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Automatic Tuning of (PID) Controller Using Particle Swarm Optimization (PSO) Algorithm for Steam Engine Speed Control (SESC)

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Abstract:

The proportional-integral-derivative (PID) controllers are the most popular controllers used in industry because of their remarkable effectiveness, simplicity of implementation and broad applicability. However, tuning of these controllers is time consuming, not easy and generally lead to poor performance especially with non-linear systems. This paper presents an artificial intelligence (AI) method of particle swarm optimization (PSO) algorithm for tuning the optimal (PID) controller parameters for steam engine speed control (SESC) system to achieve the mean objective which is the tracking between the reference speed and the output speed .This approach has superior features, including easy implementation, stable convergence characteristic and good computational efficiency over the conventional methods. The PID conventional controller had been applied and results were compared with the automatic tuning PSO-PID for (SESC) using Simulink of Matlab . Simulation results for the proposed method give optimum input/output tracking and the error equal zero without using the conventional solutions for standard engine control problems like cascade feedback gain and dither signal ,where in traditional tuning method of PID the tracking cannot achieve exactly without error, unless using conventional solutions.

Keywords: PID Controller, Particle Swarm Optimization (PSO), Steam Engine Speed Control (SESC).

توليف تلقائي للمسيطر التناسقي التكاملي التفاضلي باستخدام خوارزمية سرب الجزيئات الامثل للسيطرة على سرعة محرك بخاري

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الخلاصة:

مسيطرات ال (PID) الأكثر شعبية في الاستخدام الصناعي بسبب فعاليتها الملحوظة، بساطة التنفيذ والتطبيق الواسع. ومع ذلك، توليف هذا النوع من المسيطرات تستغرق وقت وليست سهلة، وتؤدي عموما إلى ضعف الأداء خصوصا مع الانظمةاللا خطية. يقدم البحث الحالي أسلوب من الذكاء الاصطناعي (AI) وهوخوارزمية سرب الجزيئات الأمثل (PSO) للتوليف الأمثل لمعاملات(براميترات)مسيطرال (PID) للسيطرة على سرعة محرك بخاري لتحقيق

الهدف الرئيسي وهوالتتابع الامثل بين سرعة الدخل وسرعة الخرج . والطريقة المقترحة لها ميزات متفوقة تضمن سهولة التطبيق , خصائص تقارب مستقرة والكفاءة الحسابية جيدة بخلاف الطرق التقليدية. تم تطبيق مسيطر ال(PID)التقليدي وتمت مقارنة النتائج مع التوليف التلقائي لمعاملات ال PID باستخدام ال PSO باستخدام برنامج المحاكاة في الMatlab . نتائج المحاكاة للطريقة المقترحة اعطت التتابع الامثل بين الدخل والخرج وقيمة الخطأ صفر دون استخدام الحلول التقليدية لمشاكل السيطرة على المحرك (مثل مكبر العمليات المتتالي او استخدام اشارة الدثر) ، بينما باستخدام مسيطر ال(PID) التتابع لايتحقق بدون نسبة خطأ مالم يستخدم الحلول التقليدية.

1. Introduction:

Engine speed control (ESC) still lies at the heart of some of the most sophisticated control systems in the world. For the control engineer they are intensely interesting to work with and challenging to control. In addition to speed, the petrol engine has a number of other control aspects, starting from ignition timing control, through fuel-air ratio control to the growing number of emissions and efficiency requirements that all require yet more complex control strategies. The modern car is in fact controlled by electronic control units (ECU's). The modern automotive diesel engine has an ECU of similar complexity to the petrol engine device, and all this complexity to control engines. This is why engine speed control remains relevant today – it is the application that gave rise to the theoretical analysis and design of control systems [1].

A PID controller requires exact mathematical modeling of system which be controlled; the performance of the system is questionable if there is parameter variation [2].however the PID controller is still extensively used in the industry this is due to its simplicity and the ability to apply in a wide range of situations. On the other hand tuning a PID controller is rather difficult and can be a time consuming process [3, 4].

In recent years, many intelligence algorithms are proposed to tuning the PID parameters. Tuning PID parameters by the optimal algorithms such as the Simulated Annealing (SA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO) algorithm. Chent et al. proposed a method to tune PID parameters by SA [5]. However, it is slow to search the best solution. (PSO), first introduced by Kennedy and Eberhart, is one of the modern heuristics algorithms. It was developed through simulation of a simplified social system, and has been found to be robust in solving continuous non-linear optimization problems. [6]

In this paper the objective is to determine solutions for a Dead Zone problem and implement the optimal PID controller parameters that realize efficient control of speed and regulating of steam engine. The model of an engine speed control system is determined by using Simulink in MATLAB. The PSO algorithm is presented to find the optimum Proportional, Integral and Derivative gains values of the controller without using the conventional solutions for all control problems which require some important techniques like (compensate cascade feedback gain or dither signal design) .

2. Modeling of the ESC SYSTEM:

2.1. Engine Speed Control System:

The basic elements of an engine control system are :

- A valve with which to change the supply rate of the fuel source
- A reciprocating engine
- An output shaft with flywheel and the engine load.

In a standard system, a safe fuel source is compressed air as shown in **Figure. (1),** this gives similar results to steam but without the extremes of temperature or energy.

The input valve in the standard system is also motorized so that a constant control input to the valve motor causes a constant rate of change of the valve position. The airflow rate/ valve position characteristic is also non-linear so that the control of the air flow into the engine is itself a problem. The engine is a typical four cylinder steam engine with an inertial load in the form of a flywheel, and variable load in the form of an electrical generator. To vary the electrical load a load control voltage is used. [1]

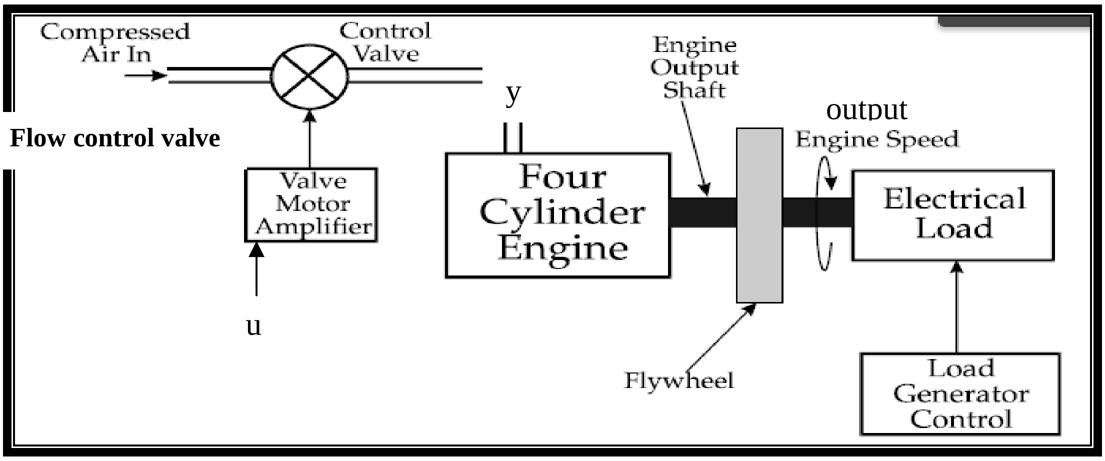


Fig. (1) Schematic diagram of Engine Speed System (open loop)

2.2 Mathematical Model of (ESC) system:

The components of the engine control system are the air control valve, the engine and the load. The air control valve in turn has two parts, the drive motor and the valve. The drive motor gives a rate of change of valve position y(t) proportional to the motor input signal u (t), so it can be modeled as an integrator with gain g_m . The valve output pressure P (t) is proportional to the valve position y(t), so it can be modeled as a gain g_v .

$$\frac{dy(t)}{dt}=g_m u(t),\ p(t)=g_v\, y(t) \qquad \text{............ (1)}$$

The engine torque $t_e(t)$ is proportional to the air pressure.

$$t_e(t)=g_e p(t) \qquad \text{............ (2)}$$

The engine torque is used to supply the engine load, frictional losses and to accelerate the engine flywheel inertia . If the engine speed is ω then we can write; [Rate of change of flywheel momentum] = (engine torque)-(frictional torque)-(load torque)

$$I\frac{dw(t)}{dt}=t_e-t_f-t_l \qquad \text{............ (3)}$$

(I) is moment of inertia of engine

The torque required to overcome friction is $t_f=bw(t)$, where b is the damping coefficient. The load torque t_l is proportional to the load demand voltage $d_l(t)$ such that; $t_l=g_l d_l(t)$ .Combining these equations give:

$$I\frac{dw(t)}{dt}+bw(t)=g_e g_v y(t)-g_l d_l(t) \qquad \text{............ (4)}$$

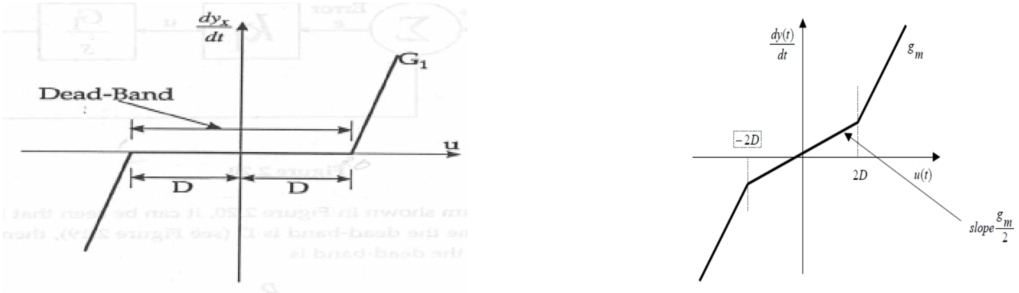
Equations (1) and (4) are the differential equation model of open loop engine speed control system. The transfer function form these are:

$$y(s)=\frac{g_m u(s)}{s} \text{...(5)}$$

$$w(s)=\frac{g_e g_v y(s)}{b+I_s}-\frac{g_l d(s)}{b+I_S} \text{........................(6)}$$

Because the input valve has a dead –zone, the gain g_m is non linear with a characteristic as shown in **Figure.(2-a)** .The air flow gain g_v is also non-linear but with a smooth characteristic ,usually power law .In normal operation the valve characteristic is locally linearised about the normal operating speed of the engine, and the dead-zone is compensated in several ways if the actuator position is measured (as in the standard engine speed control system) then high gain feedback around the actuator can reduce the effective dead-zone by a factor equal to the feedback gain. A further common procedure is to use a technique called dither. In this a periodic signal is added to the actuator input signal. The advantage of dither is that the valve dead-zone as shown in **Figure. (2-b)** is replaced by the non zero gain of $g_m/2$. In this case there is always a corrective control signal being fed to the system and the servo tracking error can be control by normal means.[7]

The dither in feedback systems was carried on by Zames and Shneydor (Zames and Shneydor 1976, Zames and Shneydor 1977).In their work Zames and Shneydor use an input-output framework to prove that dither affects stability of nonlinear systems. Essentially they show that an input-output analysis of the dithered system can be derived by looking at the smoothed system.[8]. A different approach for studying dither in nonlinear system was used by Mossaheb. In (Mossaheb 1983) it has not been used an input-output approach but a classical averaging method for showing that a sufficiently high frequency dither can make arbitrarily close the state of the dithered system and the state of the smoothed system.[9]



(a)Dead zone Characteristic dead zone

(b) Dither Compensated

Fig .(2) Non-Linear Gain Characteristic (Dead Zone)

The standard engine control problem has two main components that are found in many engine control situations. They are:

1) The requirement of controlling a non-linear input actuator (the air flow control valve)
2) The requirement of regulating the speed of the engine when the load on its output shaft changes

The solution to these control problems requires one of the following techniques:[1,7]

- Compensation for dead-zone in the actuator. A local feedback loop is used, together with some non-linear compensating mechanism to reduce the actuator dead-zone and to give direct control over the valve position.
- The use of cascade control. An inner feedback loop gives control over the position of the air flow valve and an outer feedback loop does the speed regulation.

- The use of feed forward of the load demand. When a signal is available which is proportional to the load, then the signal can be fed forward to the input of the control system to anticipate changes in load.

In this paper used the first technique .

3. Fitness Function:

Integral error is usually used as performance index of PID system parameter tuning, while ITAE is often used in optimal analysis and design. [10,11, 12]

$$ITSE = \int_0^t t.e^2(t)dt \qquad \text{............ (7)}$$

In this study, a set of good control parameters can yield a good 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 : [6]

$$FF = \left(1 - e^{-\beta}\right)(M_p + E_{SS)} + e^{\beta}(T_s - T_r) + ITSE \qquad \text{............ (8)}$$

Where:

M_P is maximum overshoot.
E_{ss} is steady state error.
T_s is the settling time.
T_r is the rise time.
b is the weighting factor to improve the performance of response(positive constant putting as input data in the software program)

4. Particle swarm optimization algorithm:

PSO is a method for optimizing hard numerical functions on metaphor of social behavior of flocks of birds and schools of fish. The original PSO algorithm is discovered through simplified social model simulation. It was first designed to emulate birds seeking food which is defined as a cornfield vector. The bird would find food through social cooperation with other birds around it (within its neighborhood).It was then expanded to multidimensional search. In PSO each particle in swarm represents a solution to the problem and it is defined with its position and velocity.[13]

The main steps in the particle swarm optimization and selection process are described as follows:

(a) Initialize a population of particles with random positions and velocities in m-dimensions of the problem space and fly them.

(b) Evaluate the fitness of each particle in the swarm.

(c) For every iteration, compare each particle's fitness with its previous best fitness (P_{best}) obtained. If the current value is better than(P_{best}), then set (P_{best})equal to the current value and the (P_{best}) location equal to the current location in the m-dimensional space.

(d) Compare(P_{best}) of particles with each other and update the swarm global best location with the greatest fitness (g_{best}).

(e) Change the velocity and position of the particle According to equations (9) and (10) respectively.

$$V_{i,m}^{(It.+1)} = W * V_{i,m}^{(It.)} + c1 * rand * \left(P_{best_{i,m}} - x_{i,m}^{(It.)}\right) + c2 * rand * (g_{best_m} - x_{i,m}^{(It.)}) \quad \ldots\ldots(9)$$

$$x_{i,m}^{(It.+1)} = x_{i,m}^{(It.)} + v_{i,m}^{(It.)} \quad \ldots\ldots\ldots\ldots (10)$$

Where:

$v_{i,m}$ &$x_{i,m}$ represent the velocity and position of the i_{th} particle with n-dimensions, respectively.

i=1,2,…..,n

m=1,2,…..,d

n = size of population.

d = Dimension.

rand= Random number between 0-1

Iter. = Iterations pointer.

W= the inertia weight factor that controls the exploration and exploitation of the search space because it dynamically adjusts velocity.

c1, c2 = Acceleration constant (positive constant) called the cognitive and social parameter respectively.

P_{best_i} = Best previous position of ith particle.

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

(f) Repeat steps (a) to (e) until convergence is reached based on some desired single or multiple criteria. [14,15]

5. Simulation results:

The simulation results will show the following cases:

5.1 open loop and closed loop step response:

For testing the stability of the system without controller, the open loop contribution for the system is shown in **Figure.(3)**and the response is shown in **Figure.(4)** . While the response of closed loop for the proposed system is shown in **Figure.(5).**As shown from the two figures the system is unregulated and unstable under disturbance rejection .

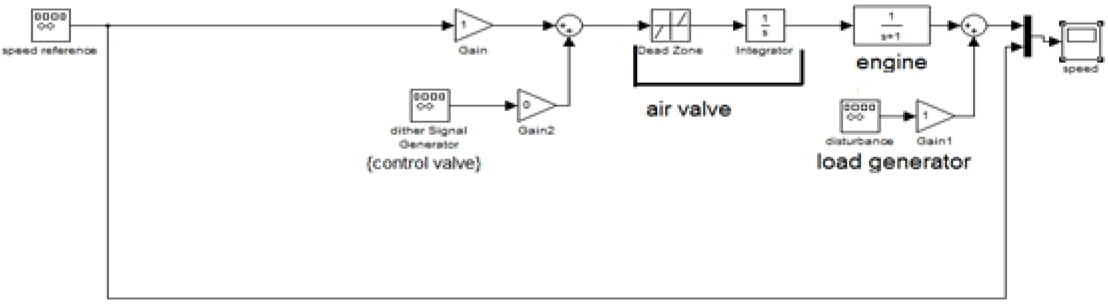
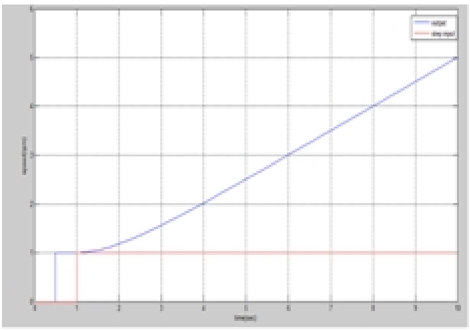


Fig .(3) Simulink of open loop steam engine system



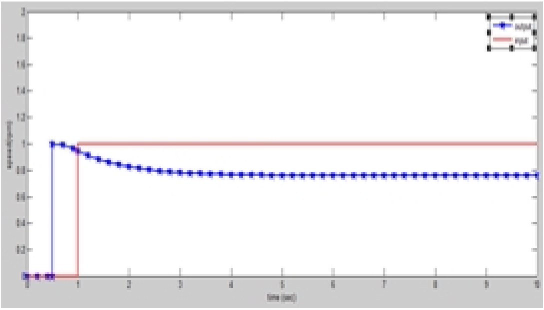


Fig .(4) open loop step response **Fig .(5)closed loop step response**

5.2 conventional PID Controller for engine speed control system:

Defining U (t) as the controller output to the process, the form of the PID algorithm is:

$$U(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad \text{..........(11)}$$

K_p: Proportional gain, K_i : Integral gain, K_d: Derivative gain, t: Time or instantaneous time ,the variable e(t)represents the tracking error which is the difference between the desired input value and the actual output , this error signal will be sent to the PID controller and the controller computes both the derivative and the integral of this error signal [16].

There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model, and then choosing P, I, and D based on the dynamic model parameters. One of the well known methods is the manual method. If the system must remain online, one tuning method is to first set K_i and K_d values to zero. Increase the K_p until the output of the loop oscillates, then K_p should be set to approximately half of that value for a "quarter amplitude decay" type response. Then increase K_i until any offset is correct in sufficient time for the process. However, too much K_i will cause instability. Finally, increase K_d, if required, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much K_d will cause excessive response and overshoot. A fast PID loop tuning usually overshoots slightly to reach the set point more quickly.[17]

In this paper, the PID controller is used to a chive a satisfactory speed regulation when increased the disturbance rejection. The best result can be obtained of the PID controller parameters are ($K_p = 4, K_i = 2, K_d = 0.5$).

To demonstrate dead-zone compensation, a conventional dither technique is used, which explained in section (2.2).The dither signal is inserted into the feedback loop just before the input to the actuator. The amplitude of the dither signal should exceed the dead-zone and the frequency of the dither should be higher than the closed loop bandwidth of the system.

To illustrate the effect of the controller parameters on the dynamic and tracking response of the closed loop system with the load placed upon it the system must be contain a simple signal generator to a provide low frequency test square signal equal 2 volt, with 1.006 Hz. The dither signal is square wave has amplitude (2volt) and a frequency of (7Hz), dead zone is (-0.5 to +0.5) and the disturbance 2 volt square wave.

The PID controller for the proposed system is shown in **Figure. (6),** the simulation results are shown in **Figures. (7)& (8)** without and with dither respectively. The response in **Figure.(7)** there is a tracking with distortion in the dynamic response so the speed unregulated. In Figure **(8)** the dither signal should linearize the system and reduce the effect of non linear gain if the distribution rejection increased, but it has a little effect a possible on the controlled variables and there is a steady state error will be increased if the operation time for system will be increased ,and lost the tracking at 2.3 sec.

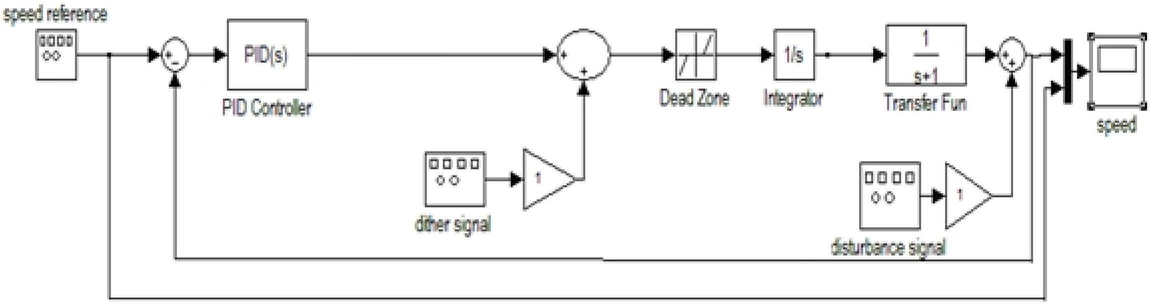


Fig .(6) Simulink model of steam engine speed control

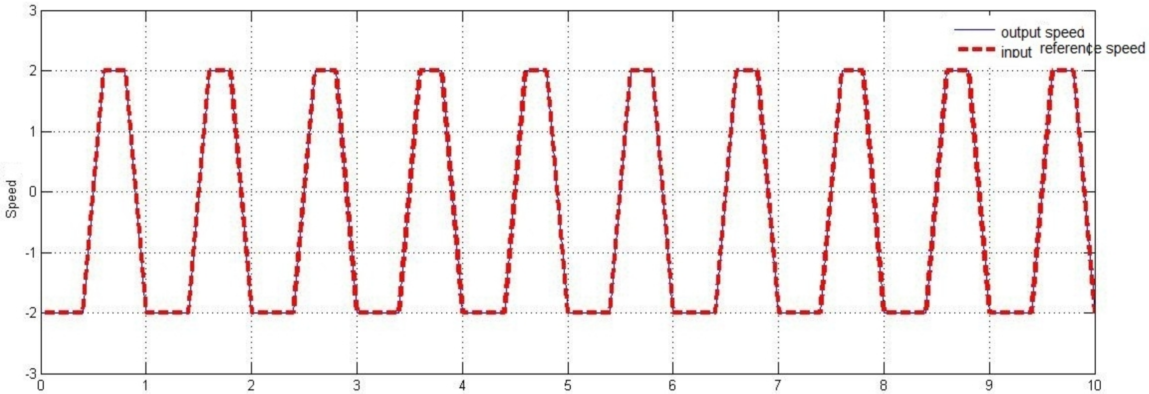


Fig.(7) speed response without dither signal

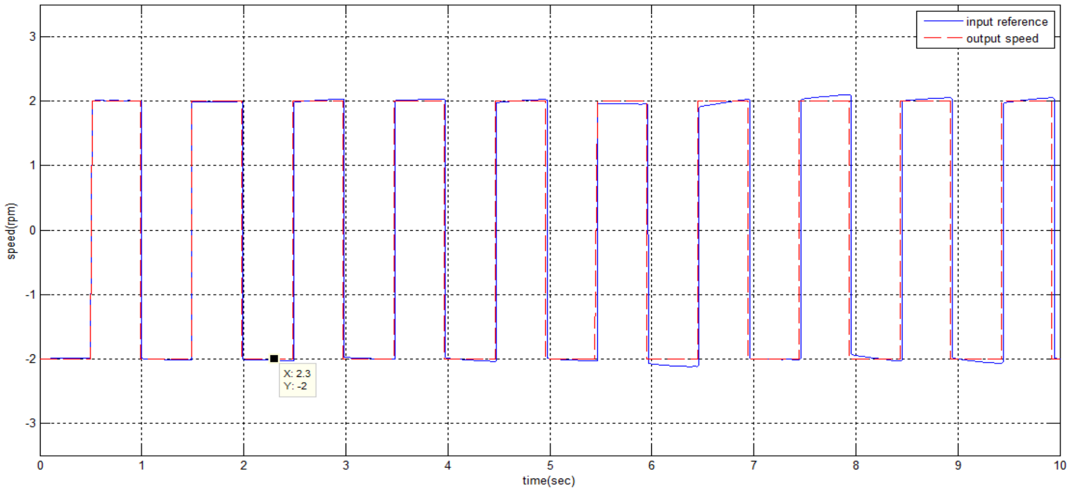


Fig .(8)speed response with dither signal

5.3 Implementation of automatic tuning PSO- PID controller:

In this paper a PSO is used to find the optimal parameters of PID controller for steam engine speed system. **Figure. (9)** shows the Simulink of the proposed system where the engine control system without using the dither signal .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 system performance of PSO-PID controller is shown in Figure. (10) which gives good regulation speed with fully tracking between input reference speed and output speed .The flow chart of PSO-PID controller is shown in Figure. (11). The PSO algorithm was simulated and tested by tuning the various parameters like population size, inertia weight and acceleration factor. The optimum PID parameter values that are achieved a better solution are: $K_p = 3.7563, K_i = 1.2755, K_d = 2.5298$.The simulation was done using the Simulink package available in Matlab interfaced with (m.file) for PSO algorithm program. The simulation time was set to 10 second; the speed reference input was 2 volt from signal generator (1.006 HZ);Particle Swarm Optimization (PSO) algorithm, parameter values are: number of iterations =10, population size=30, $w = 0.3, c_1 = c_2 = 1.2$, $b = 0.7$

ITSE=0 so error=0%

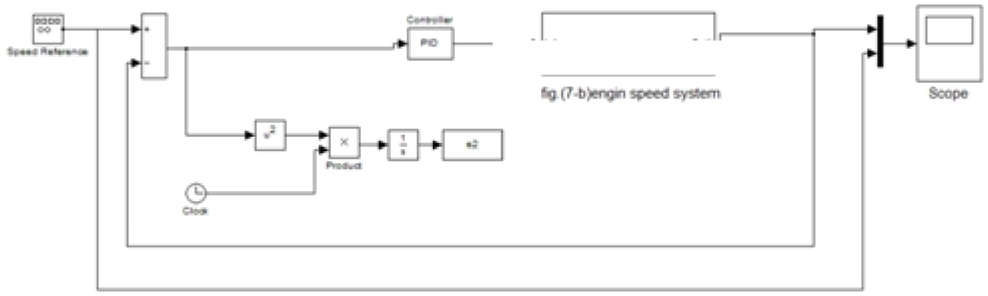


Fig .(9) Simulink of PID using PSO method for steam engine speed control system

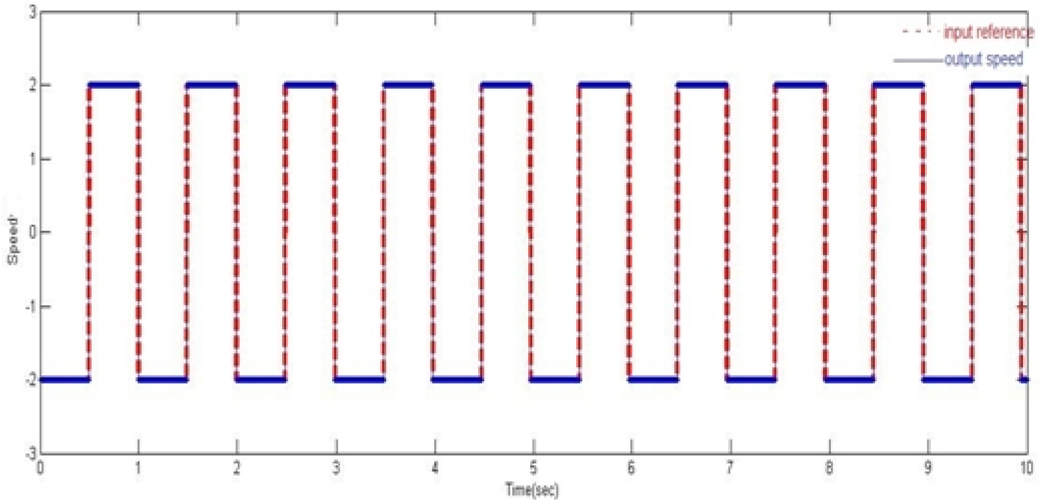


Fig .(10) System Performance of PSO-PID automatic Tuning Method.

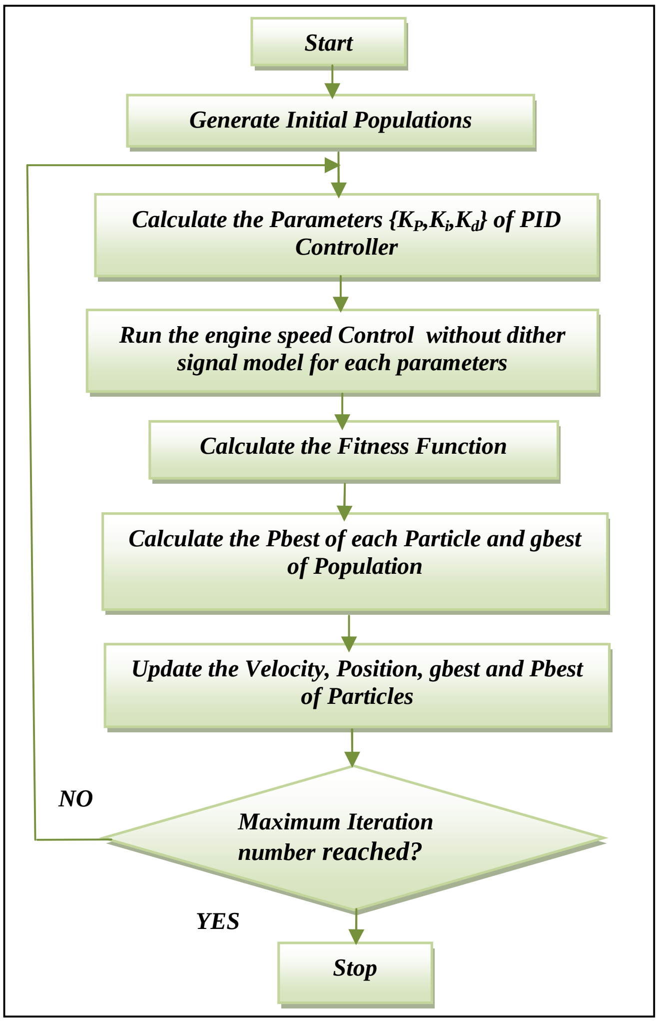


Fig .(11) The Flowchart of the PSO-PID Control System

6. Comparison results:

The intelligent PSO technique gives highly trace over of the conventional PID controller.

The speed response of PSO-PID controller comparing with the speed response of PID-conventional controller as shown in Figure.(12).The output speed with PID controller loss the tracking at (2.3 sec.) and when increase the operation time the system unregulated and increase the oscillation under any small change in disturbance rejection frequency where PSO-PID controller has highly tracking between input /output for any simulation time response and the output is like input reference meaning that the response has not any distortion or tracking error .

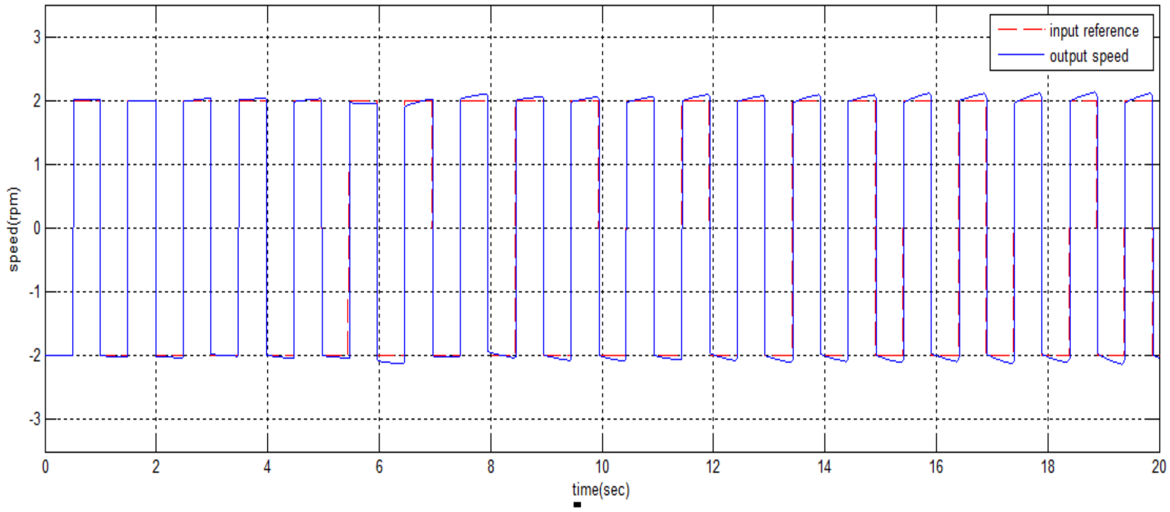


Fig .(12) Speed response of PSO-PID controller comparing with the speed response of PID-conventional controller

7. Conclusion:

In this work a PSO method is used to determine PID controller parameters automatically through simulation of steam engine speed control system. The results show that the proposed controller can perform an efficient search for the optimal PID controller by comparing with the conventional controller methods, it shows that this method have exhibited relatively good performance and the output response full tracking with speed reference for all time response and their typical characteristics show a faster and smoother response.

The advantage of using PSO tuning PID is the computational efficiency, because it is very easy of the implementation and the computation processes is very fast, comparing with conventional methods.

The PSO-PID technique gives better response than PID controller in terms of trajectory tracking.

Finally the proposed automatic tuning is intelligent method to control a non linear input an actuator and to regulate the speed of engine without using the conventional solution (dither signal) that is simplicity but its limited when using disturbance rejection in non linear system.

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