Optimal Tuning of PI Controller for Speed Control of DC motor drive using Particle Swarm Optimization

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Abstract—**This paper present a method to determine the optimal tuning of the PI controller parameter on Direct current (DC) motor drive system using particle swarm optimization (PSO) algorithm, Ziegler-Nichols (ZN) tuning and Modified Ziegler-Nichols (MZN) tuning method. The main objective of this paper is to minimize transient response specifications chosen as rise time, settling time and overshoot, for better speed response of DC motor drive. The speed control of DC motor is done using PI and PID controllers. Implementation of PID controller for DC motor speed control is done using ZN and MZN tuning method. For PSO algorithm technique, PI controller is used to improve the performance of DC motor speed control system. A comparison is made on the basis of objective function (rise time, settling time and overshoot) from output Step responses. The proposed approach had superior features, including easy implementation, stable convergence characteristic, and good computational efficiency. Fast tuning of optimum PI controller parameters yields high-quality solution. Compared with traditional ZN method and MZN method, the proposed method is found indeed more efficient and robust in improving the step response of DC motor drive system.**

Keywords-DC motor, optimal contro, particle swarm optimization, Ziegler-Nichols tuning method, PI controller, PID controller.

I. Introduction

Nowadays several control theories have been developed significantly; we do see the widely popular use of proportional-integral (PI) and proportional integral-derivative (PID) controllers in process control, motor drives, flight control, and instrumentation. The reason of this acceptability is for its simple structure which can be easily understood and implemented. Industries too can boast of the extensive use of PI and PID controllers because of its robustness and simplicity. The past decades witnessed many advancing improvements keeping in mind the requirement of the end users. Easy implementation of hardware and software has helped to gain its popularity. Several approaches have been documented in literatures for determining the PID parameters of such controllers which is first found by Ziegler- Nichols tuning [6]. Genetic Algorithm, neural network, fuzzy based approach [7, 9], particle swarm optimization techniques [1]-[5] are just a few among these numerous works.

In 1942, Ziegler-Nichols presented a tuning formula [6, 13, 14], based on time response and experiences. Although it lacks selection of parameters and has an excessive overshoot in time response, still opens the way of tuning parameters. Modified Ziegler-Nichols tuning based on Chien-Hrones-Reswick (CHR) PID tuning formula [15] for set-point regulation accommodate the response speed and overshoot. The other method used is a population-based optimization method first proposed by Eberhart and Colleagues [1, 2]. Particle swarm optimization (PSO) has attractive features like, ease of implementation and the fact that no gradient information is required. It can be used to solve a wide array of different optimization problems. Like evolutionary algorithms, PSO technique conducts search using a population of particles, corresponding to individuals. Each particle represents a candidate solution to the problem at hand thus has more efficiency for finding problem solution.

Control System Design and Analysis Technologies are widely suppress and very useful to be applied in real-time development. Some can be solved by hardware technology and by the advance used of software, control system are analyzed easily and detail. DC Motors can be used in various applications and can be used as various sizes and rates. Today their uses isn't limited in the car applications (electrics vehicle), in applications of weak power using battery system (motor of toy) or for the electric traction in the multi-machine systems too. The speed of DC motor can be adjusted to a great extent as to provide controllability easy and high performance.

In this paper, an optimal PI-PSO controller, PID-ZN controller and PID-MZN controller are developed for DC motor speed control. The performance measure to be minimized contains the following objectives of the PID controller, that will be studied separately,

1. **Minimize the rise time**, time required for system response to rise from 10% to 90% (over damped); 5% to 95%; 0% to 100% (Under damped) of the final steady state value of the desired response,
2. **Minimize the maximum overshoot**, Maximum overshoot is the maximum peak value of the response curve measured from the desired response of the system, and
3. **Minimize the settling time**, Time required for response to reach and stay within 2% of final value.

II. DC Motor Model

This DC motor system is a separately excited DC motor [7]-[10], which is often used to the velocity tuning and the position adjustment. This paper focuses on the study of DC motor linear speed control, therefore, the separately excited DC

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motor is adopted. Make use of the armature voltage control method to control the DC motor velocity, the armature voltage controls the distinguishing feature of method as the flux fixed, is also a field current fixedly. The control equivalent circuit of the DC motor by the armature voltage control method is shown in Fig. 1.

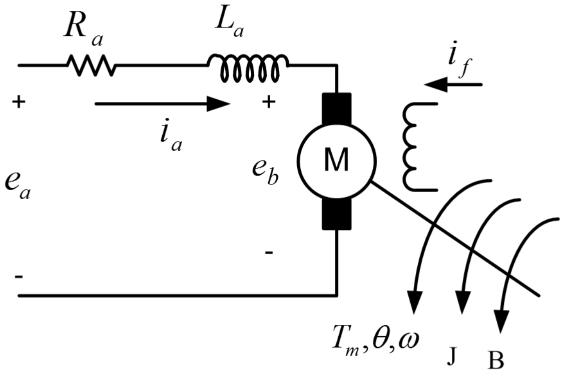

Figure 1. The control Equivalent Circuit of DC Motor using the Armature Voltage Control.

Where,

R_a : Armature resistance;

L_a : Armature inductance;

i_a : Armature current;

i_f : Field current;

e_a : Input voltage;

e_b : Back electromotive force (EMF);

T_m : Motor torque;

ω: An angular velocity of rotor;

J: Rotating inertial measurement of motor bearing;

K_b : EMF constant;

K_T : Torque constant;

B : Friction constant.

Because the back EMF e_b is proportional to speed ω directly, then

$$e_b(t) = K_b \frac{d\theta}{dt} = K_b \omega(t) \tag{1}$$

Making use of the KCL voltage law can get

$$e_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_b(t) \tag{2}$$

From Newton law, the motor torque can be obtained as

$$T_m(t) = J \frac{d^2\theta(t)}{dt} + B \frac{d\theta}{dt} = K_T i_a(t) \tag{3}$$

Take (1), (2), and (3) into Laplace transform, respectively, the equations can be formulated as

$$E_a(s) = (R_a + L_a S) I_a(s) + E_b(s) \tag{4}$$

$$E_b(s) = K_b \omega(s) \tag{5}$$

$$T_m(s) = B\omega(s) + JS\omega(s) = K_T I_a(s) \tag{6}$$

Figure 2 describes the DC motor armature control system function block diagram from equations (1) to (6).

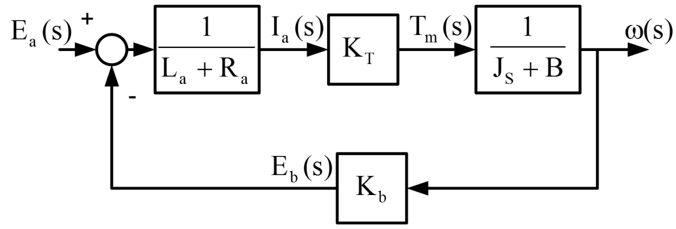

Figure 2. DC Motor Armature Voltage Control System function block diagram.

The transfer function of DC motor speed with respect to the input voltage can be written as follows,

$$G(s) = \frac{\omega(s)}{E_a(s)} = \frac{K_T}{(L_a(s) + R_a)(JS + B) + K_b K_T} \tag{7}$$

III. PI AND PID CONTROLLER

A. PI Controller

Proportional-Integral (PI) controllers [6, 14] are one of the most applicable controllers in different industries. The main important need in application of these controllers is their parameters tuning in order to gain desired result. So an accessible method with high accuracy and speed has to be used for determination of these control parameters (Kp, Ki). The control architecture used for PI controller is shown by figure 3.

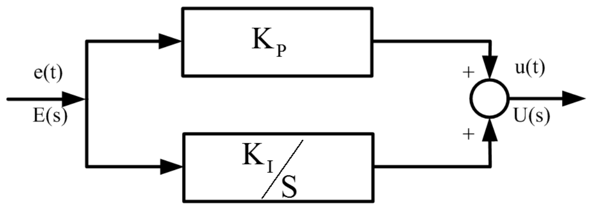

Figure 3. Block diagram of PI controller for PI-PSO controller.

PI-controllers have been applied to control almost any process one could think of, from aerospace to motion control, from slow to fast systems. With changes in system dynamics and variation in operating points PI-controllers should be retuned on a regular basis.

$$U(t) = K_P \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d(\tau) \right] \tag{8}$$

Where u(t) and e(t) denote the control and the error signals respectively, and K_P and T_i are the parameters to be tuned. The corresponding transfer function is given as,

$$K(s) = K_P \left[1 + \frac{1}{T_i(s)} \right] \tag{9}$$

B. PID Controller

Proportional-Integral-Derivative (PID) controllers [6]–[11] are widely used in industrial control systems because of the reduced number of parameters to be tuned. They provide control signals that are proportional to the error between the reference signal and the actual output (proportional action), to the integral of the error (integral action), and to the derivative of the error (derivative action), namely

$$U(t) = K_P \left[e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{d}{dt} e(t) \right] \tag{10}$$

T_d is the parameters to be tuned. The corresponding transfer function is given as

$$K(s) = K_p \left[1 + \frac{1}{T_i(s)} + T_d(s) \right] \tag{11}$$

These functions have been enough to the most control processes. Because the structure of PID controller is simple, it is the most extensive control method to be used in industry so far. The PID controller is mainly to adjust an appropriate proportional gain (K_P), integral gain (K_I), and differential gain (K_D) to achieve the optimal control performance. The PID controller system block diagram of this paper is shown in Figure 4.

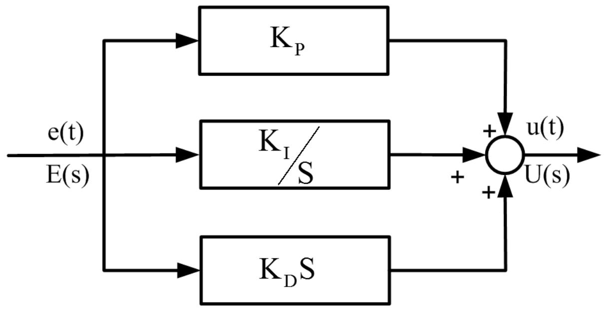

Figure 4. Block diagram of PID controller PID-ZN and PID-MZN controller.

IV. ZIEGLER-NICHOLS METHOD

A. Empirical method

This method is applied to plants with step responses of the form displayed in Fig. 5. This type of response is typical of a first order system with transportation delay. The response is characterized by two parameters, *L* the delay time and *T* the time constant. These are found by drawing a tangent to the step response at its point of inflection and noting its intersections with the time axis and the steady state value. The plant model is therefore,

$$G(s) = \frac{Ke^{-sL}}{TS+1} \tag{12}$$

Ziegler and Nichols derived the following control parameters based on this model. In real-time process control systems, a large variety of plants can be approximately modeled by (12). If the system model cannot be physically derived, experiments can be performed to extract the parameters for the approximate model (12).

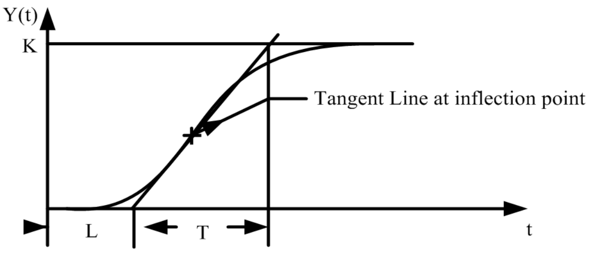

Figure 5. Response Curve for Ziegler-Nichols Method.

For instance, if the step response of the plant model can be measured through an experiment, the output signal can be recorded as sketched in Fig. 5, from which the parameters of *k*, *L*, and *T* (or *a*, where *a = kL/T*) can be extracted by the simple approach shown. More sophisticated curve fitting approaches can also be used. With *L* and a, the Ziegler–Nichols formula in Table 1 can be used to get the controller parameters.

TABLE I. ZIEGLER-NICHOLS TUNING FIRST METHOD

Controller type	*Kp*	*Ti*	*Td*
P	T/L		
PI	0.9T/L	L/0.3	
PID	1.2T/L	2L	0.5L

B. Modified Ziegler-Nichols Tuning method

Modified Ziegler-Nichols tuning using Chien–Hrones–Reswick (CHR) tuning algorithm emphasizes on set-point regulation. . In addition one qualitative specification on the response speed and overshoot can be accommodated. Compared with the traditional Ziegler–Nichols tuning formula, the CHR method uses the time constant *T* of the plant explicitly. The CHR PID controller tuning formulas are summarized in Table 2 for set-point regulation.

TABLE II. MODIFIED ZIEGLER-NICHOLS TUNING SECOND METHOD

Controller type	*Kp*	*Ti*	*Td*
P	0.7/a		
PI	0.6/a	T	
PID	0.95/a	1.4T	0.47T

Here the parameters *k, L*, and *T* are obtained from the response curve of Fig. 5. With $K_I = K_P / T_i$ and $K_D = K_P * T_d$.

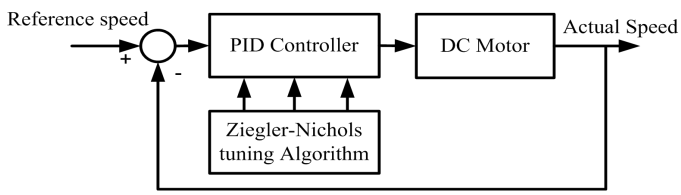

Figure 6. Block diagram of DC motor control system used by PID-ZN and PID-MZN controller.

Thus the values of K_P, Ki and Kd are obtain from tables 1 and 2 to form the transfer function for PID controller. The PID-ZN and PID-MZN controller are made by using table 1, table 2 and applied for speed control of DC shown by block diagram (Fig. 6)

V. PARTICLE SWARM OPTIMIZATION

According to the background of PSO and simulation of swarm of bird, Kennedy and Eberhart developed a PSO concept [2]-[5]. Namely, PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each agent is represented by XY axis position and also the velocity is expressed by vx (the velocity of X axis) and vy (the velocity of Y axis). Modification of the agent position is realized by the position and velocity information.

Bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. This information is analogy of personal experiences of each agent. Moreover, each agent knows the best value so far in the group (gbest) among pbests. This information is analogy of knowledge of how the other agents around them have performed. Namely, Each agent tries to modify its position using the following information:
- the current positions (x, y),
- the current velocities (vx, vy),
- the distance between the current position and pbest
- the distance between the current position and gbest

This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$V_i^{k+1} = WV_i^k + C_1 rand_1 \times (pbest_i - S_i^k) + \dots$$
$$C_2 rand_2 \times (gbest - S_i^k) \qquad (13)$$

Where,
V_i^k : Velocity of agent i at iteration k,
W: weighting function,
C_j : weighting factor,
rand: random number between 0 and 1,
S_i^k : Current position of agent i at iteration k,
$pbest_i$: pbest of agent i,
gbest: gbest of the group.

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$S_i^{k+1} = S_i^k + V_i^{k+1} \qquad (14)$$

Fig.7 shows a concept of modification of a searching point by PSO and Fig. 8 shows a searching concept with agents in a solution space. Each agent changes its current position using the integration of vectors as shown in Fig. 7.

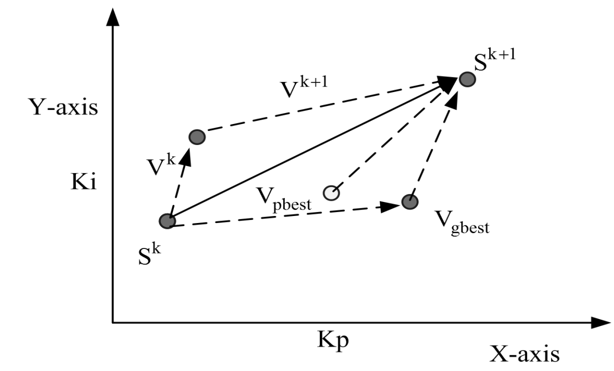

Figure 7. Concept of Modification of searching point by PSO.

Here,

S^k : Current searching point,
S_i^{k+1} : modified searching point,
V^k : Current velocity,
V_i^{k+1} : modified velocity,
V_{pbest} : Velocity based on pbest,
V_{gbest} : Velocity based on gbest.

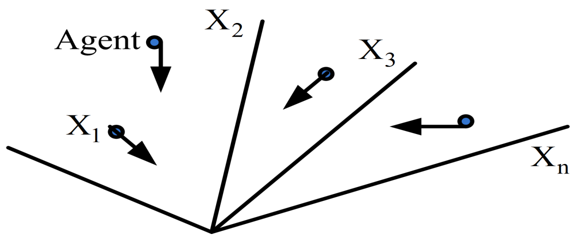

Figure 8. Searching concepts with Agents in solution space by PSO.

VI. RESULT AND ANALYSIS

A standard test model as considered is taken for study of DC motor with Z-N tuning controller. The test model below shown is completely designed in SISO tool. Fig. 6 shows the block diagram of DC motor driving an inertial load.

TABLE III. DC MOTOR PARAMETERS

Parameters	Motor 1	Motor 2
Armature Resistance Ra (Ω)	2	2
Armature Inductance La (H)	0.5	0.5
Moment of Inertia J (Kgm^2)	0.02	1.2
Friction constant B (Nms)	0.2	0.2
Torque constant K_T (Nm/A)	0.015	0.2
EMF constant K_B (Vs/rad)	0.01	0.2

From the state equation (refer (1), (2), (3)) previously, we can construct the model with the environment MATLAB

(R2010a) Simulink. The model of the DC motor in Simulink is shown in Fig. 10. The various parameters of the DC motor are shown in Table 3.

A. Empirical method

Flow Chart as shown in Fig. 9 is used for MATLAB coding to find the PID controller parameters and to get DC motor Close loop unit step response of the overall transfer function.

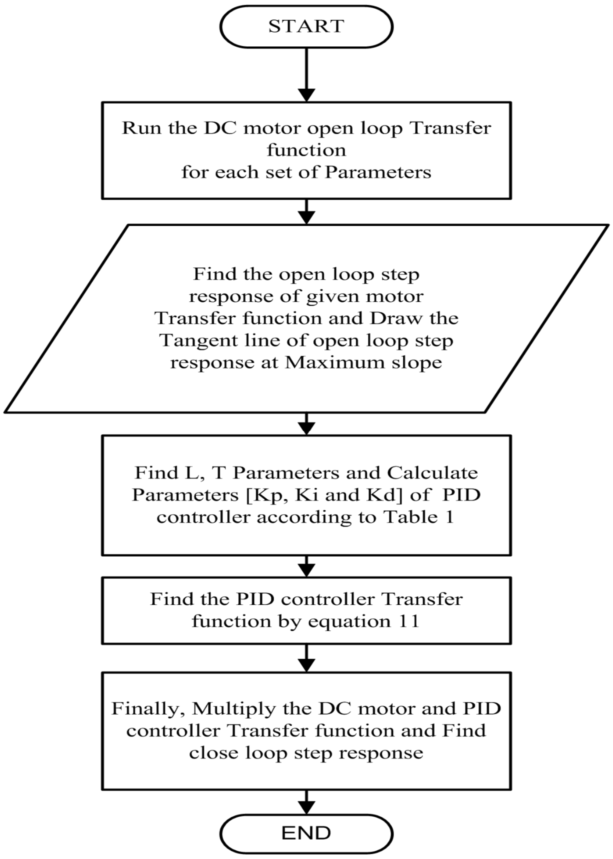

Figure 9. The Flow Chart of Ziegler-Nichols Tuning Method.

The controller is connected in cascaded fashion and step responses for different motors are shown by Fig. 12 and 13.

B. Modified Ziegler-Nichols Tuning Method

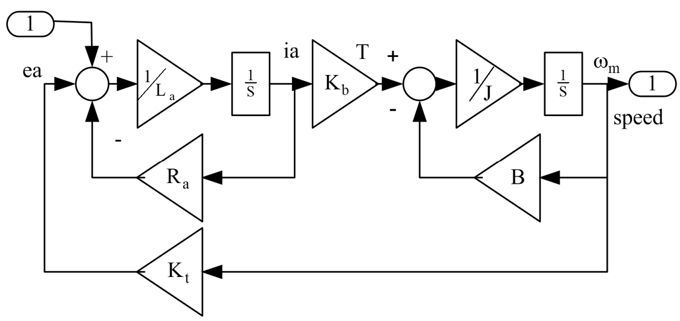

Figure 10. Matlab simulink model for Armature control of DC motor.

Using MATLAB R2010a we can design compensator by Ziegler-Nichols open loop tuning method based on Chien–Hrones–Reswick (CHR) tuning algorithm. The step responses are shown by Fig. 12 and 13.

C. Particle Swarm Optimization

Flow Chart as shown in Fig. 11 is used for MATLAB coding to find the PI controller parameters and function calling of DC motor transfer function is done to find the close loop unit step response.

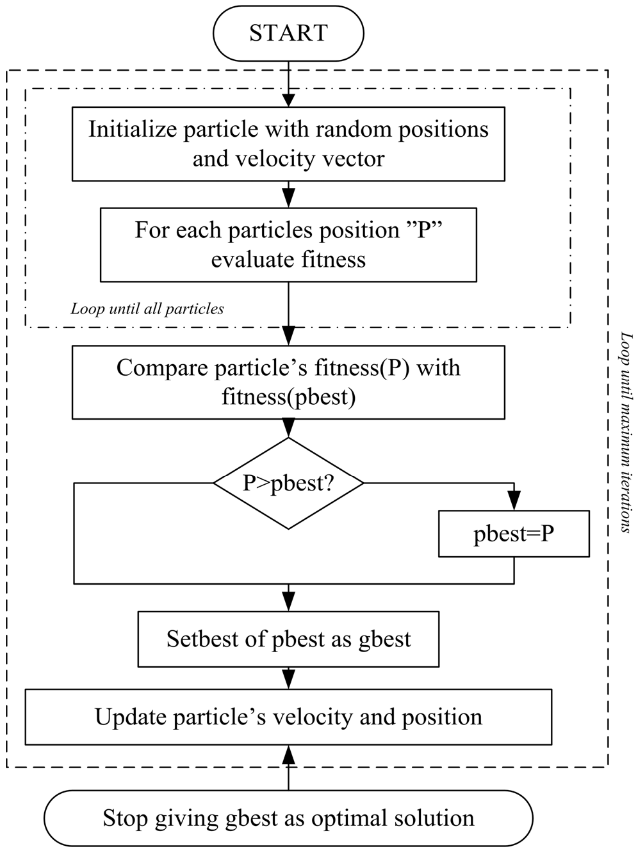

Figure 11. The Flow Chart of Particle swarm optimization Algorithm.

The Step responses by MATLAB coding, using the PSO flow chart are shown by 12 and 13.

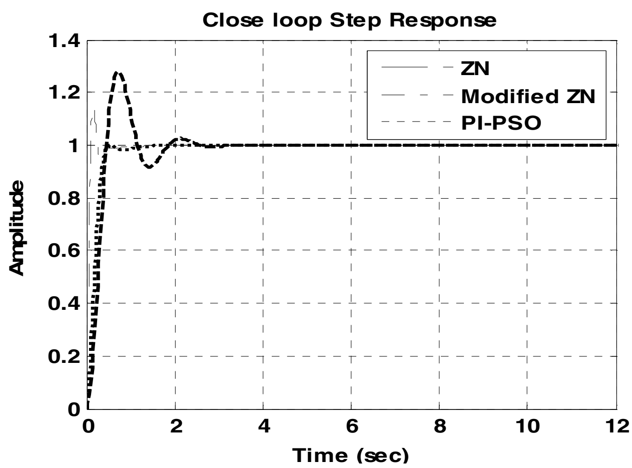

Figure 12. Motor 1.Close loop step response with PID-ZN controller, PID-MZN controller and PI-PSO controller.

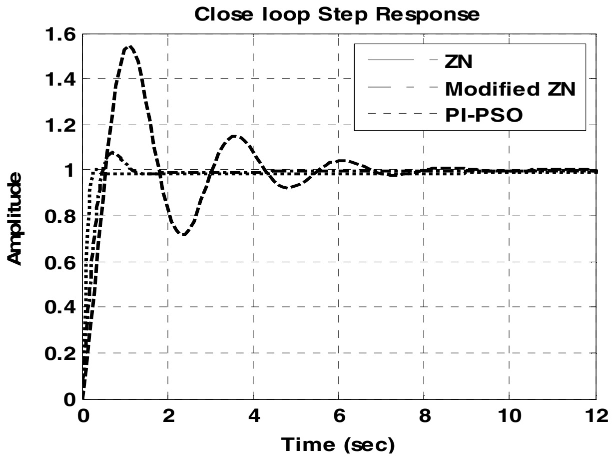

Figure 13. Motor 2. Close loop step response with PID-ZN controller, PID-MZN controller and PI-PSO controller.

TABLE I. TRANSIENT RESPONSE OF MOTOR 1

Method	Rise time (sec)	Maximum overshoot (%)	Settling time (sec)
PID-ZN controller	0.312	27.9	2.27
PID-MZN controller	0.074	14.5	0.439
PI-PSO controller	0.3907	0.042	0.6467

TABLE II. TRANSIENT RESPONSE OF MOTOR 2

Method	Rise time (sec)	Maximum overshoot (%)	Settling time (sec)
PID-ZN controller	0.377	51.8	5.68
PID-MZN controller	0.359	7.7	1.07
PI-PSO controller	0.1678	0	0.2652

VII. Conclusion

In this paper, the tuning parameters of PID controller is designed using traditional Ziegler-Nichols modified Ziegler-Nichols tuning algorithms and PI controller is designed using particle swarm optimization The results of all the three methods are checked by MATLAB coding as well as simulation. The speed of a three different DC Motor parameters is controlled by means of these three controllers. According to the results of the computer simulation, the particle swarm optimization tuned controller efficiently is better than the Ziegler-Nichols and Modified Ziegler-Nichols controller. The PI-PSO controller is the best controller which presented satisfactory performances for the objectives and it is the most robust technique.

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