

# Capstone Project: PLC Control System with Integrated PID Controller for Control System Optimization

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## Abstract

A PLC with a PID controller is a simple and effective way to increase the efficiency of a control system. This paper discusses the development of a control system and the analysis of a PID controller used for system voltage regulation. The system is also to be used as an educational tool for PLC instruction. The system implements PLC and PID control to increase the efficiency of LED lighting adjustments to voltage changes to keep the voltage level at a desired setpoint. Our system contains four key components that make up the control system which include a solar panel, a stepper motor, LED lights, and a PLC/HMI. The solar panel voltage is an input to the PLC, which reads the input voltage and then calculates the desired LED output. Because of the voltage changes, the illumination from the LEDs will try to

compensate for the solar panel voltage change. The implementation of P, PI, and PID controllers is used to optimize system performance.

## **Introduction**

The capstone project course is an intrinsic part of undergraduate education. Capstone projects are widely regarded as an excellent mechanism for assessing the outcomes of engineering and engineering technology programs and can serve as a direct measure of the quality of graduates. Capstone projects provide an opportunity for students to demonstrate their critical thinking skills and communication skills, as well as time and project management skills. The capstone course prepares students to better understand the professional roles in the engineering and technology community [1]. In many universities, senior-level capstone courses have been incorporated as an integral part of engineering and engineering technology education in an effort to correlate the practical side of engineering design and the engineering curriculum. Such courses provide an experiential learning activity in which the analytical knowledge gained from previous courses is joined with the practice of engineering in a final, hands-on project [2-4]. The development of capstone design courses and corresponding requirements have been influenced by various sources, including the Accreditation Board for Engineering and Technology (ABET), industrial advisory boards (IAB), faculty leading capstone projects, numerous industrial companies, and engineering research.

Earlier research [4-15] showed the importance of industry involvement in the capstone environment, which became more than just the financial support described above. However, support in the form of equipment, materials, and technical consulting is common and in most cases necessary [6-8]. Most industrial sponsors have a liaison engineer who assists the students and who follows the progress of the project [7, 10]. Other forms of industrial support include providing awards for meritorious designs and assisting in the evaluation of teams and projects [4]. More recent studies provide further in depth analysis on the importance of the various benefits of capstone projects for the students' preparation for real world jobs. These include, but not limited to the importance of industry involvement [16-18], familiarizing students with product development process and system engineering [16, 19-23], improvement in the professional skills of students [16, 21], providing multidisciplinary training [16, 22-25], cultivating creative problem solving skills [16, 26], and preparing students for globalization [16, 27, 28]. Recently, a new trend in conducting capstone projects became noticeable. Some capstone projects are sponsored by faculty members instead of industrial partners playing an important role of supporting some larger scale externally funded faculty research projects [16]. For example, Texas A&M University undergraduate students involved in these projects as a capstone team had to work with graduate students, faculty members, and potential customers. Software, hardware, interface, system integration, and testing all involved other researchers instead of just the capstone team [16]. These types of projects may resemble projects conducted in industrial settings, where multiple divisions have to collaborate on a single, large-scale project. The intent of this article is to share the developed at Michigan Tech an effective approach of working on the sponsored SD projects. In this article, the authors present a team of students engaged in the faculty-sponsored project with the goal of the development and proof of concept demonstration of integration of a

programmable logic controller (PLC) with the human machine interface (HMI) to create an effective PID controller. Upon completion of the project, the system will be used as a stand-alone training solution to teach PLC, HMI concepts as well as the theory of the PID controllers in introductory and advanced PLC courses in the EET program at the university. The authors describe the project requirements, the significance of the project, specific project outcomes, and assessment tools used to effectively evaluate the students' success.

The implementation of a proportional-integral-derivative (PID) controller in a control system can increase the performance of the system. PID control is a control algorithm that is widely accepted and very common among industrial control systems. The PID control algorithm is shown in Figure 1 is a closed loop system in which an input is read and the desired output is computed based on magnitude, duration and the rate of change of the error. Three types of gains are used to respond to the types of errors: proportional, integral, and derivative. The controller uses these gains to minimize the overall error of the system, which is the difference of setpoint and the system output. Proportional gain is related to the magnitude of the error, integral gain is related to the duration of the error, and the derivative gain is related to the rate of change of the error. The combination of these three gain constants is used to obtain optimal system performance. Therefore, the goal of the system is to try to keep the output value at a desired value called the set point. When the output differs from the set point value, then the system should return the output to the set point as quickly and efficiently as possible. This project is only focused on the PID control objective to "track" a step function, and other types of control objectives are out of the scope of this project and hence left as future works. The optimized system should minimize the effect of system perturbations on the output value and keep the output constant at the value of the set point [31, 32].

A programmable logic controller (PLC) is a popular component in which PID control is implemented. A PLC uses inputs of a system to control various system outputs. The main objectives of the system were to implement PID control and to function as a learning tool to teach the different aspects of PLCs and related components. Because of the wide use of PLCs in automated systems in industry, it is important for students to have a hands-on experience with the equipment [40]. Systems developed for instructional use and testing of PID controllers are important for training and system improvements. A PID controller was designed to help illustrate controller effects and the proper settings for a seminar on process controls [39]. To try to improve the PID control, an adaptive PID Controller was developed using MATLAB software [30]. Educational software aimed towards PID control has been used [29] to help students learn about PID controllers by simulating different processes and allowing the user to change the PID parameters of the controller. It is not always convenient for training to be done in the traditional laboratory environment and a portable PLC system was developed for training which can be done closer to the job [41]. With systems and instructional tools aimed towards the use of PLC and PID controllers, such as the system presented in this paper, users are able to understand and gain experience directly related to real-world applications.

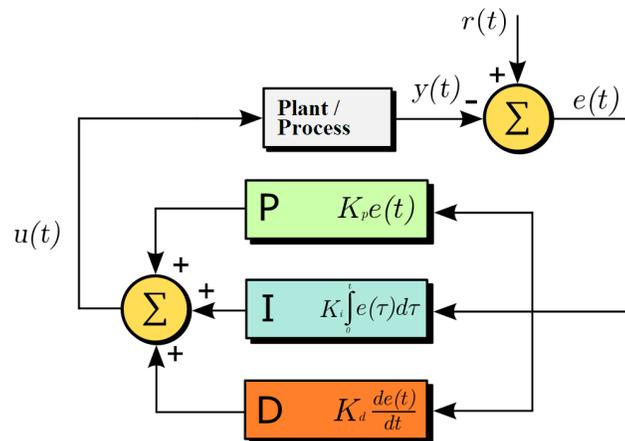


Figure 1. PID control algorithm [38]

The system design includes the integration of a solar panel, a stepper motor and LED lights that are all controlled by a PLC. An HMI is used in the system to allow the user to control various functions. HMIs are popularly used along with PLCs for control systems, where an HMI allows the user to control and monitor the system remotely. The overall function of the system consists of the LED lights aimed at the solar panel to produce a measurable output voltage. The system consists of three LED lights, two control LEDs that are controlled by the PID controller and a perturbation LED light that is user controlled.

The system is perturbed by changes in solar panel position and the perturbation light intensity and rate of change. As a result, the control lights adjust in order to keep the output of the solar panel at the set point. The perturbations to the solar panel are accomplished by the movement of the stepper motor that is coupled to the solar panel by two gears. The perturbation light is controlled by ladder logic programs implemented in the PLC. The user is able to control the stepper motor function and the perturbation light through the HMI interface.

This paper covers the aforementioned system implementation, including topics of design, system component information, programming and testing. Results of P, PI, and PID controller implementation into the system will be analyzed for system optimization.

### Capstone Course Description

In the past several years, EET program in the School of Technology at Michigan Tech was very successful in establishing collaboration with the industry. This, in turn, triggered nearly all the capstone projects conducted in the EET program to be industry sponsored. Only during the last four years, EET program has successfully completed 12 capstone projects with 10 of them being industry-sponsored. The benefits of having senior design (SD) projects industry sponsored are very significant for both the students and faculties. On the other hand, the faculty sponsored projects gain popularity as well. Students working on faculty-sponsored projects have an opportunity to participate in externally funded research or conduct faculty-

defined projects resulting in equipment that can further be used to enhance in class teaching approaches.

A capstone course in the EET program requires the application of knowledge gained in lower and upper division courses. Students participating in a capstone project demonstrate the ability to perform independent and creative work by successfully completing a major design project. Projects are normally team oriented, where the team consists of two to four members, with one member chosen as team leader. Team oriented capstone projects provide a better simulation of industrial environment, to better train today's engineers. Weekly progress reports are required, and the work culminates with a final report and oral presentations, including a poster of the project. Six credits of senior project are required for graduation, normally satisfied in two three-credit semesters.

Upon successful completion of the capstone project course, students should fulfill the following course objectives:

- Prepare background research on applied electrical engineering technology.
- Research and organize data for synthesis.
- Prepare written reports.
- Prepare and present oral reports.
- Work in teams.
- Coordinate and work to meet scheduled deadlines and facilities, manage resources, etc.
- Consider non-engineering considerations in your work (e.g., economic issues, marketing issues, esthetics).

At the beginning of the first semester, teams are required to prepare a typed project proposal in a formal memo format, including a proposed timeline. During the course of the project, student teams meet with their faculty advisor weekly to discuss the progress report. The weekly formal memo is required the day prior to each weekly meeting and addresses the following three areas: current progress, problems encountered and their resolution, and plan for the following week. To stay on the top of industry requirements sponsoring the project and to receive valuable engineering feedback, students conduct by-weekly Web conference calls with industry liaisons. The oral and written reports due near the end of each semester are to concern themselves with the progress made in each semester. The one at the end of the first semester will be a progress report, with a full final report due at the end of the second semester. To further improve the quality of capstone projects conducted in the EET program in the School of Technology (SoT) at the Michigan Tech and make students experience as participating in undergraduate research, in the middle of the second semester the team led by the faculty prepares the paper to be further submitted in one of the engineering journals or conference proceedings. In the author's opinion, this experience should become an integral part of any capstone project since it derives an additional benefits previously not included in the capstone environment. First, this requirement makes the students to fill them proud to be engaged in undergraduate research, which in-turn derives more responsibility and teamwork. Second, it provides the students with the opportunity to learn different styles of technical

writing following required formats associated with various journals and conference proceedings. The last, but not the least, it significantly improves graduates portfolio that while looking for the job can “bring to the table” more than their competitors/applicants.

### **System Components**

The control system consists of four main components: a solar panel, a stepper motor, LED lights and a PLC/HMI. Along with the main components there were various sub-components and a constructed system enclosure. The solar panel for the system is a Value Line Series, a VLS-10W solar panel. The PID controller will be used to try to keep the solar panel output voltage at the setpoint of the system. The solar panel is constructed of an anodized aluminum frame with tempered glass that houses the polycrystalline module cells. The solar panel has an open circuit voltage rating of 21.4 V, a maximum power rating of 10W and a maximum power voltage rating of 17.1 V [33]. In choosing a solar panel an important factor was the weight it would bear on the stepper motor. The VLS-10W was an ideal option as it only weighs 1.2 kg/2.6 lbs and has a small area with dimensions of 14.17 in x 10.63 in x 1.38 in.

The SureStep STP-MTR-17060 [34] is a single shaft bipolar stepper motor with 125oz/in of torque, 2amps/phase with a NEMA 17 in<sup>2</sup> frame. The required stepper motor holding torque needed to rotate the solar panel was calculated based on the solar panels weight and dimensions. The calculations for the stepper motor torque required for a solar panel weighing 2.7 lbs and dimensions of 14.17 in x 10.63 x 1.38 in are listed below:

$$\mathbf{Torque (T) = Acceleration (\alpha) \times Inertia (J)}$$

The required torque was calculated assuming that the motor must move 60 degrees per second and needs to reach that speed in 0.5 sec.

$$\text{Acceleration} = \alpha = 2 * \Pi * \text{RPS} / \text{Time}$$

( $\Pi = 3.14$ ), (RPS = 60 degree / 360 degree = 0.16667), and (Time equals = 0.5 sec), then  $\alpha = 2(3.14) (0.16667\text{rps}) / 0.5\text{sec}$

$$\mathbf{Acceleration = 2.093 \text{ rad/sec}^2}$$

Inertia =  $J = 1/12 m * (a^2 + b^2)$ ;  $m = \text{mass} = 2.7\text{lb} = 43.2\text{oz}$ ;  $a = \text{length} = 14.73 \text{ in}$ ;  
 $b = \text{width} = 10.63 \text{ in}$ ;  $J = 1187.9 * 0.00259$  (conversion factor)

$$\mathbf{Inertia = 3.07 \text{ oz-in-sec}}$$

$$T = \alpha \times J = (3.07 * 2.093); \text{ Therefore the torque is } \mathbf{T = 6.43 \text{ oz/in (at 0.16667 rps)}}$$

The selected stepper motor has a torque rating of 125oz/in, which is much higher than what is required for the solar panel but was purchased to avoid motor overloaded.

This stepper motor requires a stepper drive in order to control motor movement and function. SureStep offers various drivers that can be used to drive the STP-MTR-17060 stepper motor. The system driver needed to be highly efficient and have flexible controls to give the system

good performance options. The SureStep STP-DRV-4850 [35] was selected to drive our stepper motor; it is powered by 24-48 VDC and uses the SureStepPro software [36] for configuration.

The driver is capable of many different control modes such as step and direction, serial indexing, and velocity mode [36]. In our system, the velocity mode was implemented for easier speed control and ladder logic programming. In velocity mode the motor speed is dependent on the analog voltage value sent to the driver. The speed selection range is 0.1 rev/sec at 1 V to 0.5 rev/sec at 5 V. The STEP input of the driver is used for the Run/Stop of the motor, while the DIR input determines CW or CCW rotation. The analog value for speed is connected to the Analog Input of the driver. For smoother solar panel movement the stepper motor steps per revolution were set to 20,000 steps/rev.

Three LED lights were used in the system with each light drawing 9 watts. Each light is fully dimmable with an output of about 410 lumens apiece and a color temperature of 5400 K. The lights have a bi-pin configuration and are mounted in MR-16 sockets. Each light has a visible output as an approximate input of 8V and increases up to a maximum of 12V DC input.

An SLC-500 Allen Bradley PLC with a 5/04 CPU was used to communicate and control the entirety of the system with PID control. A Panel View 550 HMI was installed to assist in real-time monitoring of the process of the system configuration. The SLC-500 has seven rack slots for modules including the CPU. The modules used in our system include three analog I/O modules, one analog input module, and one relay output module. The PLC controls the intensity of both control lights in accordance with the solar panel output voltage using PID control.

The base of our system enclosure consisted of a 36"H x 30"W x 8"D electrical box in which the components of the system were mounted to a sub-panel. To minimize the amount of unwanted ambient light in the system, the walls of the enclosure were constructed using black plastic sheets. An additional support was added to the top of the solar panel to add stability during rotation. The open system with labeled system components is shown in Figure 2 (a) and the fully enclosed system is shown Figure 2 (b). The system consists of the solar panel fastened to a rotating stand centered on the wide side of the system facing inwards, with the LED lights mounted on stands on the opposite side facing the panel. The panel stand is rotated by a gear system that is attached to the stepper motor. The output of the solar panel is connected to the input module of the PLC, and the inputs of the lights are wired to the analog output modules of the PLC.

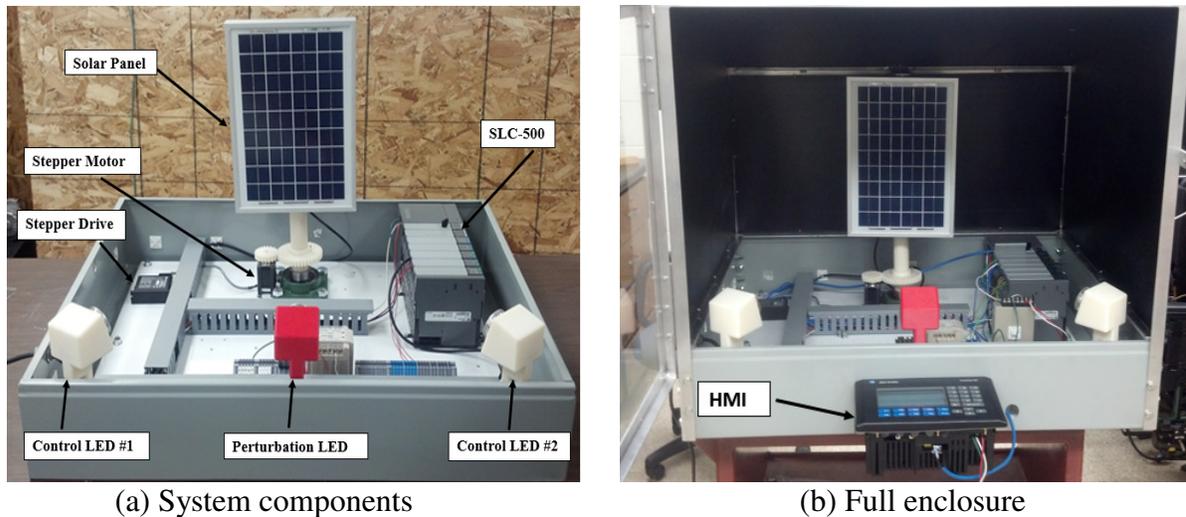


Figure 2. Complete system

### System Development

The development of the system included various system components, wiring, power supplies, etc. which will not be discussed in this paper in detail. A support stand for the solar panel was designed in SolidWorks 3-D printed. To mount the solar panel stand in the enclosure a housing mounted bearing was secured to the sub-panel and the stand base was secured within the bearing. With the solar panel position finalized and secured, it was then wired to the analog input module of the PLC. To couple the solar panel to the stepper motor, two gears were designed and 3-D printed. One gear was connected to the shaft of the stand, and the other was connected to the stepper motor shaft. For PLC control of the stepper motor, the inputs of the stepper drive are wired to the relay output module of the PLC.

The stands used to mount the three LED lights in the system enclosure were designed in SolidWorks and 3-D printed. The MR-16 bulb sockets were used for wiring and securing of the LED bulbs within the stands. The desired angles were then calculated for both the control and perturbation light stands, since the control lights would be at further distances from the solar panel than the perturbation source. The stands were arranged to aim each light at the center of the solar panel. RSLogix500 was used to program the SLC-500 PLC. The main ladder logic program includes various different system functions that were implemented as subroutines in the program. Figure 3 (a) shows the rungs of the main program that contain the directional control of the stepper motor. The position tracking of the solar panel was done via a timer and a counter and calculates the position based on the speed of the motor and how long it is enabled. The ladder logic rungs shown in Figure 3 (b) make up the subroutine, which is called when the oscillation mode is selected. The oscillation mode uses the positioning system to change the direction of the stepper motor once the panel has traveled just under 180°. The intensity range of the perturbation light can be selected range by the user and the range selections include full, half, and quarter range. The implementation of the PID

controller is accomplished by configuring both the PID setup screen shown in Figure 4 (a) and the PID block shown in Figure 4 (b).

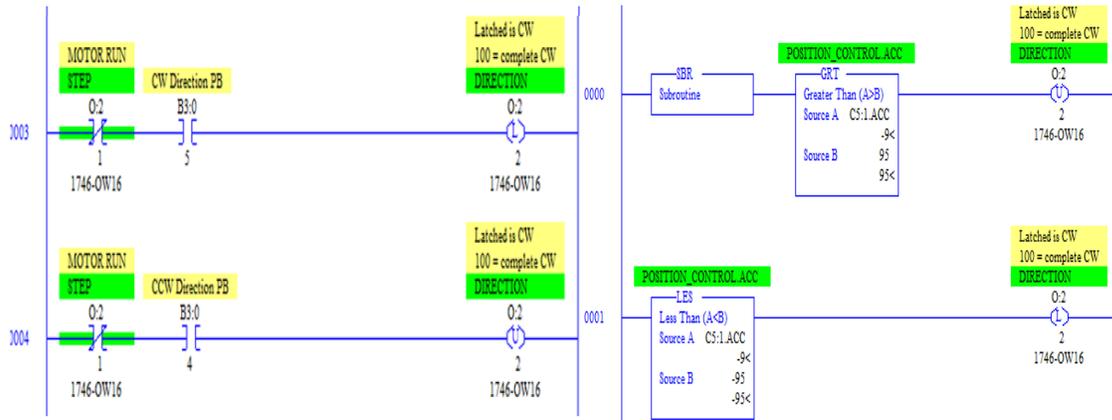


Figure 3. (a) Motor direction control (b) Oscillation mode

HMI system menus were developed using PanelBuilder32 [37] software to allow the user to easily monitor and control the various functions of the system. The main menu of the system is shown in Figure 5 (a) and is where the user is able to navigate to different control and monitoring menus. With various HMI menus the user is able to adjust the perturbation LED light intensity, start and stop oscillation, change oscillation speed, and select the intensity range. The three selectable intensity ranges are full, half, and quarter range. Various user-controlled stepper motor functions through the HMI include stepper motor starting and stopping, selection of speed, direction, and mode. The three stepper motor movement modes are oscillating, stop and manual/homing. Oscillation mode rotates the solar panel in a 180° range of motion while alternating between clockwise (CW) and counterclockwise (CCW) movement. Step mode rotates the solar panel from the center with a changing degree range.

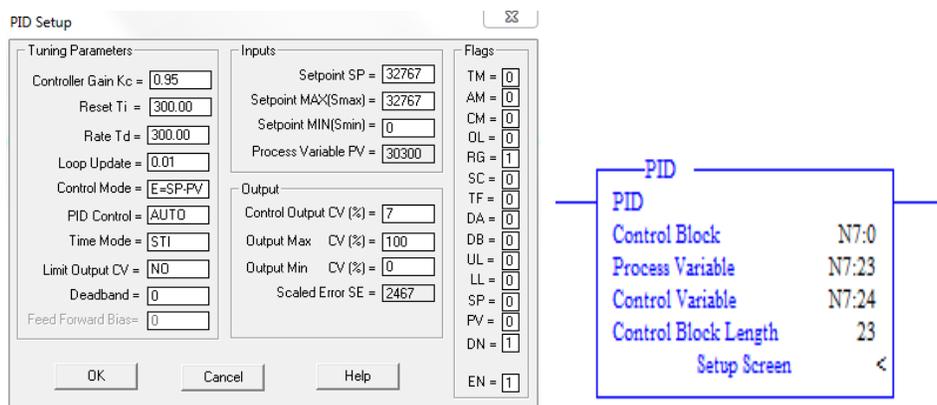


Figure 4. (a) PID setup screen, (b) PID block

The panel's initial rotation is 18° CCW from center, followed by the increase of 18° for the next rotation range. The panel rotates up to 90°, then returns to center and switches the

direction of rotation from CCW to CW and repeats the process in the CW direction. The manual/homing mode is used for complete user controlled motor movement and for resetting the system position. Figure 5 (b) shows the HMI screen which allows the user to view the solar panel output voltage on a bar graph and number indicator in real-time alongside the setpoint value.



Figure 5. (a) System main menu (b) Solar panel voltage monitoring

## Results & Discussion

The testing of the PID controller in the system consisted of the implementation of a P, PI, and PID controller. The initial testing was without any perturbations in the system and was done to see how fast and accurately the set point was reached when the system was started. Figure 6 shows the system response for implementing P controllers with proportional gains of 0.5, 0.95, and 5. The controller with a proportional gain of 5 has the fastest rise time and the slowest settling time. This controller experiences the largest overshoot and is the only P controller to experience oscillation. For a controller with the gain set to 0.95, the rise time increases and the settling time decreases. With the decrease in the proportional constant the overshoot has decreased and the oscillation has been removed. From the controller with a proportional gain of 0.5 the overshoot is completely removed, but the rise time has increased. Depending on the required rise time the proportional gain should be between 0.5-1 to minimize overshoot and steady state error; otherwise, the performance will be weak in terms overshoot, oscillations, and steady state error.

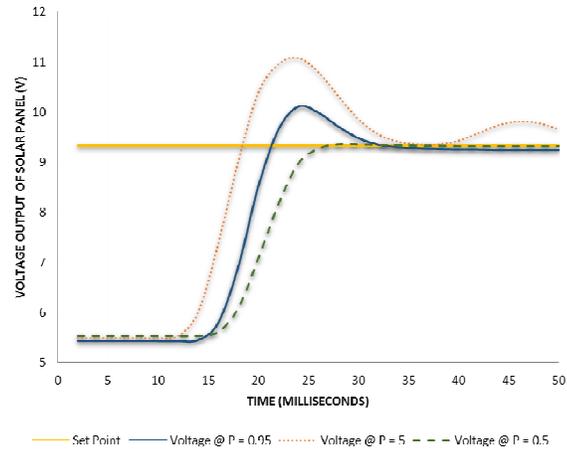


Figure 6. P controller

Figure 7 shows the system response for implementing PI controllers with constant proportional gains of 0.95 and integral gains of 1, 50, and 300. The results show that as integral gain increases the rise time and settling time both slightly increase. The integral gain should be set close to 250 to minimize rise time and additional more aggressive perturbation scenarios will be used to validate various gain settings.

Figure 8 shows the system response for implementing PID controllers with constant proportional gains of 0.95 and constant integral gains of 300 with derivative gains of 10, 75, and 300. For a low derivative gain of 10 the system response was quite unstable and never settled at the set point. For both derivative gains of 75 and 300 the system response was very similar, with slightly better overshoot for the gain of 75. In comparison to the PI controller, the addition of the derivative gain did not show a significant change in response. This was expected because testing had minimal future perturbations for the derivative gain to respond to. In Figure 8, the initial conditions are slightly different for the three test cases, and the difference is less than 0.25(V), which is an acceptable range to make a fair comparison among the three test cases. Additional testing will be done to further test the function of the PID controller and to determine the desired gain parameters for different test scenarios.

Future test cases include changing the oscillation speed and intensity of the perturbation light, rotating the solar panel at different speeds and movement patterns, and combining both test cases to maximize the system perturbations for testing.

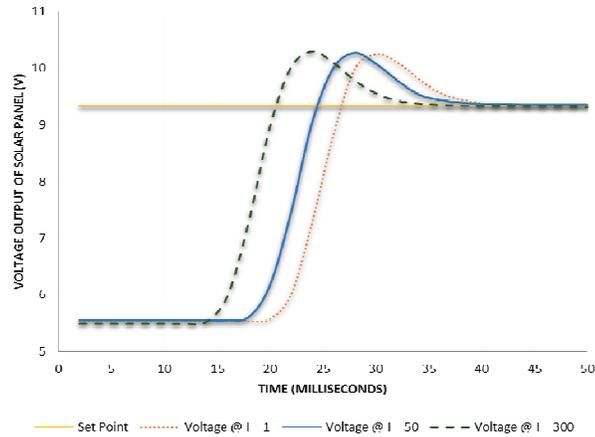


Figure 7. PI controller

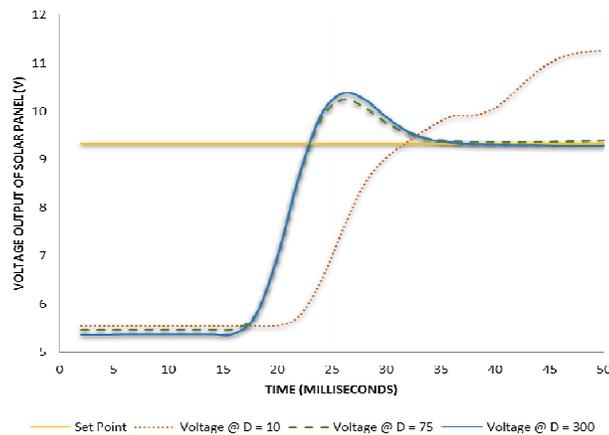


Figure 8. PID controller

## Conclusion

The PID controller was implemented into the completed system and testing confirmed the desired PID controller function. Based on initial results, an implemented PI controller with a proportional gain of 0.6 and integral gain of 250 would be ideal for the system experiencing minimal perturbations. For the system experiencing various perturbations, PID control should help with system stability.

With topics addressed in the system such as the basic input/outputs, system troubleshooting, complex PLC programming methods, HMI programming/implementation, and PID controllers, this system can be used as an educational tool for students learning basic and advanced PLC techniques. Through this capstone project, group members gained valuable experience with components such as PLCs, HMIs, solar panels, and stepper motors, and it has been a valuable learning experience completing a complex system from design to completion.

Academic programs in the School of Technology at Michigan Tech are designed to prepare technical and/or management-oriented professionals for employment in industry, education, government, and business. The EET program is constantly revamping the curriculum to meet the expectations of industry by supplying qualified technicians and technologists who have extensive hands-on experience. As part of the continuous effort leading to priority consideration of graduates from the School of Technology an EET program at Michigan Tech engaged a group of EET students in solving engineering problems as part of capstone integrating experience and to fulfill the degree program requirements. Working with the advisors, the team was challenged to integrate a programmable logic controller with the human machine interface to create an effective PID controller.

With the conclusion of this project, the team was able to meet all of the requirements given by the faculty advisor and fulfill the degree program requirements at Michigan Tech . Successful assembly and testing of the unit was accomplished. An extensive tutorial includes step-by-step instructions with images and figures on how to use HMI and PLC to run the pre-programmed operational cycle of the PID controller. The tutorial also includes detailed instructions on reconfiguring individual control functions to modify the operating cycle of the system. The situational scenario is included in the tutorial and provides all necessary steps for configuring HMI and programming PLC to achieve all the tasks. The developed tutorial along with the build PID controlled system will serve the purpose of providing the hands-on PLC, HMI, and PID theory training to the students enrolled in introductory and advanced PLC courses.

### **Future Work**

This senior design project research is being extended to further study the behavior of the optical system in-depth and to improve the performance of the PID controller. So far, it is identified that the optical system is highly nonlinear at some operating points and the nonlinearity is due to a dead-band characteristic of the optical system. To this end, the performance of the optical system (in a closed-loop configuration with the PID controller) is very different from the performance of a linear system, and hence at some operating points, the observations from the optical system contradict our expectations from a linear system. This research is being continued and the nonlinearity in the optical system is being studied in details. Therefore, this senior design research is ongoing , with the following directing future work:

- The optical system will be investigated to analyze the dynamic model of the system.
- Once the dynamic model is analyzed, different PID controller design techniques will be investigated, such as Ziegler-Nichols (ZN) and model-based techniques.

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