usage of the preceding speed (inertia), non-public influence (cognitive), and social impact (social) components. The inertia element prompts the particle to move in the same previous route and velocity. The cognitive factor improves the new particles position with the aid of evaluating it with the quality previous role observed associated with this particle. The social aspect makes the particle to follow the first-rate neighbour's direction. The velocity and position of each particle are calculated according to the following equations [12].
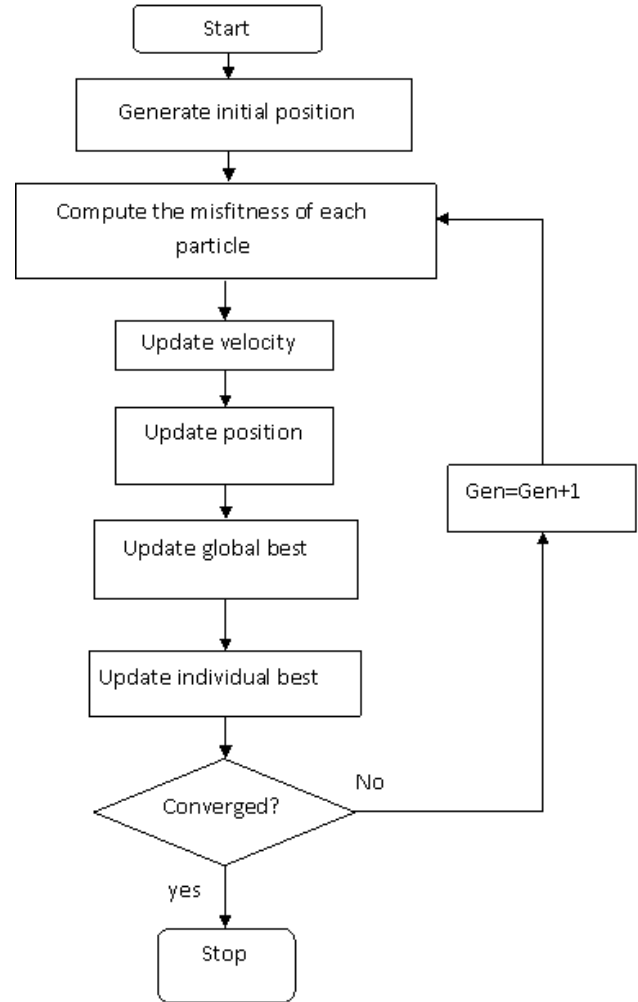

Fig. 2. Flow chart of PSO algorithm

Velocity equation:

$$v_i^{k+1} = v_i^k + c_1 r_1 \left(pBest_i - x_i^k \right) + c_2 r_2 (gBest - x_i^k)$$

$$(2)$$

Position equation:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (3)$$

Where i=1, 2,......L, and L is the number of population (swarm size); c_1 and c_2 are two positive constants, called the cognitive and social parameters respectively; r_1 and r_2 are random numbers uniformly distributed within the range [0,1]. Equation (2) is used to find the new velocity for the ith particle, while equation (3) is used to update the ith position by adding the new velocity obtained by equation (2). Steps involved in the PSO algorithm is, first initialize randomly

the velocities and positions of each particle. Based on fitness function update the velocity and position of each particle based on the equation (2 and 3). Next update the global and individual best. If the output is converged, the procedure is end, otherwise go to the next generation of the fitness function. Table 2 shows the PSO parameter values used in this work.

Table 2 PSO parameters

Parameter	Value
Number of iterations	100
Number of runs	20
Swarm size	20
Acceleration constants (c1 = c2)	1

The proposed fractional order controller parameters k_p, k_i, k_{d1}, k_{d2} and order parameters $\lambda, \mu, \mu1$ & $\mu2$ are the swarm variables.

3.2 Objective Function

IAE is used is an objective function to achieve the optimum controller gain and order values and it is given in equation (4)

$$IAE = \int_0^t |\Delta V_e(t)| dt \qquad (4)$$

Where,

$\Delta V_e(s) = \Delta V_t(s) - \Delta V_{ref}(s)$

$\Delta V_e -$ Change in error voltage (Volts)

$\Delta V_t(s) -$ Output voltage signal (Volts)

$\Delta V_{ref}(s) -$ Reference voltage signal (Volts)

In order to get the optimum controller values the objective error function value is minimized.

3.3 PSO based FOPIDD² Controller design

Contrary to the usual approach, this work considers the transfer functions of an arbitrary actual order. Such systems are named as the fractional-order systems. Fractional order systems which are based on fractional-order calculus, which is an extension of the integer order differentiation and integration for any arbitrary number [3].

This paper proposes a fractional order proportional, integral, derivative plus second order derivative ($PI^\lambda D_1^\mu D_2^{(\mu_1+\mu_2)}$) controller design and implemented in the AVR system. The structure of the proposed controller is given below,

$$C_{fopidd^2} = k_p + \frac{k_i}{s^\lambda} + k_{d1}s^\mu + k_{d2}s^{(\mu1+\mu2)} \qquad (6)$$

Where,

k_p - Proportional gain

k_i - Integral gain

k_{d1} - First derivative gain

k_{d2} - Second derivative gain

λ - Integral order

μ - First derivative order

$\mu1$ & $\mu2$ - Second derivative order

The extra second order derivative gain term k_{d2} and its order terms $\mu1, \mu2$ form the new controller equation. FOPIDD² controllers can be designed for plants with under damped step response. The proportional gain (k_p) in the controller is used to adjust the speed of the system. Integral action (k_i) is used to provide the required accuracy for the control system. Derivative action (k_d) is normally introduced to increase the damping in the system. If the gains of the controllers are changed for stability analysis the controlled process input can be unstable, i.e., its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. The saturation is used for limiting the process. Damping brings a mechanism to rest with minimal oscillation. The controller must work against the noise and disturbance. Based on that, the proposed controller is designed with non linearity and other external disturbances and the performance is analyzed. The block diagram of the proposed controller is shown in Figure 3.
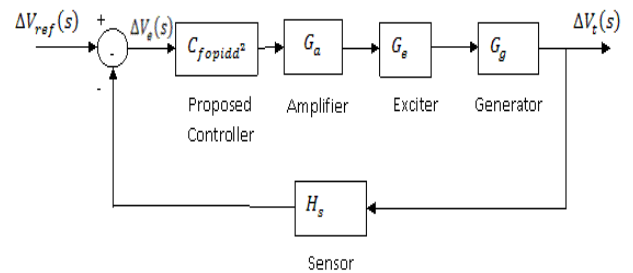

Fig. 3. $PI^\lambda D_1^\mu D_2^{(\mu_1+\mu_2)}$ controller structure for an AVR system

In mathematical point of view, the first derivative term of the error function depict if the error function is increasing or decreasing and the second derivative term show if the first derivative function is increasing or decreasing. The proposed controller second order derivative term decreases the error at the earlier stage of the process itself.

The overall transfer function of the proposed controller is given below:

$$G_{fopidd^2} = \frac{C_{fopidd^2} \, G_a G_e G_g}{1 + C_{fopidd^2} \, G_a G_e G_g H_s}$$

(7)

The transient performances such as maximum overshoot, rise time, peak time and settling time are analysed in the proposed controller.

4. Simulation Results

All the simulations are done in MATLAB R2013a software on a 32 bit core3 processor PC operating at 3 GHz with 4GB RAM. Fractional order controllers are implemented with the MATLAB FOMCON toolbox. Table 3 gives the PSO based tuned controller parameters. Table 4 gives the transient performance parameters for the controllers used in this paper.

4.1 Closed loop response

The analysis starts with the closed loop response of an AVR system without controller. The response is shown in the Figure 4.
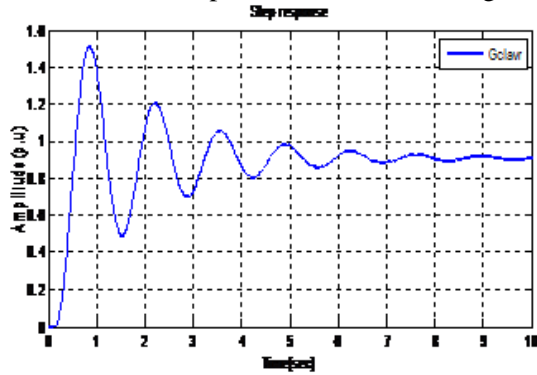

Fig. 4. Closed loop step response of an AVR system

Closed loop step response of the AVR system without controller is shown in figure 4. From figure 4, it is observed that G_{clavr} response is an under damped response with peak amplitude of 1.5051, Maximum Overshoot $(M_p) = 65.43\%$ and output settled to 98% of the steady state value.

4.2 Controllers

Figure 5 shows the test system with proposed controller. The test system is analysed with, per unit (p.u) input as reference voltage signal, unit step input as load disturbance and band limited white noise as external disturbance. The difference between the reference input and the output of the sensor is given as the error signal. IAE is found using this error signal. The error input is given to the proposed controller. The controller output is used to run the system in the optimised way. PSO based FOPIDD[2] controller and other controller parameters are given in Table 3. Table 3 shows all the controller gain and order parameter values with the three cases. They are without saturation and damping, with saturation and damping and with noise and disturbance.
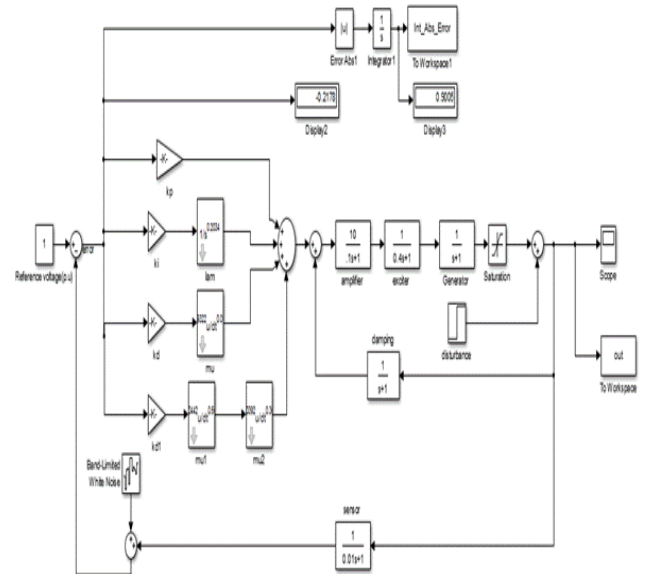

Fig.5. Simulink model for proposed controller for an AVR system

Table 3. PSO based Controller Gain values

Controller	Controller Parameters							
	K_p	K_i	K_{d1}	K_{d2}	λ	μ	μ_1	μ_2
PID	0.7024	0.28208	0.29093	-	-	-	-	-
FOPID	0.45702	0.84959	0.69316	0.74007	0.59679	-	-	-
PIDD[2]	2.96988	0.47113	0.67659	0.1128	-	-	-	-
PIDD[2] [10]	2.778	1.852	0.999	0.074	-	-	-	-

| FOPIDD² | 0.59007 | 0.23708 | 0.63706 | 0.86641 | 0.54354 | 0.61804 | 0.41397 | 0.7686 |

4.3 Time Domain Analysis

Figure 6, Figure 7 and Figure 8 shows the closed loop response of four controllers for AVR system without saturation and damping, with saturation and damping and with noise and disturbance.
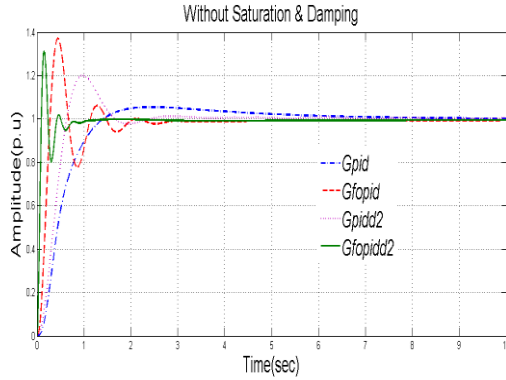

Fig.6. Closed loop response of four controllers without saturation and damping

Figure 6, it is observed that the conventional PID controller has less overshoot 5.1957% compared to the proposed controller maximum overshoot is 36.5%. The IAE of noise and disturbance in the proposed controller is 0.9005, while the IAE of noise and disturbance in the PID controller is 6.904; it is shown in figure 8. The maximum overshoot is better in PID controller, but it is not able to reject the noise and disturbance. From that, it is concluded that the proposed controller works well in rejecting the noise and disturbance and the high overshoot is cancelled out with saturation and damping.

Figure 6, Figure 7 and Figure 8 tells the rise time of the FOPIDD² is less and quick response than the other controllers.
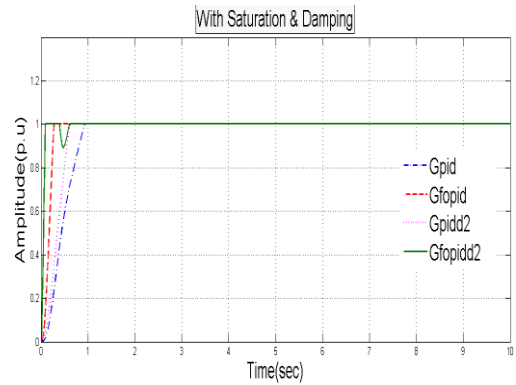

Fig.7. Closed loop response of four controllers with saturation and damping
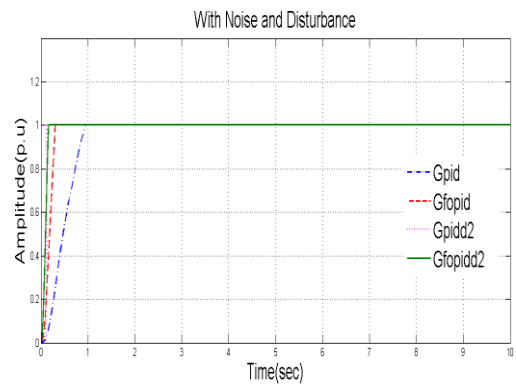

Fig.8. Closed loop response of four controllers with noise and disturbance

From all the above results, it is concluded that, robustness of the proposed controller is proved through the transient performance.

Time domain parameters such as % maximum overshoot and rise time given in the Table 4. IAE performance indices also listed in Table 4.

Table 4 Transient Performance analysis of various controllers

Case	Controller	IAE	$\% M_p$	$t_r \, (sec)$
-	Without Controller	1.591	65.4245	0.3156
Without Saturation and Damping	PID	0.7165	5.1957	0.8348
	FOPID	0.4413	38.0406	0.17922
	PIDD²	0.5186	20.0955	0.4346
	FOPIDD²	**0.7972**	**36.5478**	**0.065**
With Saturation and Damping	PID	0.4811	0	0.6345
	FOPID	0.1814	0	0.17537
	PIDD²	0.3589	0	0.4147
	FOPIDD²	**0.07943**	**0**	**0.06155**

With Noise and Disturbance	PID	1.23	-	0.6297
	FOPID	0.9643	0	0.1981
	PIDD^2	0.9258	0	0.224
	FOPIDD^2	**0.9005**	**0**	**0.06**
	PIDD^2 [10]	0.0018	0	0.0929

Figure 9 shows the convergence graph of PSO for the proposed controller without saturation and damping, with saturation and damping and with noise and disturbance.
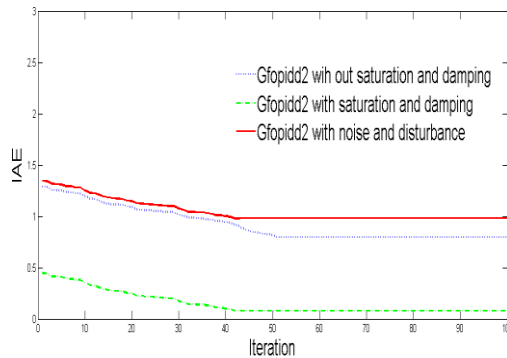

Fig.9. Convergence graph of PSO

From the above analysis and tables, the proposed controller performance is robust for the AVR system.

5. Conclusion

In this paper, a new approach of fractional order PID plus second order derivative controller is proposed for the AVR system. Controller parameters are tuned using PSO algorithm with the integral absolute error as performance criteria. The performance of the proposed $PI^{\lambda}D_1^{\mu}D_2^{(\mu_1+\mu_2)}$ controller is validated by comparing with the PID, FOPID and PIDD^2 controllers. Simulation result shows that, the proposed controller has better performance than the other controllers for the rejection of noise and disturbances besides the non-linearity. From that, it is concluded that the proposed controller is robust and works well for the AVR system which is a critical element in any power plant.

Acknowledgement

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