Performance Evaluation of Different Objective Function in PID Tuned by PSO in DC-Motor Speed Control

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Abstract. The electric motor is an electromagnetic device that converts electrical energy into mechanical energy. There are many industrial sectors using electrical motors. Almost 90% of industries still use PID control because of its simplicity, applicability, and reliability. However, the weakness of PID is that it takes a long time to tune. PSO is one of the optimization methods which can be used to tune PID. The objective function is needed when using PSO to tune PID control. Five different objective functions which are ISE, IAE, ITSE, ITAE, and MSE is compared in terms of performance and control energy. The PID controller is applied in DC motor speed control in a simulation environment. Three testing condition is carried out which is step responses, set-point changes, and disturbance rejection. The simulation result shows that in terms of performance, ITSE is the best one. On the other hand, in terms of control energy, ISE is using the lowest energy to control the plant.

1. Introduction
The electric motor is an electromagnetic device that converts electrical energy into mechanical energy. There are many industrial sectors using electrical motors. By the type of supply current, there are two kinds of electric motor which are AC and DC motor. DC motor has some advantages such as easy to control the speed or position and wide adjustable range [1-2]. However, it also has some drawbacks, one of them is, it uses mechanical commutator (brush) which cause high maintenance cost [3]. DC motors are widely used as in steel rolling mills, electric trains, electric vehicles, and robotics actuators [4].

Based on [5][6], almost 90% of industries still use PID control because of its simplicity, applicability, and reliability. However, the weakness of PID is that it takes a long time to tune [7][8]. Several methods of tuning PID controls have been proposed. This tuning method can be categorized into i) empirical methods such as Ziegler-Nichols (ZN) and Cohen-Coon (CC), ii) analytical methods such as root locus (RL) and frequency response (FR), and iii) optimization methods such as using Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) [8][9].

There are some methods that can be used in optimization-based tuning such as GA, PSO, and ACO. A. Soundararajan, et al. [10], compares the performance of PID tuned by GA and PSO in the AVR system. They conclude that PID based PSO tuning has lower settling time and overshoot. In [11] comparative study between PID-GA and PID-PSO in an industrial process is presented. The result shows that PID-PSO has better performance both in settling time and overshoot.
In [12] GA tuned PID with some objective functions are compared which is ISE (Integral of the Square Error), IAE (Integral of Absolute Magnitude of Error), ITSE (Integral of Time multiplied by the Square Error), ITAE (Integral of Time multiplied by the Absolute Error), and MSE (Mean of the Square Error) to control First Order Lag plus Time Delay (FOLPD) system. The comparison results from overshoot and settling time are shown that the IAE objective function gives the lowest overshoot (OS), while ITAE gives the smallest settling time. Whereas in [13] PSO tuned PID in the AVR system is carried out by comparing IAE, ITAE, ISE, and MSE. The result shows that the best rise-time and peak time is MSE, ITAE has the lowest overshoot, while ISE gives the lowest settling time.

In this research, the performance of the different objective functions in PID tuned by PSO in DC motor speed control will be evaluated. The previous comparison of PID tuned by PSO is applied in the AVR system [13], whereas, this study is using DC motor which has a faster dynamical response. The other contribution is the control effort which relates to energy consumption is also studied. This paper is organized as follows. Section II presents the research method including system design and control design. The result and analysis are described in Section III. Finally, the conclusion is provided in Section IV.

2. Research Method

2.1. System Design

There are three well-known methods used to control the speed of DC motors which are by variation of the flux magnet, changing the resistance of the armature, and varying the input voltage. The controlling method that is used in this research is changing the input voltage. The system used in this study is a mini conveyor with a DC motor. The DC motor used has a 12V 5.5A specification with a maximum speed of 250 rpm and a maximum torque of 10.6 kg/cm. The system model is obtained by taking motor input and output data in the form of voltage and speed using a data logger. Using this data, the transfer function of the system is derived using MATLAB System Identification. The transfer function of the system is shown in (1). The system model is a discrete model with a sampling time of 0.335 seconds.

![Figure 1. Mini conveyor system [14]](image)

\[ TF = \frac{1.091z^2}{z^2 - 0.9102z - 0.036} \] (1)

2.2. PID Tuning Using PSO

PSO was first introduced by Kennedy and Eberhart [15] which made base on the social and communication behaviour of birds, this is referred to as a particle. Every individual is assumed as a vector position and represents a potential solution of optimization problems. The particle has two essential capabilities: their memory of their own best position and knowledge of the global best [16]. The formula for calculating speed and position is shown by (2) and (3) respectively [17].

\[ \text{speed} = \text{velocity} \times \text{acceleration} \]

\[ \text{position} = \text{velocity} \times \text{time} + \text{position} \times \text{time}^2 \]
\[ V_i^{kg+1} = w(t) + V_i^{kg} + c_1 r_1 (p_i^{kg} - X_i^{kg}) + c_2 r_2 (Best_i^{kg} - X_i^{kg}) \]  
\[ X_i^{kg+1} = X_i^{kg} + V_i^{kg} \]  

where \( g = 1, 2, \ldots, G \), \( i = 1, 2, \ldots, \) population size, \( r_1 \) and \( r_2 \) is random values between 0-1, \( c_1 \) is a local learning factor, \( c_2 \) is a global learning factor. Commonly, \( c_2 \) is bigger than \( c_1 \). Figure 2 shows the flow diagram of the PSO algorithm.

PSO was used to tune PID because of its optimization capability to cope with the objective function. The use of PSO for PID tuning has been done as in [16][18]. Some objective function which used in optimal tuning of PID is listed in Table 1.

**Table 1. Some objective function**

| Fitness Function | Equation |
|------------------|----------|
| IAE              | \( \int_0^t |e(t)| \, dt \) |
| ISE              | \( \int_0^t e(t)^2 \, dt \) |
| MSE              | \( \frac{1}{t} \int_0^t (e(t))^2 \) |
| ITAE             | \( \int_0^t t e(t) \, dt \) |
| ITSE             | \( \int_0^t t e^2(t) \, dt \) |

**Figure 2.** Flow diagram of PSO algorithm

### 3. Result and Analysis

The simulation is carried out in MATLAB/ Simulink environment. Three condition testing is used which are step responses, set-point changes, and disturbance rejection. In this test, the tolerance of ± 2% is used. Both performance and energy consumption will be analyzed. The energy consumption is calculated by using the square of controller output as in [19].

#### 3.1. Step responses

Step responses are the basic testing to know the performances of the controller including rising time, settling time, and overshoot. Besides performance parameters, the energy controller also included for comparison. Figure 3 shows the step response including speed and energy controller. From the speed profile, Figure 3(a), it is clearly seen that the rise time of all the objective function is the same. Whereas, IAE and ITAE have similar speed responses with high both overshoot and undershoot with IAE has 2% lower in undershoot. ISE and ITSE also have nearly the same response, with ISE have 2%
lower in overshoot. MSE has the fastest settling time. However, it has slightly higher overshoot compare with ISE and ITSE.

In terms of energy consumption by the controller to control the plant, stated as control energy, ISE, ITSE, and MSE also have nearly the same energy as shown in Figure 3(b). Whereas ITAE has the highest one. Detail results can be seen in Table 2. From the quantitative value, Table 2, it clear that ISE has the lowest energy controller and ITAE has the highest one.

![Figure 3. Step responses profile](image)

**Table 2.** Resumes of step responses parameters

| Parameters                  | ISE   | IAE   | ITSE  | ITAE  | MSE   |
|-----------------------------|-------|-------|-------|-------|-------|
| Rise time (s)               | 2.68  | 2.68  | 2.68  | 2.68  | 2.68  |
| Settling time (s)           | 11.73 | 13.74 | 11.73 | 13.4  | 11.06 |
| Max Overshoot; Undershoot (%) | 24; 0 | 55; 18| 26; 0 | 55; 20| 27; 0 |
| Total control energy        | 1227.5| 1527.6| 1245.0| 1563.5| 1238.5|

3.2. Set-point changes
The second test is set-point changes. This test to know system performance in speed variation. In this test, the set point of the system from 0 to 30 seconds is 100 rpm then change to 50 rpm at 30 to 50 seconds. The first setpoint is the same as the previous step responses. Therefore, only the set-point changes from 100 rpm to 50 rpm will be analyzed. Figure 4 shows the result of set-point changes. It has seen that the result nearly the same as the previous test where IAE and ITAE have higher overshoot and undershoot. MSE has the highest rise time. In settling time criteria, ITSE is the fastest while MSE is the slowest. In the overshoot/undershoot criteria, IAE is the highest whereas ITSE is the lowest. From an energy point of view, ITAE consumes the highest energy to do the control action. On
the other hand, ISE is using the lowest amount of energy. The detailed parameter value can be seen in Table 3.

![Figure 4. Set-point changes profile](image)

**Table 3. Resumes of set-point changes parameters**

| Parameters                  | ISE | IAE | ITSE | ITAE | MSE |
|-----------------------------|-----|-----|------|------|-----|
| Rise time (s)               | 1.83| 1.16| 1.16 | 1.16 | 2.16|
| Settling time (s)           | 9.2 | 6.52| 5.85 | 6.52 | 9.53|
| Max Overshoot; Undershoot (%) | 0; 12| 8; 30| 0; 8 | 10; 32| 0; 16|
| Total control energy        | 1388.7| 1767.0| 1444.2| 1813.4| 1396.6|

3.3. Disturbance Rejection

The last test is the disturbance rejection. In this test, the set point of the system is 100 rpm. At time 30s, an impulse disturbance with amplitude 30 is given to the system. Figure 5 shows the system responses when a disturbance is given to the system. From Figure 5(a) it clearly is seen that all the controller has overshoot 30 when impulse disturbance given, then the controller forces the system to the set-point with different responses. ITSE is the first one to come back to the set-point, whereas MSE is the longest one. From the undershoot criteria, ITSE also the best one with no undershoot. In the energy control parameter, it consumes the lowest energy while ITAE consumes the highest one, as shown in Figure 5(b). Detail results can be seen in Table 4.

Table 5 is the resume of the value of the average parameter of all the test that has been done. It clearly is seen that ITSE is the best one in terms of settling time. ISE has the lowest overshoot while ITSE is also the best one in undershoot criteria. The last criteria, energy controller, ISE consume the lowest energy consumption whereas ITAE consumes the highest one. Since ITAE has the highest
overshoot and undershoot, it needs a lot of consuming a lot of energy. This means that the higher energy needed, the more control effort to control the plant. From Table 5, it also clearly seen that objective function that uses time (ITSE and ITAE) has a low settling time. Whereas, on the overshoot and undershoot, the objective function which uses square error is better than those using absolute error. The ITSE has the best performance overall except control energy since it combines both time and square error. Therefore, if the performance is the priority of control design, ITSE is the best objective function. On the other hand, if energy is the main concern, ISE is the best one.

Table 4. Resumes of disturbance rejection parameters

| Parameters                  | ISE   | IAE   | ITSE  | ITAE  | MSE   |
|-----------------------------|-------|-------|-------|-------|-------|
| Settling time (s)           | 5.51  | 3.84  | 1.16  | 3.84  | 7.19  |
| Max Overshoot; Undershoot (%) | 30; 3 | 30; 6 | 30; 0 | 30; 6 | 30; 3 |
| Total control energy        | 1493.7| 1803.8| 1516.4| 1841.1| 1504.1|

Table 5. Resumes of the average parameters value from all the test

| Parameters                  | ISE     | IAE     | ITSE    | ITAE    | MSE    |
|-----------------------------|---------|---------|---------|---------|--------|
| Settling time (s)           | 10.04   | 8.93    | 7.81    | 8.81    | 10.04  |
| Max Overshoot; Undershoot (%) | 18; 5  | 31; 18  | 18.67; | 31.67; | 19; 6.33|
| Control energy              | 1334.97 | 1687.20 | 1377.80| 1730.10| 1343.90|
4. Conclusion
One of the weaknesses of PID control is it consumes a lot of time to tune. PSO is one of the optimization methods which can be used to tune PID. The objective function is needed when using PSO to tune PID control. Five different objective function which is ISE, IAE, ITSE, ITAE, and MSE was already compared in terms of performance and control energy. The PID controller is applied in DC motor speed control in the simulation environment. The simulation result shows that in terms of performance, ITSE is the best one. On the other hand, in terms of control energy, ISE is using the lowest energy to control the plant.

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