PARTICLE SWARM OPTIMIZATION BASED OPTIMUM PID CONTROLLER FOR GOVERNOR SYSTEM OF SYNCHRONOUS GENERATOR

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Abstract:

This paper presents a Particle Swarm Optimization (PSO) method for determining the optimal proportional – integral-derivative (PID) controller parameters for governor control of a synchronous generator .The proposed approach has superior features, including easy implementation, stable convergence characteristic and good computational efficiency. The synchronous generator is modeled and the PSO algorithm is implemented in simulink of matlab. The simulation results demonstrates the effectiveness of the designed system in terms of reduced settling time, peak overshoot and oscillations of frequency devaition. The results are compared with traditional trial and error tuning of the PID controller. Which gives in the PSO-PID controller: maximum positive overshoot of frequency deviation =0 and negative overshoot of frequency deviation =-0.042, Settling time= 7sec. Whereas, in conventional trial and error tuning: maximum positive overshoot of frequency deviation =0.002 and negative overshoot of frequency deviation =-0.03, Settling time= 11sec.

Keywords:

PID Controller, Particle Swarm Optimization, Synchronous Generator ,Governor system.

الحركة المثلى لأسراب الجزيئات الأسناد الأفضل لمسيطر التناسقي التكاملي التفاضلي للسيطرة على نظام الحاكم للمولد المتزامن

الخلاصة:

يقدم هذا البحث طريقة الحركة المثلى لاسراب الجزيئات في تحديد معاملات المسيطر التناسقي التكاملي التفاضلي للسيطرة على نظام الحاكم للمولد المتزامن. وهذه الطريقة المقترحة لها ميزات متفوقة تضمن بسهولة التطبيق , خصائص تقارب مستقرة والكفاءة الحسابية جيدة .ان المولد المتزامن تم تمثيله وخوارزمية الحركة المثلى لاسراب الجزيئات تم تنفيذه في برنامج المحاكاة في **matlab** ونتائج المحاكاة يعرض فعالية النظام المصمم من ناحية تقليل وقت الاستقرار ، تجاوز **overshoot** وتذبذبات التردد المشتق **deviation** . والنتائج تم مقارنتها مع الطريقة التقليدية التجربة والخطأ .حيث كانت النتائج في طريقة الحركة المثلى للاسراب الجزيئات :تجاوزالاطلاق الاقصى الموجب للتردد المشتق = 0 وتجاوزالاطلاق السالب للتردد المشتق =0.042- وزمن الاستقرار = 7ثانية اما في الطريقة التقليدية

التجربة والخطأ: تجاوز الاطلاق الاقصى الموجب للتردد المشتق= 0.002 وتجاوزالاطلاق السالب للتردد المشتق = 0.03- وزمن الاستقرار =11ثانية.

1. Introduction:

The PID (Proportional-Integral-Derivative) control is one of the earliest control strategies. It has been widely used in the industrial control fields. Its widespread acceptability can be recognized by: the familiarity with which it is perceived amongst researchers and practitioners within the control community, simple structure and effectiveness of algorithm, relative ease and high speed of adjustment with minimal down-time and wide range of applications where its reliability and robustness produces excellent control performances. However, successful applications of PID controllers require the satisfactory tuning of three parameters - which are proportional gain (KP), integral time constant (KI), and derivative time constant (KD) - according to the dynamics of the process. Unfortunately, it has been quite difficult to tune properly the gains of PID controllers because many industrial plants are often burdened with problems such as high order, time delays, and nonlinearities [1] .

Traditionally, these parameters are determined by a trial and error approach. Manual tuning of PID controller is very tedious, time consuming and laborious to implement, especially where the performance of the controller mainly depends on the experiences of design engineers. In recent years, many tuning methods have been proposed to reduce the time consumption on determining the three controller parameters. The most well known tuning method is the Ziegler-Nichols tuning formula ; it determines suitable parameters by observing a gain and a frequency on which the plant becomes oscillatory. Considering the limitations of the Ziegler-Nichols method and some empirical techniques in raising the performance of PID controller, recently artificial intelligence techniques such as fuzzy logic , fuzzy neural network , and some stochastic search and optimization algorithms such as simulated annealing , genetic algorithm, particle swarm optimization approach , immune algorithm , and ant colony optimization have been applied to improve the performances of PID controllers [2].

In this paper the objective is to find and implement the best PID controller parameters that realize efficient control of speed and frequency.

The model of the Governor of single area power system is designed using simulink in MATLAB. The PSO algorithm is developed to find the optimum Proportional, Integral and Derivative gains of the controller. These values of PID gains are sent to workspace and shared with the simulink model for simulation under different loads.

2. Modeling and Simulation of Synchronous Machine:

The overall accuracy of the power system stability is primarily decided by how correctly the Synchronous Generators within the system are modeled. The proposed simulation model is developed as a fourth order machine time constants in order to improve frequency deviation responses [3]. With proper modeling of the synchronous machine in the power system, a better understanding of how the machine reacts under

sudden large disturbances during transient conditions can be achieved, and hence a better power system governor controllers of the synchronous generator can be designed .
The used synchronous generator name plate is :3-ph SG, 380 v., 5 kw, 4 poles, 50 Hz.
The values of the constants required for turbine and governor system is shown in table (1).
Some assumptions were taken into consideration and made prior to the design of the simulation model, these assumptions are:
-The SG. turbine in this model produce a constant torque with a constant speed maintained during steady state operation.
-The SG. output terminals are connected to infinite bus bar that has various load changes.
- Only basic and linear models of the power system components will be used.
-All the time constants of the SG. which are used in this model of all components are assumed to be the optimum time constants extracted based on the values given in Walton[3].
The stability of a SG. depends on the inertia constant and the angular momentum.
The rotational inertia equations describe the effect of unbalance between electromagnetic torque and mechanical torque of individual machines.
By having small perturbation and small deviation in speed, the swing equation becomes [4]:

$$d\Delta\omega / dt = (1/2H)\,(\Delta P_m - \Delta P_e) \qquad (1)$$

then $d\Delta\omega / dt = d^2\delta / dt$

H = inertia constant
ΔP_m = change in mechanical power
ΔP_e = change in electrical power
$\Delta\omega$ = change in speed (elec. rad/sec)
δ = rotor angle (rad.)
Using Laplace Transformation, equation (1) becomes :

$$d\delta / dt = \Delta\omega(s) = (1/2Hs)\,[\Delta P_m(s) - \Delta P_e(s)] \qquad (2)$$

A more appropriate way to describe the swing equation is to include a damping factor that is not accounted for in the calculation of electrical power *Pe*. Therefore, a term proportional to speed deviation should be included.
The speed load characteristic of a composite load describing such issue is approximated by [5]:

$$\Delta P_e = \Delta P_L + K_D\,\Delta\omega \qquad (3)$$

where K_D is the damping factor or
coefficient in per unit power divided by per unit frequency. $K_D\,\Delta\omega$ is the frequency-sensitive load change and ΔP_L is the non frequency-sensitive load change. Figure (1) presents a block diagram representation of a load change derived from the swing equation with the aid of equation (3) or:

$$\Delta\omega(s) = [\Delta Pm(s) - \Delta P_L(s)]\,[1/(2Hs) \qquad .(4)$$

Figure (2) represents a simplified block diagram of the Governor and AVR of the synchronous generator with the two feedback quantities
(voltage and frequency).
The following proposed models are needed to study the effect of using the PID controllers and PSO-PID controller which represent on the fourth order model of synchronous generator for frequency deviation stability control and how this stability have been enhanced.

2.1 Generator Model

A fourth order model of the SG. consists of a generator gain plus four pairs of pole-zero time constants can be modeled. In terms of expressing this as a transfer function, then the following equation is given [6]:

$$V_t(s)/V_F(s) = K_G \frac{(1+sT_{Z1})\ (1+sT_{Z2})\ (1+sT_{Z3})\ (1+sT_{Z4})}{(1+sT_{P1})\ (1+sT_{P2})\ (1+sT_{P3})\ (1+sT_{P4})} \qquad (5)$$

There are two ways in MATLAB Simulink to design the machine model, these are:
1. Using power system block set which is a set of ready-made [7].
2.Using blocks of transfer functions of the machine to manipulate the design model. However, using blocks of the transfer function to represent the components in the power system is capable of having higher order machine time constants as inputs. This can be achieved by the illustration shown in Figure (3) [8,9].
Where: K_G = Gain of the generator, T_Z = Time constant of the zero, T_P = Time constant of the pole, V_F = Field voltage of the SG, V_t = Terminal voltage of the SG.

2.2 Exciter model

The most basic form of expressing the exciter model can be represented by a gain K_E and a single time constant T_E :

$$V_F\ (s) / V_R\ (s) = K_E\ / (1 + sT_E) \qquad (6)$$

V_R = the output voltage of the regulator (AVR), V_F = field voltage . The excitation system

amplifier is represented similarly by a gain K_A and a time constant T_A. The transfer function of the amplifier is:

$$V_R(s)/ \Delta V_e(s)=K_A / (1+ sT_A) \qquad (7)$$

Where: ΔV_e = Voltage error = reference voltage (V_{ref}) - output voltage of the sensor(V_S).

2.3 Sensor Model

The terminal voltage of the SG. is being fed back by using a potential transformer that is connected to the bridge rectifiers. The sensor is also being modeled, likewise as the exciter:

$$V_S(s) / V_t(s) = K_R / (1 + sT_R) \qquad (8)$$

V_S = output voltage of the sensor, K_R and T_R are the gain and time constant of the sensor .

2.4 Automatic Voltage Regulator (AVR) Mode

In most modern systems, the AVR is a controller that senses the generator output voltage then initiates corrective action by changing the exciter control in the desired direction [10].

A simple AVR is created with a 1st order model of SG as shown in the Figure (4).

From this block diagram, the closed loop transfer function of a 1st order relating the generator terminal voltage $V_t(s)$ to the reference voltage $V_{ref}(s)$ can be written as follow:

$$V_t(s) / V_{ref}(s) = \frac{K_A K_E K_G (1+sT_R)}{(1+sT_A)(1+sT_E)(1+sT_{G1})(1+sT_R)+K_A K_E K_G} \qquad (9)$$

2.5 Turbine Model

The simplest form of model for a non-reheat steam turbine can be approximated by using a single time constant T_T. The model for turbine associates the changes in mechanical power ΔP_m with the changes in steam valve position $\Delta \text{€}_V$ is given as:

$$G_T(s) = \Delta P_m(s) / \Delta \text{€}_V(s) = 1 / 1 + St_t \qquad (10)$$

2.6 Governor Model

The speed governor mechanism works as a comparator to determine the difference between the reference set power ΔP_{ref} and the power $(1/R)\Delta\omega$ as shown in Figure (5).

The speed governor output ΔS_g is therefore:

$$\Delta S_g (s) = \Delta P_{ref} (s) - (1/ R)\Delta\omega(s) \qquad (11)$$

where R represents the drop. Speed governor output ΔS_g is being converted to steam valve position $\Delta \text{€}_V$ through the hydraulic amplifier. Assuming a linearized model with a single time constant T_g:

$$\Delta \text{€}_V(s) = (1 / (1 + s\, T_g))\, \Delta S_g(s) \qquad (12)$$

The final simulation model for a 4th order SG without controller for 0.6 p.u load change can be developed in "Matlab" as shown in Figure (6) and the output performance of the system can be shown in fig.(7) . Its seen from figure that the response for frequency deviation($\Delta\omega$) without controller oscillates for a period of 14.03 seconds before settling down to zero deviation. There is an overshoot error occurring at 1.6 seconds. The ideal response is to keep the deviation (oscillation) as close to zero as possible at the minimum period of time.

3. The PID Controller:

It is an important matter for the stable electrical power service of the synchronous generator with a high efficiency and a fast response. Until now, the analog PID controller is generally used for the governor system because of its simplicity and low cost. The governor system model controlled by the PID controller can be expressed by figure (8).The PID controller calculations involve three parameters that must be determined for the given process, to give the desirable output responses for the plant are : Proportional gain, Integral gain and Derivative gain (K_P, K_I and K_D respectively). The transfer function of the PID controller looks like the following [11] :

$$C(s) = K_p + K_i / s + K_d s = (K_d s^2 + K_p s + K_i) /s \qquad (13)$$

Kp = Proportional gain, Ki = Integral gain, and Kd = Derivative gain. The error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is given as:

$$u= Kp.e +Ki \int e.dt + Kd\, de/dt \qquad (14)$$

This signal will be sent to the plant, and the new output (y) will be obtained. This new output (y) will be sent back to the sensor again to find the new error signal (e). The controller takes this new error signal and computes its derivative and its integral again. This process will continuous until the desired output achieved.

In this paper, the best result can be obtained of the PID controller parameters, by using trial and error method, to achieve the frequency deviation of the non-linear synchronous generator in the governing system:
K_P= 0.8, K_I= 0.001, and K_D= 0.6. Which give a transient system response to the unit step input for 0.6 p.u load change:

- max. positive overshot of frequency deviation =0.002 and negative overshot of frequency deviation =-0.03.
- Settling time=11 sec.
- Steady state error= 0%.

The output performance of the system for 0.6 p.u load change can be shown in figure (9).

4.Particle Swarm Optimization:

PSO is one of the optimization techniques first proposed by Eberhart and Colleagues [12, 13]. This method has been found to be robust in solving problems featuring non-linearity and non-differentiability, which is derived from the social-psychological theory. The technique is derived from research on swarm such as fish schooling and bird flocking. In the PSO algorithm, instead of using evolutionary operators such as mutation and crossover to manipulate algorithms, the population dynamics simulates a "bird flocks" behavior, where social sharing of information takes place and individuals can profit from the discoveries and previous experience of all the other companions during the search for food. Thus, each companion, called particle, in the population, which is called swarm, is assumed to " *fly* " in many direction over the search space in order to meet the demand fitness function [12 ,13, 14, 15].

For n-variables optimization problem a flock of particles are put into the n-dimensional search space with randomly chosen velocities and positions knowing their best values, so far (P_{best}) and the position in the n-dimensional space [12, 13]. The velocity of each particle, adjusted accordingly to its own flying experience and the other particles flying experience. For example, the i_{th} particle is represented, as:,

$$x_i = (x_{i,1}, x_{i,2}, \dots\dots x_{i,n}) \qquad (15)$$

In n-dimensional space, the best previous position of the i_{th} particle is recorded as:

$$P_{best_i} = (P_{best_{i,1}}, P_{best_{i,2}}, \dots\dots P_{best_{i,n}}). \qquad (16)$$

The modified velocity and position of each particle can be calculated using the current velocity and distance from ($P_{best_{i,d}}$) to (g_{best_d}) as shown in the following formula [12, 13, 14, 15]:

$$V_{i,m}^{(It.+1)} = W * V_{i,m}^{(It.)} + c1 * rand * \left(P_{best_{i,m}} - x_{i,m}^{(It.)}\right) + c2 * rand * \left(g_{best_m} - x_{i,m}^{(It.)}\right) \qquad (17)$$

$$x_{i,m}^{(It.+1)} = x_{i,m}^{(It.)} + v_{i,m}^{(It.)} \qquad (18)$$

$i=1,2,\dots\dots,n$

$m=1,2,\dots\dots,d$

Where;
n = Number of particles.

d = Dimension.

Iter. = Iterations pointer.

$V_{i,m}^{(It.)}$ = Velocity of particle no. *i* at iteration It.

W = Inertia weight factor.

c1,c2 = Acceleration constant.

rand = Random number between 0-1.

$x_{i,m}^{(It.)}$ = Current position of particle *i* at iteration It.

P_{best_i} = Best previous position of i_{th} particle.

g_{best_m} = Best particle among all the particles in the population.

5. Implementing PSO –PID Controller

A. Fitness Function:

The most common performance criteria are Integrated Absolute Error (IAE), the Integrated of Time weight Square Error (ITSE) and Integrated of Square Error (ISE) that can be evaluated analytically in frequency domain [14, 16, and 17].
These three integral performance criteria in the frequency domain have their own advantage and disadvantage. For example, disadvantage of IAE and ISE criteria is that its minimization can result in a response with relatively small overshoot but a long settling time, because the ISE performance criteria weights all errors equally independent of time. Although, the ITSE performance criterion can overcome the disadvantage of ISE criterion. The performance criterion formula for, IAE, ISE, and ITSE are as follows [17]:

$$IAE = \int_0^t |r(t) - y(t)|\,dt = \int_0^\infty |e(t)|\,dt \qquad (19)$$

$$ISE = \int_0^t e^2(t)\,dt \quad \dots\dots \qquad (20)$$

$$ITSE = \int_0^t t.e^2(t)\,dt \quad \dots\dots \qquad (21)$$

In this paper, the integrated of time weight square error ITSE is used for evaluating the PID controller. A set of good control parameters can yield a good step response that will result in performance criteria minimization in the time domain, this performance criterion is called Fitness Function (FF) which can be formulated as follows [1]:

$$FF = \left(1 - e^{-\beta}\right)\left(M_p + E_{ss}\right) + e^{-\beta}\left(T_s - T_r\right) + ITSE \qquad (22)$$

Where:

M_P is maximum overshoot.

E_{ss} is steady state error.

T_s is the settling time.

T_r is the rise time.

β is the weighting factor can set to be larger than 0.7 to reduce the overshoot and steady state error, also can be smaller than 0.7 to reduce the rise time and settling time.

B. Proposed PSO - PID Controller

In this paper a PSO is used to find the optimal parameters of governor PID control system. Fig. (10) shows the block diagram of optimal PID control for the governor system. In the proposed PSO method each particle contains three members *P*, *I* and *D* . It means that the search space has three dimension and particles must ‘fly’ in a three dimensional space. The flow chart of PSO-PID controller is shown in fig.(11) and the system performance of PSO-PID controller is shown in Fig. (12). The PSO algorithm was simulated and tested by tuning the various parameters like poplation size, inertia weight and acceleration factor. The optimum parameter values that achieved better solution are listed in table (2).

The simulation was done using the simulink package available in Matlab. The frequency deviation response is simulated using PSO based PID controller, for 0.6 p.u of load change. The simulation time was set to 20 second. The frequency deviation response for a change in load of 0.6 p.u is shown in fig.(12).

Particle Swarm Optimization (PSO) algorithm, parameter values are:

K_p =0.5, K_i =0, K_d =0.4, that the frequency deviation response gives by the unit step input;

- max. positive overshoot of frequency deviation =0 and negative overshoot of frequency deviation =-0.042
- Settling time = 7Sec.
- Steady state error = 0%.
- ITSE = 0.005163

6. Comparison Results

A coparison on dynamic performances between various controllers for governor system are represented in table (3). The settling time, oscillations and overshoot are compared for a load change of 0.6 p.u. It is observed from the table that the frequency deviation responses of the 4th order SG . model for 0.6 p.u load change without controller ,with PID controller and PSO-PID controller. Its seen from the table that the PSO-PID controller exhibits relatively good performance with very less settling time, overshoot and transient oscillations.

7. Conclusion:

The quality of the power supply is determined by the constancy of frequency and voltage. Minimum frequency deviation and good terminal voltage response are the characteristics of a reliable power supply.

In this work a PSO method is used to determine PID controller parameters is obtained through simulation of synchronous generator for governor. The results its show that the proposed controller can perform an efficient search for the optimal PID controller. By comparison with the conventional controller methods, it shows that this method have large settling time, overshoot and oscillations. Hence , when PSO-PID algorithms are used to control governor system, their typical characteristics show a faster and smoother response.

8. References:

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Table (1) Values of the constants required for turbine and governing system (all values are in per unit)

ΔP_{ref}	K_D	R	H	T_g	T_T
0	**0.8**	**0.05**	**10**	**0.2**	**0.5**

Table (2) parameters of PSO Algorithms

Number of iteration	**25**
Population Size	**20**
w_{max}.	**0.3**
$c_1 = c_2$	**1.2**

Table (3) frequency deviation response for 0.6 p.u. load change without controller, with PID controller and with PSO-PID

Results	**Without Con.**	**PID-Con.**	**PSO-PID**
Maximum positive overshoot	**0.03**	**0.002**	**0**
Negative overshoot	**-0.04**	**-0.03**	**-0.042**
Settling time (Sec.)	**14.03**	**11**	**7**

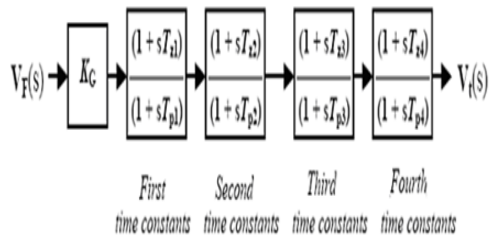


Figure (1) Block diagram representing a 4th order SG time constants model

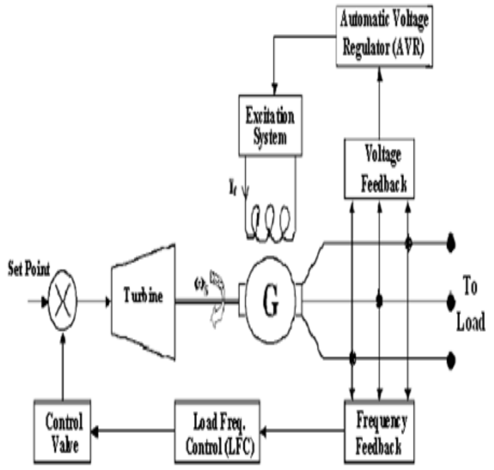


Figure (2) Block Diagram of Governor and AVR of the SG

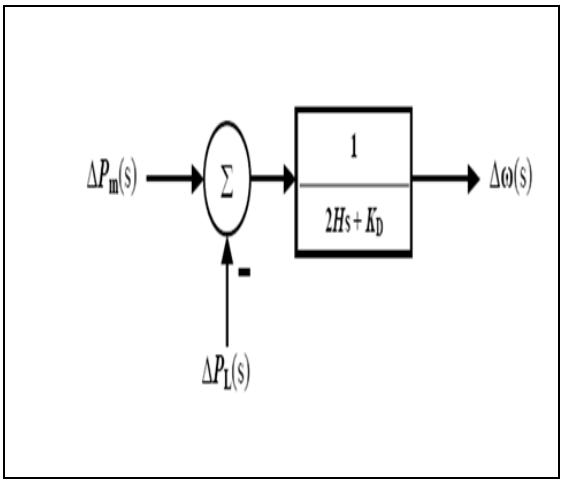


Figure (3) Block diagram of a load change model

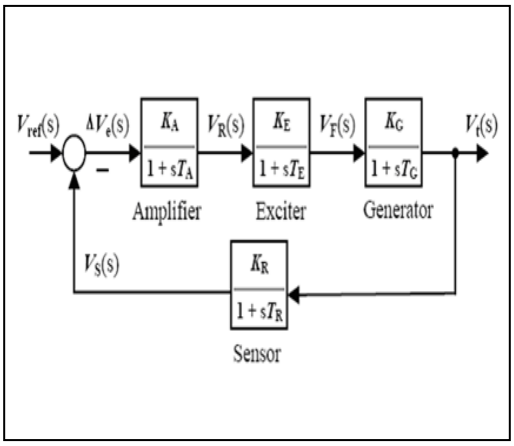


Figure (4) Block diagram of a simple AVR .

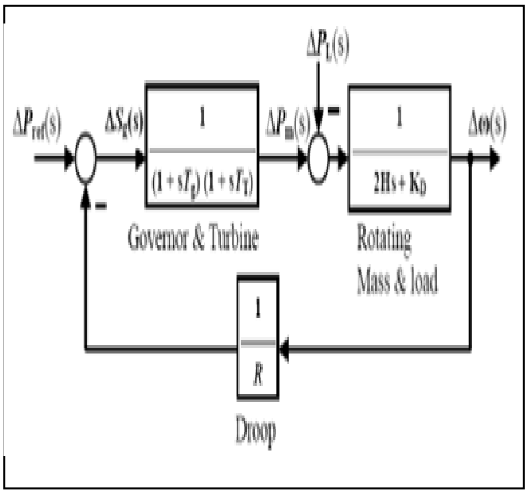


Figure (5) Power system load frequency control (LFC) block diagram

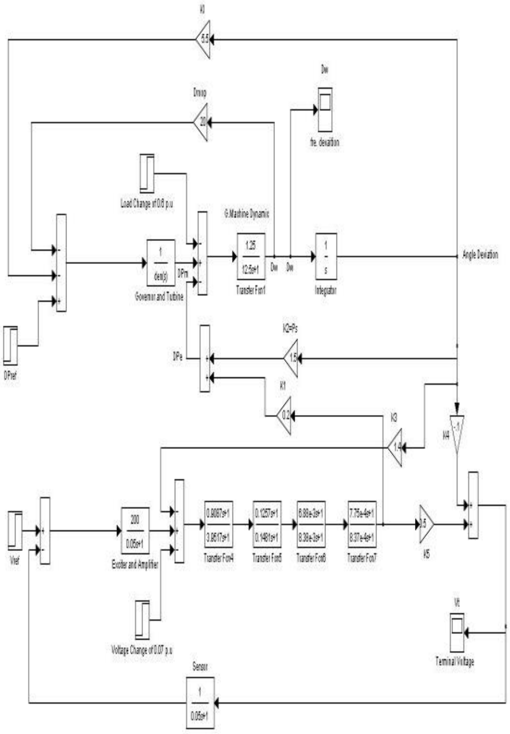


Figure (6) Matlab - Simulink Simulation Model for the 4th Order SG. without Controller

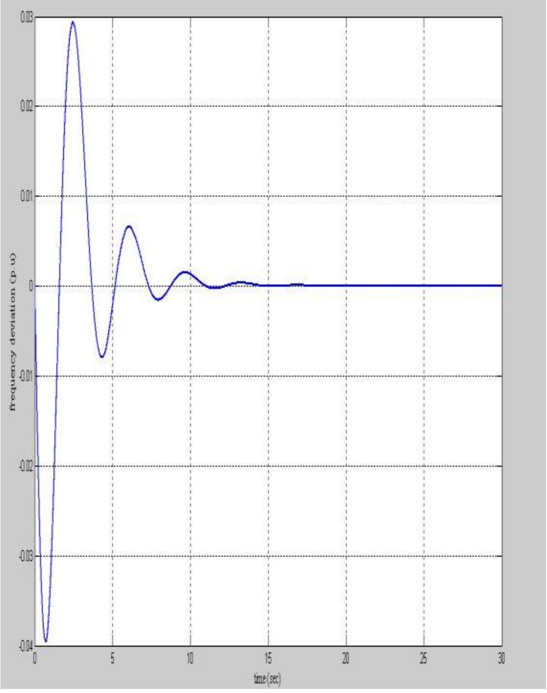


Figure (7) Frequency deviation (Δω) for the simulation model without controller

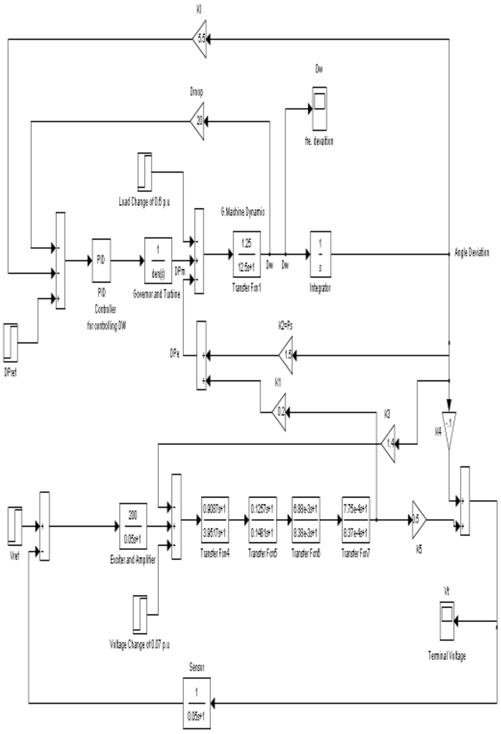


Figure (8) Block diagram of the proposed governor system with PID controllers

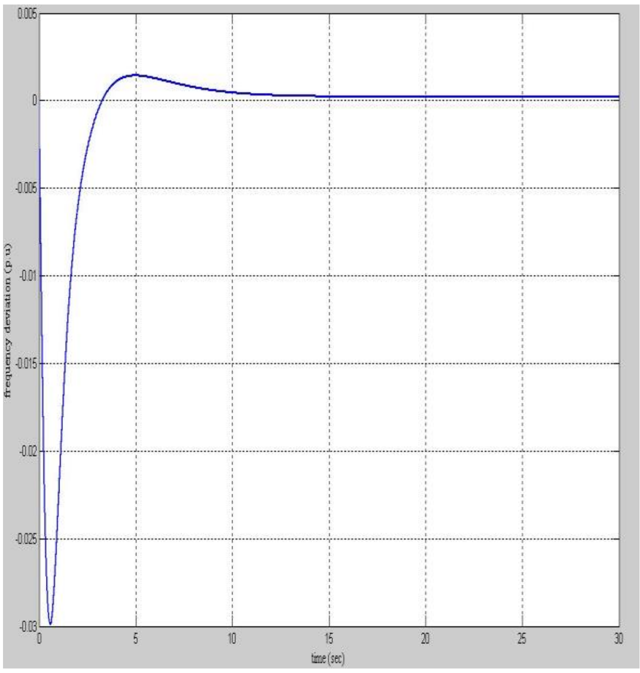
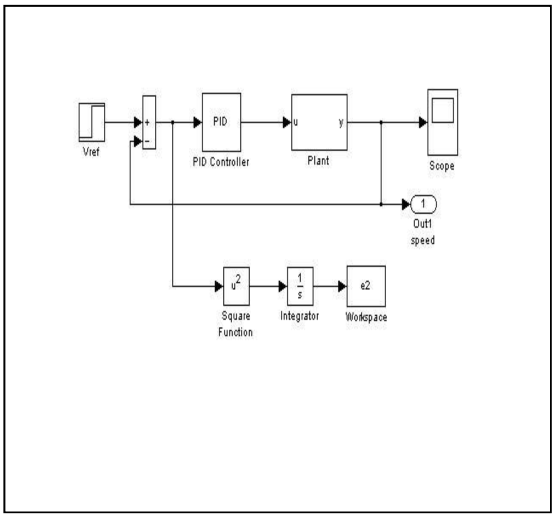


Figure (9) Frequency deviation (Δω) step response for 0.6 p.u load change with PID controller



Figure(10) Optima PID control of S.G

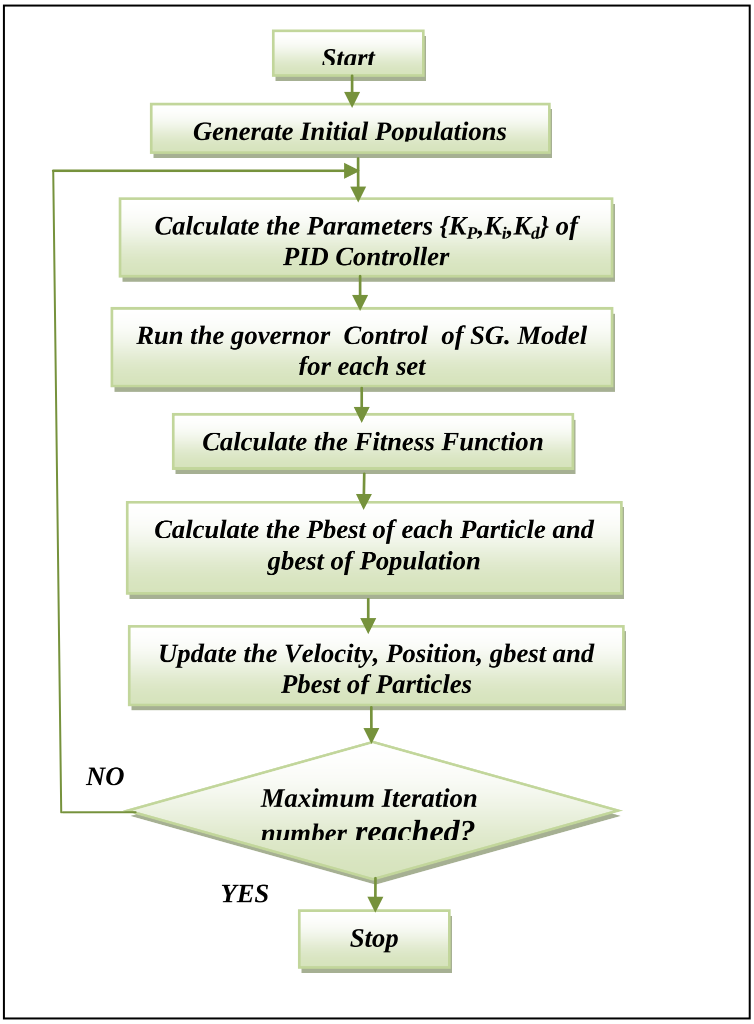


Figure (11) The Flowchart of the PSO-PID Control System

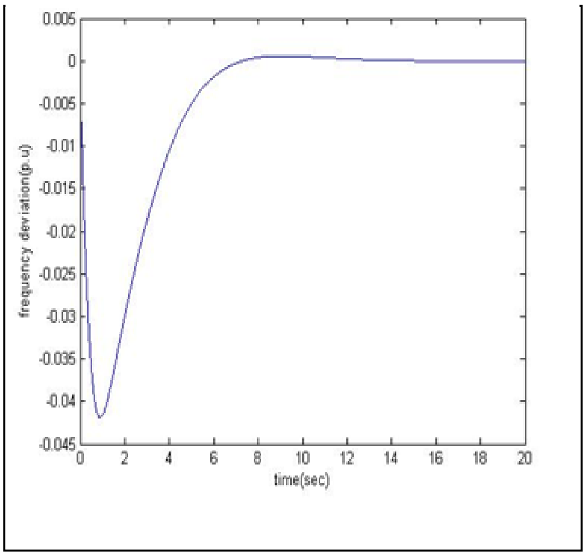


Figure (12) System Performance of PSO-PID Tuning Method

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