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Auto Tuning of PID Controller Using Swarm Intelligence

M. H. T. Omar, W. M. Ali, M. Z. Mostafa

Abstract – *A control system is a device or set of devices used to manage, command, direct or regulate the behavior of other devices to provide desired system response. PID controllers are the most popular controllers because of their effectiveness, simplicity of implementation and broad applicability. However, PID controller tuning is considered as an obstacle towards having an efficient and stable control system, where most of the PID controllers in practice are tuned by traditional techniques or by manual tuning which are difficult and time consuming. This paper presents a study for the methodology and application of Swarm intelligence for the tuning of the PID controllers compared to two other methods, first one is the traditional tuning method presented by Ziegler Nichols method, and second one is the random search method. Four case studies are included to emphasize the effectiveness of tuning using swarm. Simulation results showed that the PID controller, tuned by PSO method, provides accurately the desired closed loop dynamics (overshoot, rise time, settling time, and steady state error). So, PSO method could be considered as an effective and reliable auto tuning method for the PID controllers.* ***Copyright © 2011 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Particle Swarm Optimization, Automatic Control, PID Controller, Artificial Intelligence, Ziegler and Nichols Method, Random Search Method*

Nomenclature

X_o^i	Initial position
V_o^i	Initial velocity
r	Random variable that can take any value between 0 and 1
V^i_{k+1}	Velocity of particle i at time k+1
w	Inertia factor, (range: 0.4 to 1.4)
c_1	Self confidence, (range: 1.5 to 2)
c_2	Swarm confidence, (range: 2 to 2.5)
p_k^g	Position of the particle with best global fitness at current move
p^i	Best position of particle "i" in current and all previous moves
v^i_k	Position of particle "i" in the design space at time "k"
x^i_k	Position of particle "i" in the design space at time "k"
Δt	Time increment

I. Introduction

In some cases, the operators have to record various indications for use in day-to-day operation of the facility. The information recorded helps the operator evaluate the current condition of the system and take the appropriate actions if the conditions are not as expected. Requiring the operator to take all of the required corrective actions is impractical, or sometimes impossible, especially if a large number of indications must be monitored. For this reason, most systems are controlled automatically once they are operating under normal conditions. Automatic controls greatly reduce the burden on the operator and make his job manageable [1].

Proportional Integral Derivative (PID) controller provides a generic and efficient solution to real world control problems [2]–[5]. Due to its simplicity, excellent and optimal performance in many applications, PID controllers are used in more than 95% of closed-loop industrial processes [6], So, PID control has stimulated and sustained research to get the optimum PID controller [7], and to find the methodology for PID tuning because the tuning process could be considered as on of the most important and tricky things [8]. Tuning is the art of selecting values for the tuning parameters *Kp* (proportional gain), *Ti* (reset time), and *Td* (derivative time) so that the controller will be able to eliminate an error quickly without causing the process variable to fluctuate excessively. In other word, these tuning parameters are chosen to meet prescribed performance criteria [9]. Classically theses performance criteria specified in terms of rise and settling times, overshoot, and steady state error, following a step change in the demand signal. The optimum behavior on a process or set point change varies depending on the application. Some processes must not allow an overshoot of the process variable beyond the set point if, for example, this would be unsafe. Other processes must minimize the energy expended in reaching a new set point [10]. The

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PID controller must be tuned for the particular process loop. Without such tuning, it will not be able to function, where tuning is part of the design of the loop. There is no single definition of best tuned that applies to all loops [11], [12].

The effect of the PID controller tuning parameters on system dynamics of the control loop [13]-[15], and the Initial tuning parameters values of PID controller for common control loops [16]-[18], is shown in Tables I and II, respectively.

TABLE I
RELATION BETWEEN PID CONTROLLER TUNING PARAMETERS AND SYSTEM DYNAMICS

	Kp	Ki	Kd
Tr	Decrease	Decrease	Minor
Mp	Increase	Increase	Decrease
Ts	Minor	Increase	Decrease
Ess	Decrease	Eliminate	Minor

TABLE II
INITIAL TUNING PARAMETERS VALUES OF PID CONTROLLER FOR COMMON CONTROL LOOPS

Loop Type	P (PB) %	I (Rrep/min)	D (min)
Flow	50 : 500	20 : 200	----
Liquid pressure	50 : 500	20 : 200	----
Gas pressure	1 : 50	0.02 : 10	0.02:0.1
Liquid level	1 : 50	0.1 : 1	0.01:0.05
Temperature	2 : 100	0.02 : 5	0.1:20

The settings shown in Table II are rough estimated, and don't apply to all controllers. The PID controller should be started from these values to find the proper PID settings for every certain system [19], [20]. There are several prescriptive rules used in PID tuning. One of the most famous traditional tuning methods is that proposed by Ziegler and Nichols in the 1940's. In 1942, Ziegler and Nichols, both employees of Taylor Instruments, described simple mathematical procedures, the first and second methods respectively, for tuning PID controllers. These procedures are now accepted as standard in control systems practice and still widely used today [20]. Practically most of vendors and users apply these methods or some simple modifications of them in the PID controller tuning [22]. Ziegler-Nichols formulas are based on plant step responses [21]. The closed-loop system of methods has a poor damping and robustness, which could be considered as essential drawbacks with this method. Consequently there have been many attempts to overcome these drawbacks [22].

Many random search methods, such as evolutionary computation have recently received much interest for achieving high efficiency and searching global optimal solution in problem space [23]. In this paper, a new branch of evolutionary computation is applied, namely swarm intelligence to the PID controller to get the optimal tuning parameters that could adjust system response to fit the required system dynamics and compare these results with the Ziegler-Nichols and the randomized methods.

II. Swarm Intelligence

II.1. History

Particle Swarm Optimization (PSO) technique based on the ability of a flock of birds or a school of fish to capitalize on their collective knowledge in finding food or avoiding predators [24]. PSO was originally inspired by the study of bird flocking behavior by biologist Frank Heppner in the 1970s [25]. PSO technique was invented by James Kennedy and Russell Eberhart in the mid-1990s while attempting to simulate the choreographed, graceful motion of swarms of birds as part of a study investigating the notion of collective intelligence in biological populations [26].

II.2. The Basic PSO Algorithm, Flow Chart

In PSO, a set of randomly generated solutions (initial swarm) propagates in the design space towards the optimal solution over a number of iterations (moves). Each swarm member or particle has a small memory that enables it to remember the best position it found so far and its goodness. Particles are affected by their own experience (best found position) and their neighbors' experiences (best found position by the neighbors) [24].

The basic PSO algorithm consists of three steps, namely, generation of particles and their information, movements and new information vector. These staps can be considered as generating particle's positions and velocities, velocity update, and finally, position update.

x_{max} and x_{min} donating the upper and lower bonds could be considered as the basic parameters that are used to generate the positions (x^i_k), and velocities, (v^i_k) of the initial swarm of particles as shown in Equations (1) and (2) [27]:

$$x_0^i = x_{min} + rand\left(x_{max} - x_{min}\right) \quad (1)$$

$$v_0^i = \frac{x_{min} + rand\left(x_{max} - x_{min}\right)}{\Delta t} = \frac{position}{time} \quad (2)$$

The second step which is the position update is based mainly on particles' fitness values.

The fitness function value of a particle not only determines which particle has the best global value in the current swarm (p^g_k), but also determines the best position of each particle over time (p^i), in the current and all previous moves.

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These two pieces of information (p^g_k and p^i) for each particle in the swarm are used to provide a search direction for the next iteration, to ensure good coverage of the design space and to avoid entrapment in local optima [28].

The three values that effect the new search velocity, namely, current motion (v^i_k), particle own memory ($rand\frac{\left(p^i - x^i_k\right)}{\Delta t}$), and swarm influence ($rand\frac{\left(p^i_k - x^i_k\right)}{\Delta t}$), are incorporated via a summation approach as shown in Equation (3) with three weight factors, namely, inertia factor (w), self confidence factor (c_1), and swarm confidence factor (c_2):

$$v^i_{k+1} = wv^i_k + c_1\ rand\frac{\left(p^i - x^i_k\right)}{\Delta t} + c_2\ rand\frac{\left(p^g_k - x^i_k\right)}{\Delta t} \quad (3)$$

The research presented in this paper based on setting the three weight factors w, c_1, and c_2 as 0.4, 1.1, and 1.1 respectively.

The third step which is the position update is expressed in Equation (4) and shown in Fig. 1 [29], [30]:

$$x^i_{k+1} = x^i_k + v^i_{k+1}\Delta t \quad (4)$$

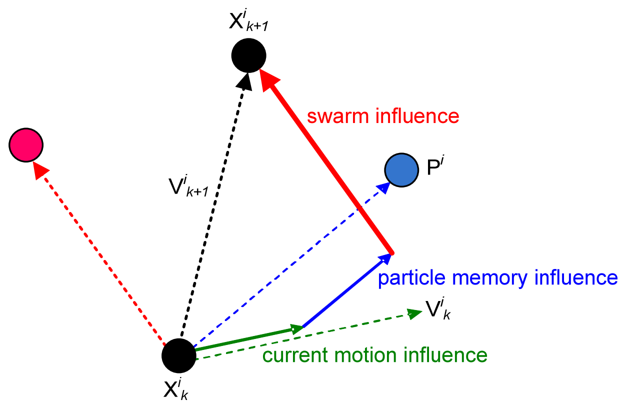

Fig. 1. Depiction of the velocity and position updates in PSO

The three above motioned PSO steps should be repeated until a desired convergence criterion is met. In the PSO algorithm implemented in this paper, the stopping criteria is that the actual error obtained from the proposed PSO tuning method should be smaller than the desired error. Total error equals to the summing of all constraints' error (over shoot, settling time, rising time, steady state).

There are wide PSO applications in engineering systems, around 650 PSO applications, so, it is very difficult to collect all these applications in a single paper. Some of theses applications are Antennas, Biomedical, Control, Design, Distribution Networks, Entertainment, Image and Video, Electronics and Electromagnetics, Modeling, Neural Networks, Power Systems (which include automatic generation control) [31], [32], Robotics, Scheduling (which include generator and transmission maintenance scheduling, power generation scheduling, tasks scheduling in distributed computer system, scheduling in battery energy storage systems), Security and Military, Sensor Networks, and Signal Processing [33].

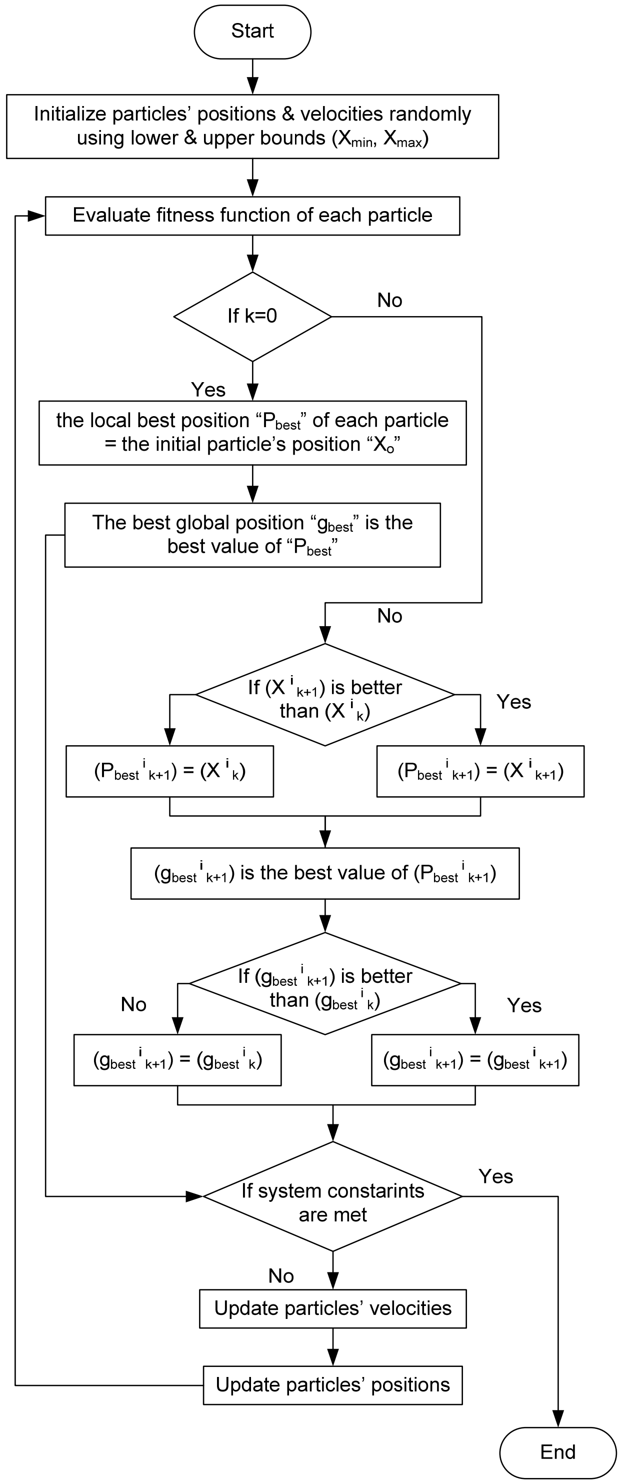

Fig. 2. General form of PSO algorithm

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III. Applying Swarm Intelligence to the Auto Tuning Problem

The structure of the proposed PSO tuning algorithm will be described in this section. This structure is implemented by means of a Matlab program. The flow chart of the proposed PSO program is shown below.

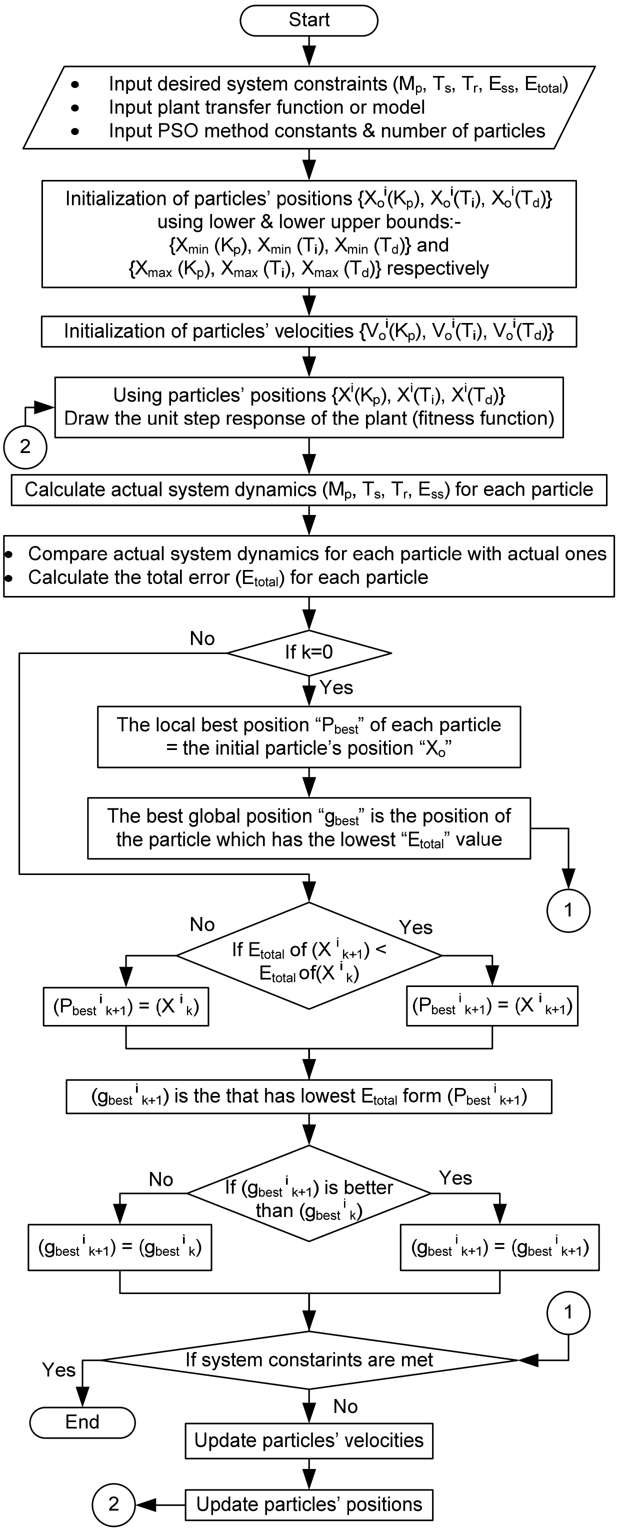

Fig. 3. Flowchart of PID controller tuning using PSO program

IV. Case Studies

The objective of this research is to statistically compare the performance of the three proposed tuning methods, Z-N, Randomized, and PSO, and to illustrate the effectiveness of the proposed approach using a representative set of test plants that are of diverse properties.

In this section, four cases are implanted to present examples for a real plant where the proposed tuning methods and a comparison study between them are carried out. These case studies are listed below.

IV.1. Case Study (1): Linear Hydraulic System

This hydraulic system as shown in Fig. 3. is mainly based on a direct operated control valve which is used to control the position, and velocity of a double acting hydraulic cylinder through a hydraulic fluid flow driven by a hydraulic pump. The position of the hydraulic cylinder along its stroke is measured using a linear variable differential transformer (LVDT). The feedback signal coming from the LVDT and the set point are fed to a PID controller to drive the output control signal of the control valve [34].

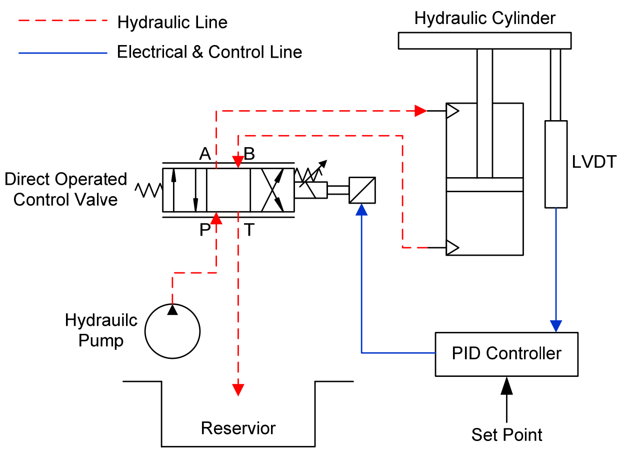

Fig. 4. Process and instrumentation diagram of the hydraulic system

Plant transfer function is:

$$\frac{0.236}{2.8e^{-7}S^3 + 1.06e^{-3}S^2 + S} \tag{5}$$

System constraints:

- Desired Overshoot < 1.3
- Desired Settling time < 0.4 Seconds
- Desired Rising time < 0.03 Seconds
- Desired offset $< 5\%$
- Desired error $\leq 0.5\%$
- If the actual constraint is less than the desired one, the error will be considered equal to zero.

Results:

the overall output of unit step response for this case study and its summarized results are shown in Fig. 5, and Table III respectively.

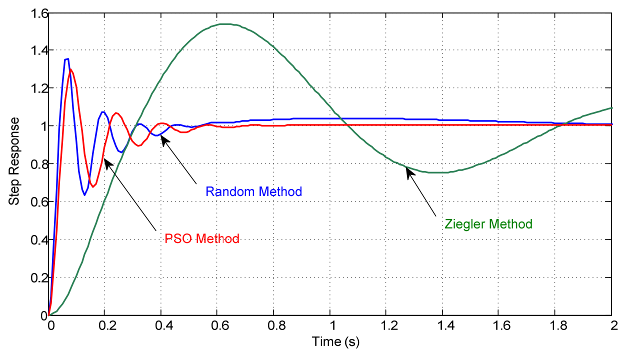

Fig. 5. The step response of three tuning algorithms

TABLE III
COMPARISON BETWEEN THREE TUNING METHODS

	Z-N	PSO	Random
Kp	12.1846	87.2847	67.8492
Ti	0.1603	7.3310	0.5569
Td	0.0401	0.1617	0.3406
Actual M_p	1.5389	1.2982	1.3663
Actual T_s	2.01	0.3600	0.2950
Actual T_r	0.22	0.03	0.0250
e_{ss} *error*	0	0	0
Error (%)	1054.2	0	5.0980
No. of iterations	1	80	1000

IV.2. Case Study (2) Linear Electrical Control with Disturbance (D.C motor)

Plant transfer function is [35]:

$$\frac{0.01}{0.005S^2+0.06S+0.1001} \tag{6}$$

System constraints:

- Desired Overshoot < 1.4
- Desired Settling time < 0.05 Seconds
- Desired Rising time < 0.01 Seconds
- Desired offset < 1 %
- Desired error $\leq 0.5\%$
- If the actual constraint is less than the desired one, the error will be considered equal to zero.

Results:

the overall output of unit step response for this case study and its summarized results are shown in Fig. 6, and Table IV respectively.

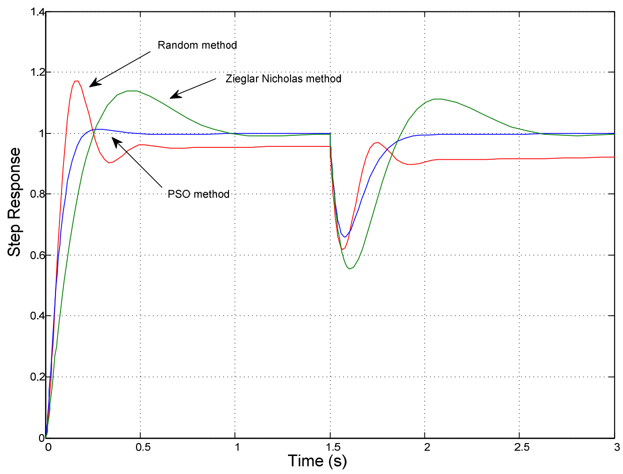

Fig. 6. The step response of three tuning algorithms

TABLE IV
COMPARISON BETWEEN THREE TUNING METHODS

	Z-N	PSO	Random
Kp	45.62	90.1199	170.61
Ti	0.2545	0.6122	7.538
Td	0.0636	0.05939	0.0135
Actual M_p	1.1474	1.0129	1.16
Actual T_s	0.76	0.4	0.47
Actual T_r	0.2	0.13	0.08
e_{ss} error	0`	0	4.5%
Error (%)	12.8799	0	10.409
No. of iterations	1	60	1000

IV.3. Case Study(3)(Linear Thermal Control System with Delay

It is a thermal control system, where an electrically heated aluminum block is surrounded by a water jacket, into which is inserted a platinum resistance thermometer "RTD". The control problem is to maintain the process temperature under variation of heat losses (by changing the cooling water flow rate) at a certain set-point. The required process temperature (set-point) is adjusted by graduated dial on the panel. The error signal is used to drive the PID controller. The controller processes the incoming temperature deviation signal to power the heater. The schematic diagram of the system is shown in Fig. 7 [36].

Plant transfer function is:

$$\frac{1.165*e^{-2.5S}}{25S+1} \tag{7}$$

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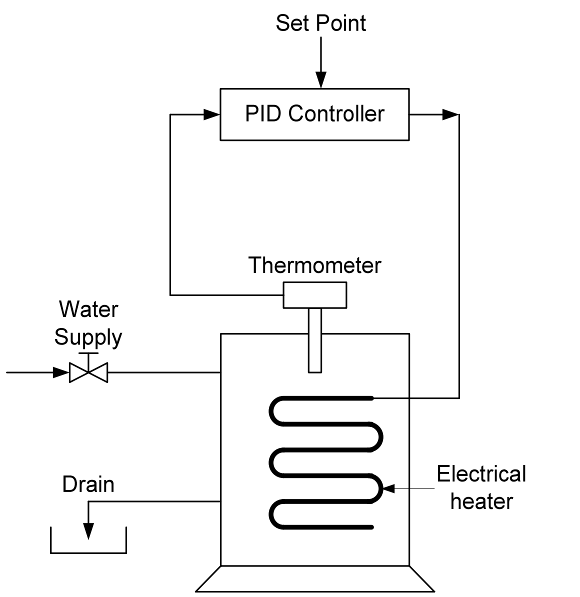

Fig. 7. Schematic diagram of temperature process

System constraints

- Desired Overshoot < 1.2
- Desired Settling time < 30 Seconds
- Desired Rising time < 10 Seconds
- Desired offset < 5 %
- Desired error $\leq 0.5\%$
- If the actual constraint is less than the desired one, the error will be considered equal to zero.

Results:

the overall output of unit step response for this case study and its summarized results are shown in Fig. 8, and Table V respectively.

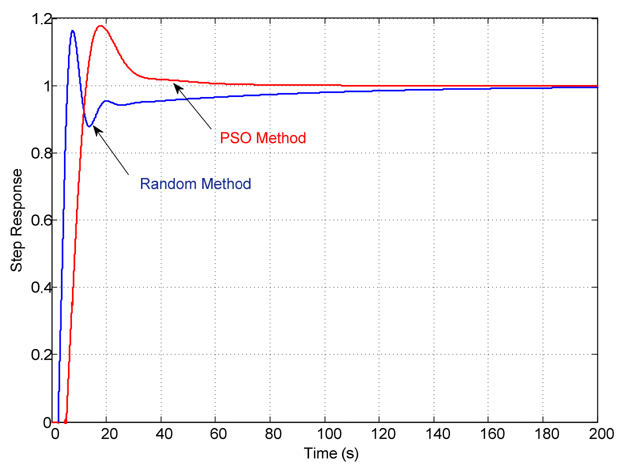

Fig. 8. The step response of different tuning methods

IV.4. Case Study (4): Non-Linear Permanent Magnet Synch. Motor

The d-q model can be expressed in state-space form as follows, considering that, all quantities in the rotor reference frame are referred to the stator [37]:

$$\frac{di_d}{dt} = \frac{\left(V_d - R_s i_d + \omega_r L_q i_q\right)}{L_d} \tag{8}$$

$$\frac{di_q}{dt} = \frac{\left(V_q - R_s i_q - \omega_r L_d i_d - \omega_r \lambda_{af}\right)}{L_q} \tag{9}$$

$$\frac{d\omega_r}{dt} = \frac{\left(T_e - B\omega_r - T_l\right)}{j} \tag{10}$$

$$\frac{d\theta}{dt} = \omega_r \tag{11}$$

where:

- L_q, L_d: The q and d axis inductances
- R_s: Resistance of the stator windings
- i_q, i_d: The q and d axis currents
- V_q, V_d: The q and d axis voltages
- ω_r: Angular velocity of the rotor
- λ_{af}: Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
- B: The damping constant in Newton per radian per second
- T_e: Electromagnetic torque

TABLE V
COMPARISON BETWEEN THREE TUNING METHODS

	Z-N	PSO	Random
Kp	106.9	2.0248	0.2676
Ti	0.4702	12.801	34.81
Td	0.1175	1.7429	5.44
Actual M_p	Very high	1.178	1.164
Actual T_s	Very high	28.66	32.17
Actual T_r	Very high	5.56	2.68
e_{ss} error	Very high	0	0
Error (%)	Very high	0	7.233
No. of iterations	1	110	1000

System constraints:

- Desired Overshoot < 1.4
- Desired Settling time < 0.05 Seconds
- Desired Rising time < 0.01 Seconds
- Desired offset < 1 %
- Desired error $\leq 0.5\%$
- If the actual constraint is less than the desired one, the error will be considered equal to zero.

Results:

the characteristics of permanent magnet synchronous motor that result by applying the PSO method are shown

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in Figs. 9 – 12, these figures are illustrating, the three phase current, voltages, torque versus time, and output speed respectively

The overall output of unit step response for this case study and its summarized results are shown in Fig. 11, and Table VI respectively.

In the four above mentioned case studies, the only the method that can achieve the desired system constraints is the PSO method where it has 0% error unlike the two other methods, considering that, in case study (2), and (4), the Z-N method can't be applied because these system are a liner system with disturbances and a nonlinear system respectively.

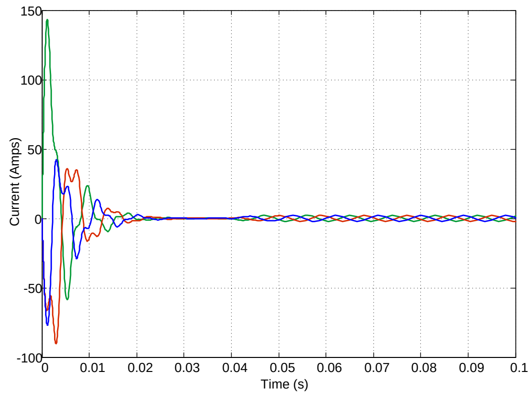

Fig. 9. Three phases current before and after loading

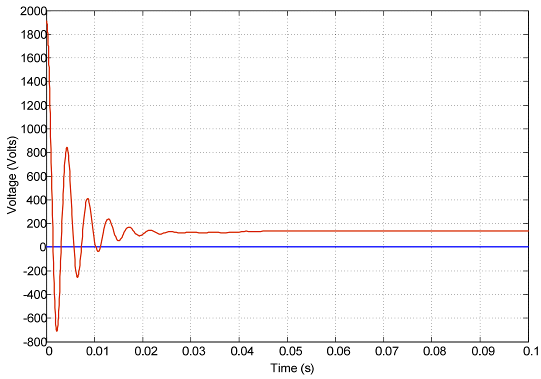

Fig. 10. vd,vq voltages

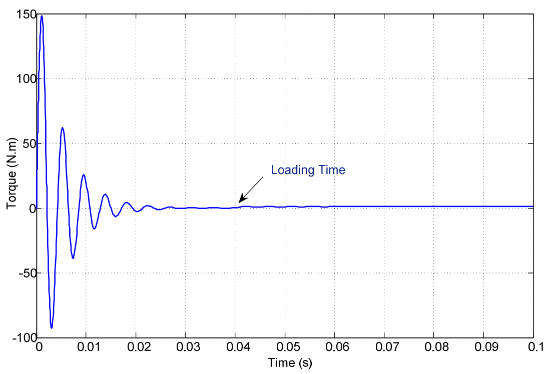

Fig. 11. Torque versus time before and after loading

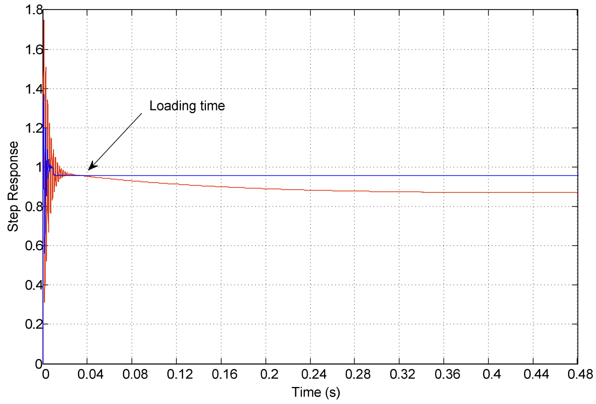

Fig. 12. The step response of PSO and Randomized methods

TABLE VI
COMPARISON BETWEEN THREE TUNING METHODS

	PSO	Random
Kp	2.5594	1.12
Ti	1.5572	2.2077
Td	0	0.16966
Actual M_p	1.3667	1.7466
Actual T_s	0.0132	0.0114
Actual T_r	1.4 *10-3	0.45*10-4
e_{ss} error	0	12.93%
Error (%)	0	37.6884
No. of iterations	21 X 10 = 210	1000

V. Discussion

The features of the three proposed auto-tuning methods are summarized in the following points:-

- *Ziegler-Nichols method*: It can only obtain one system response for any certain plant regardless the desired system response (dynamics). So, the error may or may not be high; it is a matter of luck. For this reason, it couldn't be considered as a reliable method.
- *Random method*: It is a random search way, where a preset number of iteration is implemented. The large number of iterations the high probability to obtain accurate results. The main disadvantage point of this method is that, although there are too many implemented iterations, but this can't grantee obtaining the required system dynamics as well as the long consumed time due to the large number of iterations.
- *PSO method*: It is a random search method but it combined with an artificial intelligence features, so, it can get the required system dynamics accurately in a very short time (small number of iterations).

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VI. Conclusion

PSO is one of the new artificial intelligence branches that have many applications in several fields. Automatic control field is one of the fields that could employ the PSO. This work proposes a new process between the artificial intelligence which is presented in PSO and automatic control which is presented in PID controller. Regarding to the above mentioned case studies which represent several control systems and different conditions, clearly, the best and the most effective tuning method is the PSO method, where the accurate result is obtained in very fast time. The PSO has an additional unique advantage which is that, it could adapt any change in system conditions, and/or obtain different system dynamics accurately in a short time period; time is very critical point in control systems. So, it could be considered as an efficient method for auto-tuning process of the PID controller to solve the problems of the former tuning methods. It could be considered as a breakthrough in the automatic control field where the features of artificial intelligence and automatic control are allied to form an optimum solution of auto-tuning of PID controller.

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Authors' information

Eng. Mohamed H. T. Omar Has received his BSc degree in communications and electronics from Alexandria University, Faculty of Engineering, in 2000. From 2000 to 2005 he worked as Electrical engineer in AWGA and ABB Susa companies in Egypt and Al-Khalij Company in KSA respectively. Since 2005 he is working as Instrumentation and Automatic Control engineer in Egyptian Natural Gas Co. (Gasco).

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Dr. Walid M. Aly Has received his Ph. D. on 2004 in the field of Electrical Engineering from the faculty of engineering, Alexandria University, Egypt. His research interests are Artificial Intelligence techniques, Electronic Design automation & intelligent engineering systems. Currently he works as a full time lecturer at Arab Academy for Science, Technology & Maritime Transport.

Prof. Dr. M. Z. Mostafa is a professor in the Electrical Engineering Department, Faculty of Engineering, Alexandria Unversity. He recived his Ph. D. dgree in 1973 from the Unversity of Paris, France. He is the author or co-author of serveral thechnical papers on automatic control and electric drives.

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