PID Controller Tuning Methods Comparison with Particle Swarm Optimization for FOPTD System

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Abstract

Temperature Measurement is one of the major controlling parameters in all process industries. A closed loop system is formed by connecting a controller with that process with the combination of various transducers leading to stability. This paper deals with comparison of various PID control tuning techniques and Particle Swarm Optimization (PSO) technique. A single input single output (SISO) Real Time system is taken and Transfer function is identified. Control Transfer Function for the Transfer Function has been determined. Control parameters such as Proportional Gain, Time and Derivative Time are observed and tabulated. Performance indices such as Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE), Mean Square Error (MSE) have been simulated. Comparison between PID Controller, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) has been carried out to determine the best controller for the temperature system.

Keywords: Transducers, PID controller, PSO, FOPTD model, ISE, IAE, ITAE, MSE.

I. INTRODUCTION

Process Control opened the door of Second Revolution, where the functions of human brain and need for the continuous presences of human observers were also taken care of by machines.

During the 1940s, Ziegler and Nichols found the three mode controllers with proportional, integral, and derivative(PID) which has some attributes such as robustness and reliability. PID controller can be understood as a controller that takes the present, past and future of error into consideration. Control parameters play a essential role in tuning of PID controllers. Here, KP, KI, KD are controller parameters to be selected, often by Trial and Error or by the use of a lookup table in industry practice. Driving the error to zero in a desirable manner is the bottom line of the controller tuning.

For designing and tuning of the controller, the following objectives should be considered:

- Obtain the Process Reaction Curve for the process.
- Determine the transfer function of the model using Process Reaction Curve.
- Calculate the controller parameters and obtain the Control Transfer Function.
- Validate the controller performance and modify accordingly.

The transfer function of PID controller is:

\[ G(s) = K_c \left(1 + \frac{1}{TS} +Td \right) = K_p + \frac{KI}{S} + K_d \ldots \ldots (1) \]

Where, \( K_p \) is the proportional gain, \( T_I \) is the integral time, \( T_D \) is the derivative time [14].

A PID controller provides a control signal that has a component proportional to the tracking error of a system, a component proportional to the accumulation of this error over time and a component proportional to the time rate of change of this error. This module will cover these different components and some of their different combinations that can be used for control purposes.

Designing and tuning a PID controller demands flexible algorithms, if multiple and conflicting objectives are to be achieved. A conventionally tuned PID controller with fixed parameters may usually derive lesser control performance when it comes to system demands. The conventional tuning techniques lack the intelligence and flexibility which would increase the performance rate and also improvise the stability and error criterion [16, 17].

Genetic Algorithm are good at taking larger, potential huge, search and navigating them looking for optimal combinations of things and solutions which we might not find in a life time. Genetic Algorithm is very different from most of the traditional optimization methods. Genetic Algorithms need design space to be converted to genetic space. So, genetic algorithms work with a coding of variables. The advantage of working with a coding of variable space is that coding discretizes the search space even though the function may be continuous. A more striking difference between genetic algorithms and most traditional optimization
method is that GA use a population of points at one time in contrast to the single point approach by traditional optimization methods. This means that GA processes a number of designs at the same time. As we have seen earlier, to improve the search direction in traditional optimization methods, transition rules are used and they are deterministic in nature but randomized operators. Random operators improve the search space in an adaptive manner.

Optimization algorithms are another area that has been receiving increased attention in the past few years by the research community as well as the industry. An optimization algorithm is a numerical method or algorithm for finding the maxima or the minima of a function operating with certain constraints [5]. A technique which is based on Swarm Optimization is the Particle Swarm Optimization (PSO) technique.

A swarm consists of individuals called particles, each of which represents a different possible set of the unknown parameters to be optimized [6]. The “swarm” is initialized with a population of random solutions. In a PSO particles fly about in a multi-dimensional search space adjusting its position according to its own experience and the experience of its neighboring particle [7]. The goal is to efficiently search the solution space by swarming the particles towards the best fitting solution encountered in previous iterations with the intention of encountering better solutions through the course of the process and eventually converging on a single minimum or maximum solution [8].

II. PRACTICAL SETUP OF HEATING TANK SYSTEM

- Type of Control: SCADA
- Control Unit: Digital indicating controller with RS 485 communication
- Communication: USB port using RS 485-USB converter
- Temperature Sensor: Type RTD, PT 100
- Heating Control: Proportional power controller(SSR), input 4-20mA D.C., Capacity 20 A
- Rota meter: 6-60 LPH
- Process Tank: SS304, Capacity 0.5 lit, insulated
- Overall dimensions: 400w*400D*330H mm

A step input is applied to solid state relay (SSR) and temperature of RTD (PT 100) is recorded in excel format. Stored data is used to plot open loop step response in MATLAB.

A. Determination of System Model

In the design of model based controller, system model is an important element. White box model requires complete and correct physical data of the system under consideration. But this data is not available for the system described. Hence, system model id determined through system identification. We used Step signal to the system for the determination of model. We considered FOPTD model. This step response locates the system parameters like steady state gain, time delay and the time constant of the process from which model obtained is of general form as,

\[ G(s) = \frac{kp e^{-τas}}{Is + 1} \]

Where, \( kp \) is steady state gain of system, \( τs \) is time constant of system, \( τd \) is dead time of system.

Hence, we get FOPDT model from Figure 1 as,

\[ Gp(s) = 2.2 * \frac{e^{-6s}}{40.484s + 1} \]

(Water flow through Rota meter is kept at 40 LPH) [1].

B. Controller Design for FOPTD Systems

The single loop controller configuration is shown in Fig.2
III. TUNING METHODS

The PID controller tuning methods are classified into two main categories
- Closed loop methods
- Open loop methods

Closed loop tuning techniques refer to methods that tune the controller during automatic state in which the plant is operating in closed loop. The open loop techniques refer to methods that tune the controller when it is in manual state and the plant operates in open loop. The closed loop methods considered for simulation are Ziegler-Nichols method [20], Modified Ziegler-Nichols method, Tyreus-Luyben method, Damped oscillation method and IMC method. Open loop methods are C-H-R method Minimum error criteria (IAE, ISE, ITAE, MSE) method. Before proceeding with a brief discussion of these methods it is important to note that the non-interacting PID controller transfer function is:

\[
G(S) = K_c \left(1 + \frac{1}{T_I s} + T_D s\right) \ldots (2)
\]

Where, \(K_c\) = proportional gain, \(T_I\) = Integral time, \(T_D\) = derivative time

A. The C-H-R Method

This method that has proposed by Chien, Hrones and Reswich is a modification of open loop Ziegler and Nichols method. They proposed to use “quickest response without overshoot” or “quickest response with 20% overshoot” as design criterion. They also made the important observation that tuning for set point responses and load disturbance responses are different.

To tune the controller according to the CHR method the parameters of first order plus dead time model are determined in the same manner of the Z-N method [4].

Proportional, integral and derivative constants are \(K_c=3.6803\) \(K_I=0.306\) \(K_D=11.04\)

B. Genetic Algorithm for PID Tuning

GA was first introduced by John Holland. It is an optimization technique inspired by the mechanisms of natural selection. GA starts with an initial population containing a number of chromosomes where each one represents a solution of the problem in which its performance is evaluated based on a fitness function.

Based on the fitness of individual and defined probability, a group of chromosomes is selected to undergo three common stages: selection, crossover and mutation. The application of these three basic operations will allow the creation of new individuals to yield better solutions than the parents, leading to the optimal solution [3,6,7,8,10].

Proportional, integral and derivative constants are \(K_c=4.6379\) \(K_I=0.11357\) \(K_D=9.9406\)

![Flowchart of Genetic Algorithm](image)
1) Reproduction
During the reproduction phase the fitness value of each chromosome is assessed. This value is used in the selection process to provide bias towards fitter individuals. Just like in natural evolution, a fit chromosome has a higher probability of being selected for reproduction. The probability of an individual being selected is thus related to its fitness, ensuring that fitter individuals are more likely to leave offspring [5].

2) Crossover
Once the selection process is complete, the crossover algorithm is initiated. The crossover operations swap certain parts of the two selected strings in a bid to capture the good parts of old chromosomes and create better new ones. The crossover probability indicates how often crossover is performed. The simplest crossover technique is the Single Point Crossover.
Example: If the strings 100110 and 101001 are selected for crossover and the value of k is randomly set to 2 then the newly created strings will be 100110 and 101010 as shown [5].

3) Mutation
Mutation is the occasional random alteration of a value of a string position. It is considered a background operator in the genetic algorithm. The probability of mutation is normally low because a high mutation rate would destroy fit strings and degenerate the genetic algorithm into a random search. Once a string is selected for mutation, a randomly chosen element of the string is changed or ‘mutated’. For example, if the GA chooses bit position 3 for mutation in the binary string 100101, the resulting string is 100001 as the third bit in the string is flipped [5].

C. Particle Swarm Optimization for PID Tuning
Particle swarm optimization (PSO) is an algorithm modeled on swarm intelligence that finds a solution to an optimization problem in a search space or model and predicts social behavior in the presence of objectives. The PSO is a stochastic, population-based computer algorithm modeled on swarm intelligence. Swarm intelligence is based on social-psychological principles and provides insights into social behavior, as well as contributing to engineering applications. This book presents information on particle swarm optimization such as using mono-objective and multi-objective particle swarm optimization for the tuning of process control laws; convergence issues in particle swarm optimization and vehicle routing problems using enhanced particle swarm optimization.

Proportional, integral and derivative constants are \( K_p = 4.5238 \), \( K_i = 0.10476 \), \( K_d = 0.013904 \)

IV. TUNING METHOD FOR MINIMUM ERROR INTEGRAL CRITERIA
As mentioned before tuning for \( \frac{1}{4} \) decay ratio often leads to oscillatory responses and also this criterion considers only two points of the closed loop response (the first two peaks). The alternative approach is to develop controller design relation based on a performance index that considers the entire closed loop response.

Some of such indexes are as below:

Modern complex control systems usually require more sophisticated performance criteria than those presented so far. The error and time are very important factors that must be considered simultaneously. A performance index is a single measure of a system’s performance that emphasizes those characteristics of the response that are deemed to be important. The notion of a performance index is very important in estimator design using linear-state-variable feedback. A fairly useful performance index is the integral of the absolute magnitude of the error (IAE) criterion.

\[
\text{IAE} = \int_0^\infty |e(t)| \, dt
\]

By utilizing the magnitude of the error, this integral expression increases for either positive or negative error, and results in a fairly good under-damped system. For a second order system, this error has a minimum for a damping ratio of approximately 0.7. Another useful performance index is the integral of the square of the error (ISE) criterion.

\[
\text{ISE} = \int_0^\infty e^2(t) \, dt
\]

By focusing on the square of the error function, it penalizes both positive and negative values of the error. For a second order system, this error has a minimum for a damping ratio of approximately 0.5 [14,15,16]. A very useful criterion that penalizes long-duration transients is known as the integral of time multiplied by the absolute value of the error (ITAE). This performance index is much more selective than the IAE or the ISE. The minimum value of its integral is much more definable as the system parameters are varied. For a second order system, this error has a minimum for a damping ratio of approximately 0.7.

\[
\text{ITAE} = \int_0^\infty t \cdot |e(t)| \, dt
\]

Other figure of merit which has been proposed is the integral of time multiplied by the squared error (ITSE) or mean squared error (MSE) [14, 15, 16]. The performance index is

\[
\text{MSE} = \int_0^\infty t \cdot e^2(t) \, dt
\]
V. RESULT AND COMPARISON

A. Comparison of Curves between CHR, GA and PSO

![Comparison of Curves between CHR, GA and PSO](image)

B. Comparison of time domain specifications for set point

The Comparison of tuning methods of CHR, GA and PSO PID controllers are plotted below.

<table>
<thead>
<tr>
<th>Controller</th>
<th>CHR controller</th>
<th>GA controller</th>
<th>PSO controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (seconds)</td>
<td>4.5</td>
<td>4.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Peak time (seconds)</td>
<td>17</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Overshoot (%)</td>
<td>36.5</td>
<td>12.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Settling time (seconds)</td>
<td>64</td>
<td>17</td>
<td>14</td>
</tr>
</tbody>
</table>

C. Comparison of performance index

The Comparison of performance index of ITAE, IAE, ISE, MSE of CHR, GA and PSO PID Controllers are given below.

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>CHR controller</th>
<th>GA controller</th>
<th>PSO controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITAE</td>
<td>884.0878</td>
<td>170.5447</td>
<td>747.86</td>
</tr>
<tr>
<td>IAE</td>
<td>701.5868</td>
<td>73.1886</td>
<td>718.07</td>
</tr>
<tr>
<td>ISE</td>
<td>0.0032</td>
<td>0.000803</td>
<td>0.000043</td>
</tr>
<tr>
<td>MSE (e^-004)</td>
<td>3.7803</td>
<td>2.3240</td>
<td>0.377</td>
</tr>
</tbody>
</table>

VI. ROBUSTNESS ANALYSIS

Robustness of the controller is defined as its ability to tolerate a certain amount of change in the process parameters without causing the feedback system to go unstable. Robustness investigation is done by varying the model parameters by twenty percent. In order to investigate the robustness of model in presence of uncertainties, the model parameters are randomly altered. For model obtained, k=2.2, td=6 sec and tp= 40.484 sec. Let, these parameters be deviated as much as 20% from their nominal values due to model uncertainty. Let, there is 20% decrease in dead time and 20% increase in gain and time constant. Therefore, new model is:

\[ G(s) = 2.64 \cdot \frac{e^{-4.8s}}{48.581s + 1} \]

VII. CONCLUSION

The Temperature System is controlled by a three degree controller. The Three controller parameters such as Proportional Band, Integral Time and Derivative Time have been sent to the Controller. Due to the Performance of the controller, the Process achieved its steady state. The Simulation of the Process that is controlled has been done through MATLAB. The Comparison of Time domain specifications of the Chien, Hrones and Reswich (CHR), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) PID controllers have been obtained. Performance Indices Comparison has also be done.

Based on the compared results, Particle Swarm Optimization (PSO) PID Controller provides the better response and obtains the steady state much quicker than CHR and GA PID Controllers. Integral Square Error (ISE) of Particle Swarm Optimization (PSO) PID Controller gives minimum error than CHR and GA PID Controllers.
REFERENCES


