Application of the PID Control to the Programmable Logic Controller Course

Abstract

The proportional, integral, and derivative (PID) control is the most widely used control technique in the automation industries. The importance of the PID control is emphasized in various automatic control courses. This topic could easily be incorporated into the programmable logic controller (PLC) course with both static and dynamic teaching components.

In this paper, the integration of the PID function into the PLC course is described. The proposed new PID teaching components consist of an oven heater and a light dimming control as the static applications, and the closed-loop velocity control of a permanent magnet DC motor (PMDCM) as the dynamic application. The RSLogix500 ladder logic programming software from Rockwell Automation has the PID function. After the theoretical background of the PID control is discussed, the PID function of the SLC500 will be introduced. The first exercise is the pure mathematical implementation of the PID control algorithm using only mathematical PLC instructions. The Excel spreadsheet is used to verify the mathematical PID control algorithm. This will give more insight into the PID control. Following this, the class completes the exercise with the PID instruction in RSLogix500. Both methods will be compared in terms of speed, complexity, and accuracy.

The laboratory assignments in controlling the oven heater temperature and dimming the lamp are given to the students so that they experience the effectiveness of the PID control. The students will practice the scaling of input and output variables and loop closure through this exercise. The closed-loop control concept is emphasized through these exercises. The closed-loop PMDCM control is the last assignment of the PID teaching components. The two PMDCMs are connected back-to-back to form a motor-generator set. The PMDCM generator works as a tachometer to close the velocity loop. The various step responses of the proposed PID controller based on the SLC500 PLC are investigated to decide the optimal tuning of the velocity control loop. The assessment methods are included in the assessment section.

Introduction

The teaching of the PID control concept is never trivial. Especially in PLC courses, the demonstration and exercise of the dynamic PID control, in addition to the static applications, are very important to emulate the real world applications. The various new PID teaching components in both static and dynamic applications are introduced to the advanced PLC course, EMET430 at Penn State Berks, and some results are summarized in this paper.

The SLC500 PLC training station at Penn State Berks consists of the SLC 5/04 processor and nine Input/Output (I/O) modules installed on a ten-slot modular chassis as shown in Figure 1. Four normally-open (NO) pushbutton switches (green), four normally-closed (NC) pushbutton switches (red), and eight selector switches are provided for the simulation of static PLC
applications. A four-digit thumbwheel switch and LED display are also provided. The details of the modules are summarized in Table 1.

The effective way to teach the PID concept is to visualize the end results of the process control with and without the PID control function in the control loop. The open- and closed-loop transient response methods developed by Ziegler-Nichols\(^1\) are introduced in order to investigate the effectiveness of the PID function for the process loop tuning. The Ziegler-Nichols method is applied for both static and dynamic applications.

The lecture on the PID control loop tuning methods is given to the students first. Then the investigation of the effectiveness of the PID tuning is exercised with Excel spreadsheet. The students change PID gains and observe the effects through the step response curves of the process variable (PV). Next the students will exercise the static and dynamic applications with SLC500 PLC. The difference between the PID function implemented mathematical functions and the embedded PID instruction will be examined. The static applications included are the

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Table 1. Details of SLC500 Ten-Slot Modular System

<table>
<thead>
<tr>
<th>Chassis Slot Location</th>
<th>Part Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1747-L541</td>
<td>SLC 5/04 CPU – 16K Mem. OS401</td>
</tr>
<tr>
<td>1</td>
<td>1746-OA16</td>
<td>16-Input (TRIAC) 100/240 VAC</td>
</tr>
<tr>
<td>2</td>
<td>1747-SDN</td>
<td>DeviceNet Scanner</td>
</tr>
<tr>
<td>3</td>
<td>1746-IB16</td>
<td>16-Input (SINK) 24 VDC</td>
</tr>
<tr>
<td>4</td>
<td>1746-OB16</td>
<td>16-Output (TRANS-SRC) 24 VDC</td>
</tr>
<tr>
<td>5</td>
<td>1746-IB16</td>
<td>16-Input (SINK) 24 VDC</td>
</tr>
<tr>
<td>6</td>
<td>1746-OB16</td>
<td>16-Output (TRANS-SRC) 24 VDC</td>
</tr>
<tr>
<td>7</td>
<td>1746-NI04V</td>
<td>Analog 2 Ch In/2 Ch Voltage Out</td>
</tr>
<tr>
<td>8</td>
<td>1746-NI04I</td>
<td>Analog 2 Ch In/2 Ch Current Out</td>
</tr>
<tr>
<td>9</td>
<td>1746-NT4</td>
<td>Analog 4 Ch Thermocouple Input</td>
</tr>
</tbody>
</table>
oven temperature control and the lamp light intensity control. The dynamic control application is the velocity control of a PMDCM.

**PID Tuning Exercise with Excel Spreadsheet**

The Microsoft Excel spreadsheet is an excellent tool to demonstrate the various PID gain responses. The following PID equation is used to generate data to plot the various responses by changing $K_C$, $T_I$, and $T_D$ utilizing an embedded graph function:

$$CV(n) = K_C\left[E(n) + \frac{1}{T_I}\int E(n)\,dt + T_D\cdot \frac{dPV(n)}{dt}\right] + Bias \quad (1)$$

where,

$CV(n) =$ control variable sample  
$PV(n) =$ process variable sample  
$E(n) =$ error sample  
$K_C =$ controller gain  
$T_I =$ reset gain constant  
$T_D =$ rate gain constant  
$dt =$ time between samples  
$Bias =$ offset

A sample Excel spreadsheet and the system response are shown in Figure 2. This example illustrates the PID temperature control of an oven. Students could easily visualize the effects of

![Figure 2. Demonstration of a PID oven temperature control with Excel spreadsheet](image-url)
PID gain values on the total system dynamic response. In order to evaluate how the PID parameter affects the system dynamics, tuning criteria - such as rise time, overshoot, settling time and steady-state error - are measured and compared each other.

**Ziegler-Nichols Tuning Methods**

Both open- and closed-loop Ziegler-Nichols tuning methods are introduced to the class for process tuning exercises.

**Tuning by Step Test Response Method for Open-Loop Systems**

The Ziegler-Nichols step test response method is used for process tuning relying on accurate determination of process characteristics by performing multiple tests. First, the control system is configured and the CV is adjusted in steps. As changes are made, the changes in PV should be recorded. The constants $K_C$, $T_I$, and $T_D$ for the PID equation are determined by the data collected.

The steps to tune the open-loop system with this method are:

1. Set the controller in the manual mode and allow the process to line out.
2. Apply a small step change in the controller output in the range of 3~5%.
3. Obtain a plot of the process reaction curve. On the process reaction curve a line is drawn tangent to the slope of the process variable at its steepest point.
4. From the reaction curve the values of the dead time $\theta$, the time constant $T_c$ and the process gain $G_p$ are determined.
   - The dead time $\theta$ is the time from the controller output change to the point where the tangent line intersects the value of the process variable at the start of the test.
   - The time constant is the time from the end of $\theta$ to the point where the change in PV reaches 63.2% of its final value.
   - The process gain is defined as (2)

\[
G_p = \%\Delta PV = \frac{\Delta PV}{\%\Delta CV} = \frac{PV_{\text{max}} - PV_{\text{min}}}{\Delta CV} \times 100
\]

- Calculate tuning parameters $K_C$, $T_I$, and $T_D$ for the PID controller with following equations

(2)
\[ K_c = 1.2 \times \frac{1}{G_p} \times \frac{T_c}{\theta} \]

\[ T_I = 2\theta \]

\[ T_D = 0.5\theta \]

(a) Initial setup of the PID function parameters

(b) Reaction curve

Figure 3. Tuning of an oven controller with the Ziegler-Nichols method for open-loop system
As a static PID application example, the ladder logic program of a temperature control of an oven is assigned to students. In this exercise, the PID function of the RSLogix500 and dynamic data exchange (DDE) function in RSLinx are used. The DDE function enables data trend with the Excel spreadsheet. The initial setup of the RSLogix500 PID function is shown in Figure 3(a); \( K_c = 3, T_I = 0.6 \) and \( T_D = 0 \). The obtained reaction curve is shown in Figure 3(b) in which the dead time \( \theta \), the time constant \( T_c \) and the process gain \( G_p \) are determined by drawing a tangent to the slope of the PV (marked as ‘value’ in the graph) at its steepest point. \( K_c, T_I, \) and \( T_D \) values are calculated with equation (3) by substituting the obtained dead time \( \theta \), the time constant \( T_c \), and the process gain \( G_p \). These procedures may be repeated to get the closest optimal response as possible. The final competition between teams is given to find the optimally tuned controller which shows fastest response with minimum overshoot.

**Ziegler-Nichols Continuous Method for the Closed-Loop Systems**

The second method is the Ziegler-Nichols closed-loop test. This test is widely used in the process industry, but the drawback is that it requires someone to deliberately put the process system into oscillation to determine the ultimate gain and period of a closed-loop system. The steps to tune a closed-loop with this method are:

Step 1. With the loop in automatic mode enter a new set point (SP) slightly above or below the desired setpoint. Allow the process to line out.

Step 2. Place the controller in manual mode and the process should continue to be stable.

Step 3. Turn off integral and derivative action and set the proportional gain to a small value. If integral action cannot be turned off, then set it to the highest possible value. If derivative action cannot be turned off, then set it to the lowest possible value.

Step 4. Place the controller in automatic mode.

Step 5. Change the SP of the operating SP. An offset or error should be observed between PV and SP.

Step 6. Carefully increase the proportional gain in steps. After each increase, disturb the loop by introducing a small step change in SP, and observe the system response. Continue until oscillations are apparent.

Step 7. Record this value of gain as the ultimate gain, \( K_{CU} \).

Step 8. Record the resulting period as the ultimate period, \( T_U \).

Step 9. Calculate the tuning parameters \( K_c, T_I, \) and \( T_D \) for the PID controller with the following equations

\[
\begin{align*}
K_c &= 0.6 \times K_{CU} \\
T_I &= \frac{T_U}{2} \\
T_D &= \frac{T_U}{8}
\end{align*}
\]

(4)

The Ziegler-Nichols closed-loop tuning method is applied to the automated PLC controlled lighting lab as shown in Figure 4. A 1746-NIO4V analog I/O module is used for this experiment. The cadmium sulfide (CdS) photocell bridge as a transducer provides the voltage proportional to the light intensity which is controlled by the dc controlled dimmer. The bridge circuit sends
electrical signals to the 1746-NIO4V module that contains continuous information about the level of lighting from the lamp installed near the transducer. A ladder logic diagram will be designed to control the lighting to a specific setpoint using a scale with parameters (SCP) instruction. The SCP instructions will be used to scale the analog signals for I/O module. A dc controlled electronic dimmer will be used to control the level of lamp intensity.

To remove the ambient effect from the transducer, the bridge output voltage must set to zero by adjusting a potentiometer in the bridge. The minimum and maximum PV should be found first with the lamp turned off and the 120V ac applied to the lamp, respectively. These values are used to set the PV input range from the photocell bridge. The above-mentioned initial test will be performed without connecting the PLC. Next, minimum and maximum CV values should be found with the lamp off and on, respectively. These values are used to determine the CV output range to the dc controlled dimmer using a SCP instruction. The setpoint for the process becomes the difference between the maximum and minimum PV divided by two.

The snapshots of unstable and stable waveforms are shown in Figure 5. In order to get unstable response, the light path between the bridge and lamp should be interrupted and the controller gain $K_C$ will be increased until the lamp oscillates. The ultimate gain, $K_{CU}$ and the ultimate period, $T_U$ are obtained from Figure 5(a). After calculating the tuning parameters $K_C$, $T_I$, and $T_D$ from equation (4), then use them as the setup parameters in the PID instruction, and run the ladder logic program. A sample result of the tuned PID controller response is shown in Figure 5(b). The tuned PID controller shows stable response whenever the light path is interrupted.

(a) Simplified block diagram
(b) Experimental setup

Figure 4. Automated PLC controlled lighting

(a) Before tuning: oscillation method for the closed-loop system

(b) After tuning: oscillation method for the closed-loop system

Figure 5. Experimental CV waveforms before and after tuning

PLC Controlled Velocity Servo Drive with PID

So far the principle of the PID controller, the Ziegler-Nichols tuning method, and their application to two static applications have been introduced. The dynamic application is the tuning of PMDCM velocity loop with the PID function in RSLogix500 software.

Two PMDCM are connected back-to-back to form the motor-generator set as shown in Figure 6. The dc controlled PMDCM controller provides the PWM output voltage. The PMDCM is Model C13-L19W40 from Moog Inc. The control voltage range of the dc controlled PMDCM controller
and corresponding motor-generator characteristics are listed in Table 2 below. The 1746-NIO4V analog module is used for this application. In order to limit the input range to +10V maximum, a resistor divider network is needed for the output terminal of the tachometer. A scaling is necessary for both input and output signals to match with the input and output ranges of the 1746-NIO4V module.

<table>
<thead>
<tr>
<th>Dc Control Voltage, V</th>
<th>Tachometer Voltage, V</th>
<th>Motor Speed, r/min</th>
<th>Direction of Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+10</td>
<td>+16</td>
<td>6300</td>
<td>CW</td>
</tr>
<tr>
<td>+5</td>
<td>0</td>
<td>0</td>
<td>Standstill</td>
</tr>
<tr>
<td>0</td>
<td>-16</td>
<td>6300</td>
<td>CCW</td>
</tr>
</tbody>
</table>

The tuning method for the velocity servo control system is the same as the case with the automated PLC controlled lighting. The differences are the dc control voltage is treated as the CV and the tachometer voltage is employed for the PV.

The $K_C$ will be increased until the motor becomes unstable as shown in Figure 7(a). The ultimate gain, $K_{CU}$, and the ultimate period, $T_U$ are estimated from this waveform. The calculation of the tuning parameters $K_C$, $T_I$, and $T_D$ will be done using equation (4). The calculated values will be inserted into the PID instruction.

A stable response of the tuned PID controller for the velocity servo drive is shown in Figure 7(b). The tuned PID controller shows stable response when the motor velocity has changed in step-like fashion.
Figure 6. Back-to-back PMDCMs as the motor-generator set and PMDCM controller

(a) Before tuning

(b) After tuning

Figure 7. Sample waveforms of CV before and after tuning

Assessment

The major topics students could learn from each teaching component are

- Excel Spreadsheet: Tuning criteria such as rise time, overshoot, settling time, and steady-state error, and so on.
- Static Application #1 – Oven Temperature Control (Ziegler-Nichols Step Test Response Method for Open-Loop Systems): RSLinx, DDE, SCP instruction, three-term PID tuning parameters ($K_C$, $T_I$ and $T_D$), reaction curve parameters (dead time, $\theta$, time constant, $T_C$, and process gain, $G_p$).
• Static Application #2 – Automated PLC Controlled Lighting (Ziegler-Nichols Continuous Method for the Closed-Loop Systems): SCP instruction, ultimate gain, $K_{CU}$, ultimate period, $T_U$.

• Dynamic Application – PLC Controlled Velocity Servo Drive with PID (Ziegler-Nichols Continuous Method for the Closed-Loop Systems): SCP instruction, ultimate gain, $K_{CU}$, ultimate period, $T_U$.

The assessment of the newly developed PID teaching components consists of demonstration and report writing of each lab. The students will demonstrate the uniqueness of the solution they come up with. During the demonstration, the depth of understanding of materials is measured.

The assessment rubric is shown in Table 3.

Table 3. Assessment Rubric

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>5</td>
</tr>
<tr>
<td>Design Input</td>
<td>5</td>
</tr>
<tr>
<td>Design Output</td>
<td>5</td>
</tr>
<tr>
<td>Design Verification</td>
<td>10</td>
</tr>
<tr>
<td>Design Validation</td>
<td>10</td>
</tr>
<tr>
<td>Conclusions</td>
<td>15</td>
</tr>
<tr>
<td>References</td>
<td>5</td>
</tr>
<tr>
<td>RSLogix500 Project Report</td>
<td>25</td>
</tr>
<tr>
<td>RSLogix500.rss File</td>
<td>10</td>
</tr>
<tr>
<td>Uniqueness Demonstration</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

The format of a report of the laboratory project design exercise consists of:

• **Objective** – The objective section should include a brief assertion of the goals of the project design exercise. It should contain the essence of the design and not a sequential list of assigned tasks or requirements.

• **Design Input** – The design input section should summarize all requirements imposed on the design project and any other pertinent data.

• **Design Output** – The discussion should outline how the requirements of the project were met. With it students should include ladder logic diagrams, ladder logic instructions used, process flow charts, and other pertinent data. They should define what parts (rungs, pages, etc.) of the project design were done by which team members. Students may reference the project handout provided at any point and it will be included with their report in an appendix. Students may also refer to other sources. However, they should be sure to declare them in a reference section.
- **Design Verification** – The design verification section should address how the requirements were verified. It should include information on the process of verification and what equipment was used to test and debug the design. It should also include truth tables, field device list, graphs, figures, and/or diagrams etc.

- **Design Validation** – The design validation section should summarize the results from design verification testing. It should indicate whether all the requirements were met. If any requirements could not be met, they should be listed in this section. The students should refer to the RSLogix500 project report.

- **Conclusions** – The conclusions section should also summarize what students learned by executing the project and should identify problems encountered other than equipment problems during the lab session.

- **References** – The references should be any resources relevant to the assigned lab topics.

- **RSLogix500 Project Report** – The RSLogix500 report should reflect the following options in the configuration and ladder options dialog:

![Figure 8. RSLogix500 project report options](image1)

![Figure 9. RSLogix500 ladder setup option](image2)
• **RSLogix500 File** - The ladder logic diagram should include a title as ‘Lab #_Your Name .rss’ and as many rung comments as possible. The developed and tested file should be submitted via ANGEL, the Penn State proprietary course management system.

• **Uniqueness Demonstration** - The developed and tested ladder logic program should demonstrate its operation and uniqueness to the instructor during lab.

In addition to the formal report, during the oven temperature control lab, the competition between students will be performed to encourage them for their fast and accurate tuning results. The most well-tuned PID control loop provides the fastest response and modest overshoot.

**Conclusion**

The objective of the newly developed PID teaching components is to provide students with not only fundamental theory but also hands-on experience through lab exercises. The various hands-on teaching components are designed to make students able to confirm the effectiveness of the PID function in the process control loop. The proposed lab exercises are the visual indication tools to help students understand the characteristics of the PID function easily. Based on the newly developed teaching components, the students develop essential skills, too. They will be ready for the real world settings in the automation and process industries by exercising the tuning of the controllers for various applications.

**Acknowledgement**

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**References**


