PID CONTROLLER

Waleed Umer – S5336317

PRACTICAL ELECTRONICS

Instructor : Dr. Faisal Mohd-Yasin

CONTENTS

1.0 - INTRODUCTION

OBJECTIVES AND OUTCOMES

The main objective of the project is to apply the knowledge acquired in practical electronics to the design and implementation of a PID controller. It also aims to explore and develop every step required to build an electronic prototype. The expected results of the project will provide a comprehensive understanding of electronic components (operational amplifiers, resistors, capacitors, sensors, etc.) and their configurations in real-world applications.

On the topic of PID controllers, the project is detailed in its explanation. Although it does not present any real-world applications, it explains the different modes of operation of the PID controller—P, PI, PD, and PID—when the setpoint command is a sinusoidal, impulse, triangular, or square wave signal.

Each mode has its advantages and disadvantages which are discussed, as are the frequencies where these limitations exist. This analysis provides the unique advantages and disadvantages of each mode and provides a comprehensive view of how each mode performs under different conditions.

2.0 - APPLICATION

The PID controller, as we have seen, can be a useful part of the controllers we use in practical control systems. This section will highlight three significant applications of PID controllers in the real world:

1. Temperature control : We mentioned earlier that keeping the temperature in our houses regulated is an essential aspect of heating, ventilation, and air-conditioning (HVAC) systems. Not surprisingly, PID control is also commonly used in industrial applications where we need to keep the temperature of something that can change quickly. For example, one could for controlling the temperature in a furnace. This would be where the temperature of a furnace must remain at a precise temperature to achieve consistent results, even with fluctuations or disturbance in the system [4].

2. Speed control: Being able to accurately and precisely control the speed of a motor is another application of PID control. For example, with a car engine, you want a certain amount of gas to go in your engine to achieve a desired speed. Through PID control, one can regulate the flow of gas into the engine to achieve a certain, desired speed. This is seen in the automation of a conveyor belt system where you want to move a give a belt a certain speed from the motor [5].

3. Process control: This last example can be applied in a situation where you have a chemical process you want to control. This could be a chemical reactor where you are trying to produce a specific amount of product Y from reactants X1 and X2. This system will run optimally with the right amount of reactants being pumped in. A PID controller will adjust the flow rates to make sure we have the right pressure and composition to help the distillation column run efficiently, ensuring the results are consistent[6].

MARKET ANALYSIS

Without undergoing extensive practical tests with a load such as a DC motor, the product has no potential commercial value for application. Nonetheless, it can be used in a range of signal control applications within a specified range.
The below are the costs for individual components using the circuit; the minimum quantity of PCBs that can be ordered to manufacture is five per quantity and the costs for PCB production is $18, and the delivery charge is an additional $5.

COST OF THE PROJECT

LIST OF PARTS[1]

Comment	Description	Quantity	Total Cost AUD
CAPACITOR POL	Polarized Cap	1	$1.92
TL074	TL074/LF347 Quad Low Noise JFET Op-Amp Linear [3]	1	$1.58
Header 4	Header, 4-Pin	4	$1.10
TL072	TL072 Bi Low Noise JFET Op-Amp Linear	1	$1.66
RESISTOR	1/4 W Res	11	$7.52
Potentiometer	Breadboard Compatible	4	$7.00
Manufacturing & Delivery	**Printed Circuit Board**		**18+5$**

TOTAL COST OF MATERIALS	**$43.78**

LABOR COST

ACTIVITY	HOURS	COST PER HOUR	TOTAL COST
Altium design	**4**	**$25**	**$100**
Circuit wiring and testing	**12**	**$25**	**$300**
Soldering process	**2**	**$20**	**$40**
TOTAL COST OF LABOR			$440

TOTAL COST OF THE PROJECT

Developing, testing, and producing the prototype not only involves high initial costs, but also involves relatively simple parts and functions. Our cost estimate for the materials, including PCB manufacturing and shipping, is approximately $44 based on current online prices. For mass production, parts would be sourced at wholesale prices significantly decreasing the costs. Our production quality and cost-effectiveness could be enhanced by streamlining the soldering process. Overall, the total cost to develop and produce the prototype is approximately $440.

3.0 -INITIAL DESIGN

BASIC THEORY

A Proportional-Integral-Derivative (PID) controller is an indispensable instrument in control systems engineering and is ubiquitous in modern industry. It’s a system that keeps a process within a given setpoint by minimising the error between the process variable and the setpoint. One computes the controller output from three parts: the first one (P) relies on the current error, a second one (I) accumulates errors over time, and a third (D) anticipates future errors by considering the rate of change of error. Hence, the combined effect makes the system behave in such a way that it truly knows how to deliver desired adequate tuning for precise and stable control of a large class of dynamic systems[1],[2].

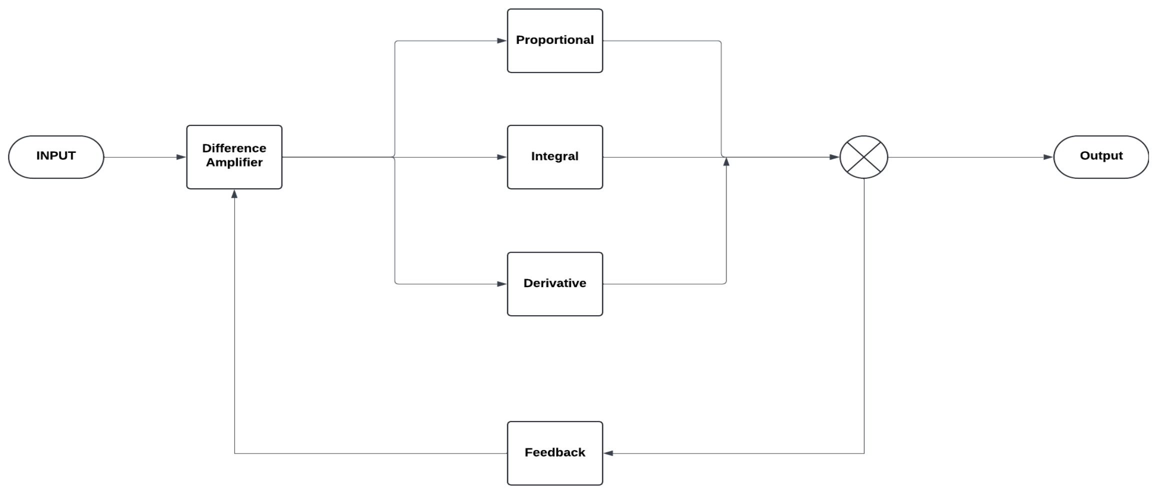

Figure 3.01 Basic PID Diagram

ELEMENTS OF A PID

PROPORTIONAL STAGE

Proportional is the part of a PID Controller that puts a gain on the error signal. It dictates how much of a gain this Controller will see from the error to the setpoint. The goal is to dictate the gain of the system, and the percent of not only the Controller but also on the overall system. So the proportional gain (Kc) will define in turn how much but also very quickly this system will react to this error signal. If we take a proportional gain that is very high, we can see a very quick reaction and this system can start to 'oscillate'.

INTEGRAL STAGE

A PID controller, on the other hand, incorporates a short-term memory that increases the responsiveness by accumulating past errors. This accumulated value is used to change the setpoint of the controlled output in order to bring the process variable more quickly to its desired value. The gain of this component is determined by the chosen ratio between the feedback capacitor and the resistor, ensuring errors of long duration will be eliminated, eventually.

DERIVATIVE STAGE

The differentiator part of a PID controller quantifies the error's time rate of change, contributing a negative value to the controlled output as the growth rate of the error increases. It reduces overshoot by slowing down system response at approach to set-point by process variable, thus, ideally preventing any overshooting. When there are big deviations in the system, derivative component performs a significant task to ensure that it runs smoothly. It also minimizes oscillations and helps settle down the system along with an integral portion.

ANALOGUE CIRCUITS OF PID:

The PID controller design process consisted of different stages.

Initially, the analogue circuits belonging to the proportional, integral, derivative, summation and subtractor stages were defined. The topology used in each stage are shown below:

1. Proportional circuit:

$$\text{Gain} = K_p = 10$$

We chose a moderate gain for the proportional stage to ensure that the PID output approaches the reference value quickly, meeting our requirement for systems with moderate to high frequencies. This not only shortens the response time but also makes it easier to observe the PID signal intercepting the system signal, especially during demonstrations with an oscilloscope. Initially, we set this gain, but later, we can fine-tune it to the desired value using a Trimpot (potentiometer) simply by adjusting its knob.

2. Integral circuit:

$$voltage\ gain = K_i = 1$$
$$CutOff\ Frequency = 800\text{Hz}$$

To maintain circuit simplicity, the gain value of the integral stage was set to 1, and a low-pass integral filter output was buffered with a gain of 1, deviating from the conventional integral circuit. This adjustment streamlined circuit analysis. To offset the lack of gain in the integral, gain was introduced to the summing stage of the PID circuit. This modification ensures proper functionality and simplifies the overall circuit design.

3. Differentiation circuit:

$$Derivative\ gain = Kd = 1$$

To maintain circuit simplicity, similar to integral stage, the gain value of the derivative stage was set to 1, and a low-pass differential filter output was buffered with a gain of 1, deviating from the conventional differential circuit. This adjustment streamlined circuit analysis. To offset the lack of gain in the differential stage, gain was introduced to the summing stage of the PID circuit. This modification ensures proper functionality and simplifies the overall circuit design.

4. Summation circuit:

To simplify the design process, all resistors were standardized to the same value (1 KΩ). Since we set gain of the integral and differential stage of the circuit , a gain of 10 is introduced at the summation stage . This approach maintains signal integrity and facilitates straightforward analysis and adjustment of the circuit.

5. Difference Amplifier circuit:

Similarly to the summation stage, unit gains are established for the difference amplification stage initially to maintain the system's performance unaffected. This approach ensures stability and consistency in the system's operation, minimizing any potential impact on its overall performance.

ASSEMBLED PID CONTROLLER CIRCUIT:

Employing the Proteus circuit design software , entire PID controller was modelled and an approximate response of the system was obtained. In the following image you can see the integration of all the circuits mentioned in the previous section.

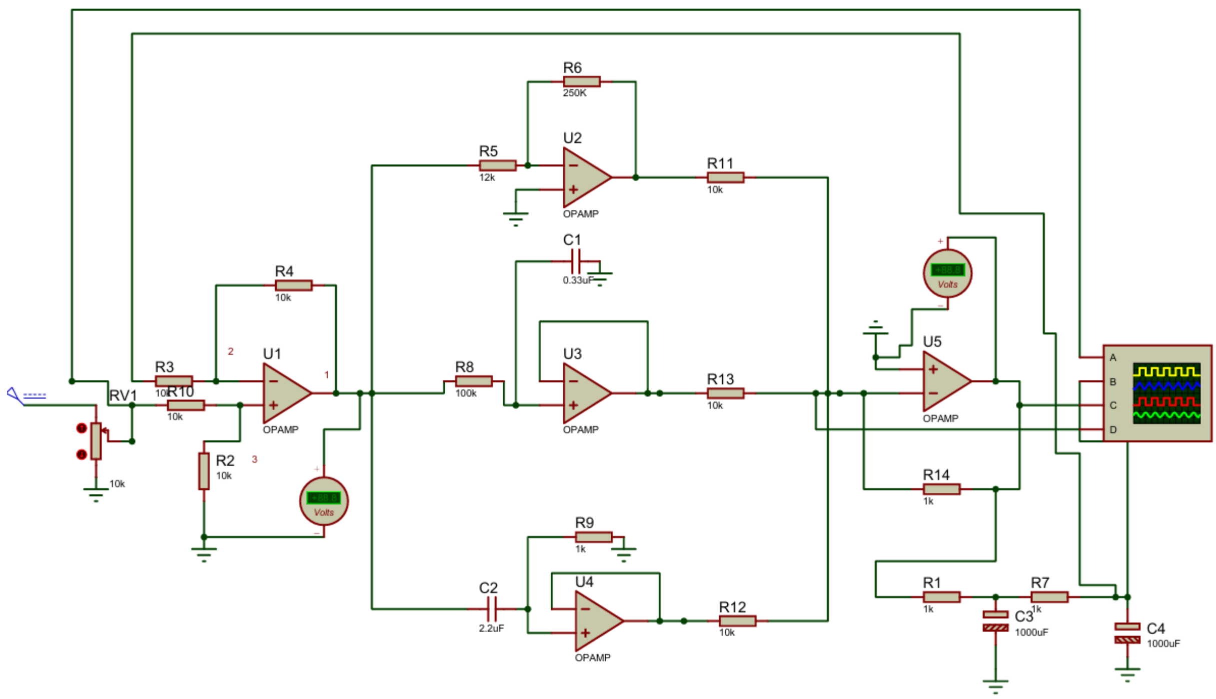

Figure 3.02 Proteus Implementation of PID

In this Figure 3.2 . A simulated circuit of PID controller shown on proteus

BREADBOARD CIRCUIT RESULT

The simulated system was transferred to real circuits and elements on a breadboard. The result of this implementation is shown below Figure 3.3.

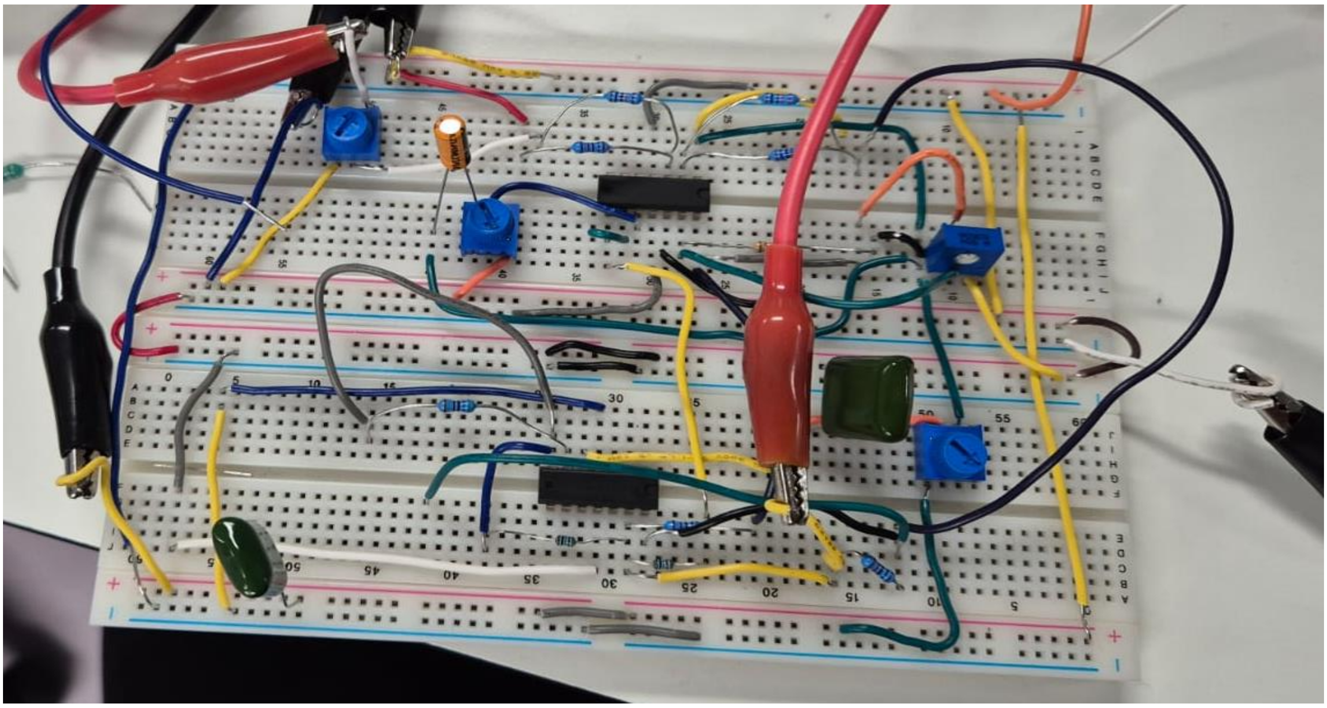

Figure 3.3 Breadboard Implementation of PID

This circuit played a crucial role in conducting a wide range of tests, allowing for modifications to resistors, capacitors, op-amps, and transistors. Through these tests, we were able to define the response characteristics of the desired PID system, subsequently obtaining the values of fixed resistors and capacitors. These values were then applied practically on the PCB, facilitating an efficient and effective implementation process.

ALTIUM PCB AND SCHEMATIC DESIGN

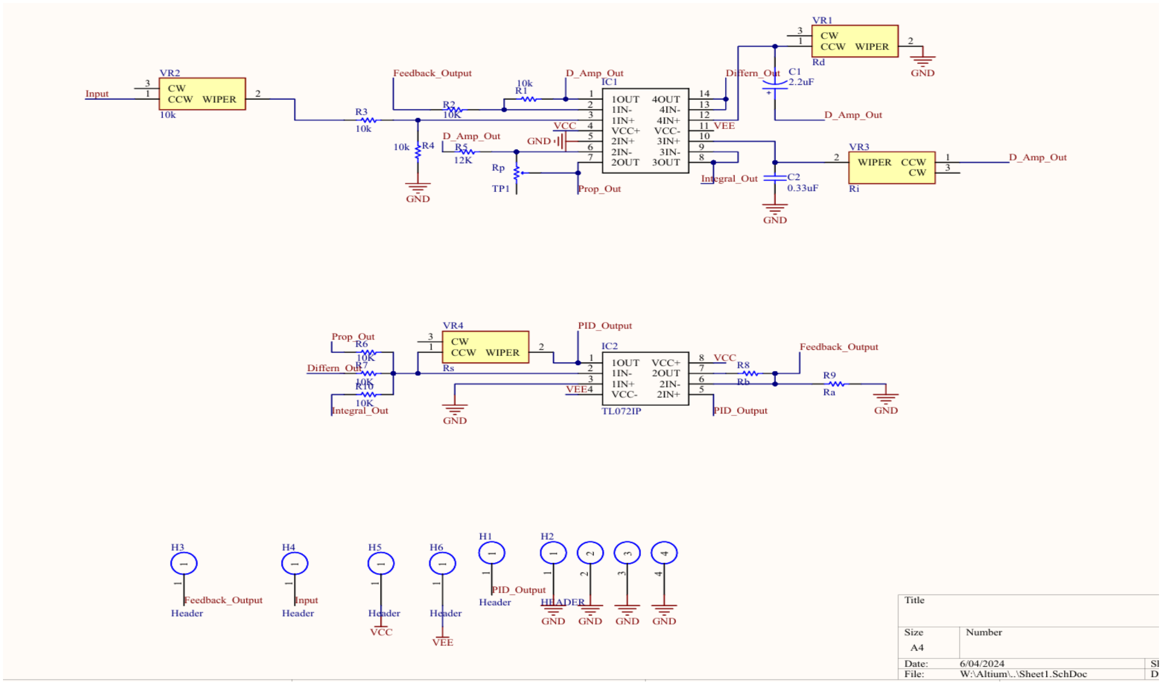

Figure 03.4 PCB Schematic of PID

We started our circuit design journey in Proteus, which made simulating and tweaking component values a breeze. After settling on the initial design, we shifted gears to Altium, where countless hours were spent refining and discussing component choices and how they fit into our circuit.

Once we were happy with the design, we dove into PCB layout, going through three iterations before we had a final version ready for manufacturing. We relied heavily on the component libraries provided by the lab attendant in Altium.

We made sure to keep things simple by sticking to single-sided PCB tracks, making manual soldering a lot easier and reducing the risk of damaging anything. Plus, we included a ground plane on the bottom side of the board for added stability. Figure 3.5 shows manufacturing script of PCB design

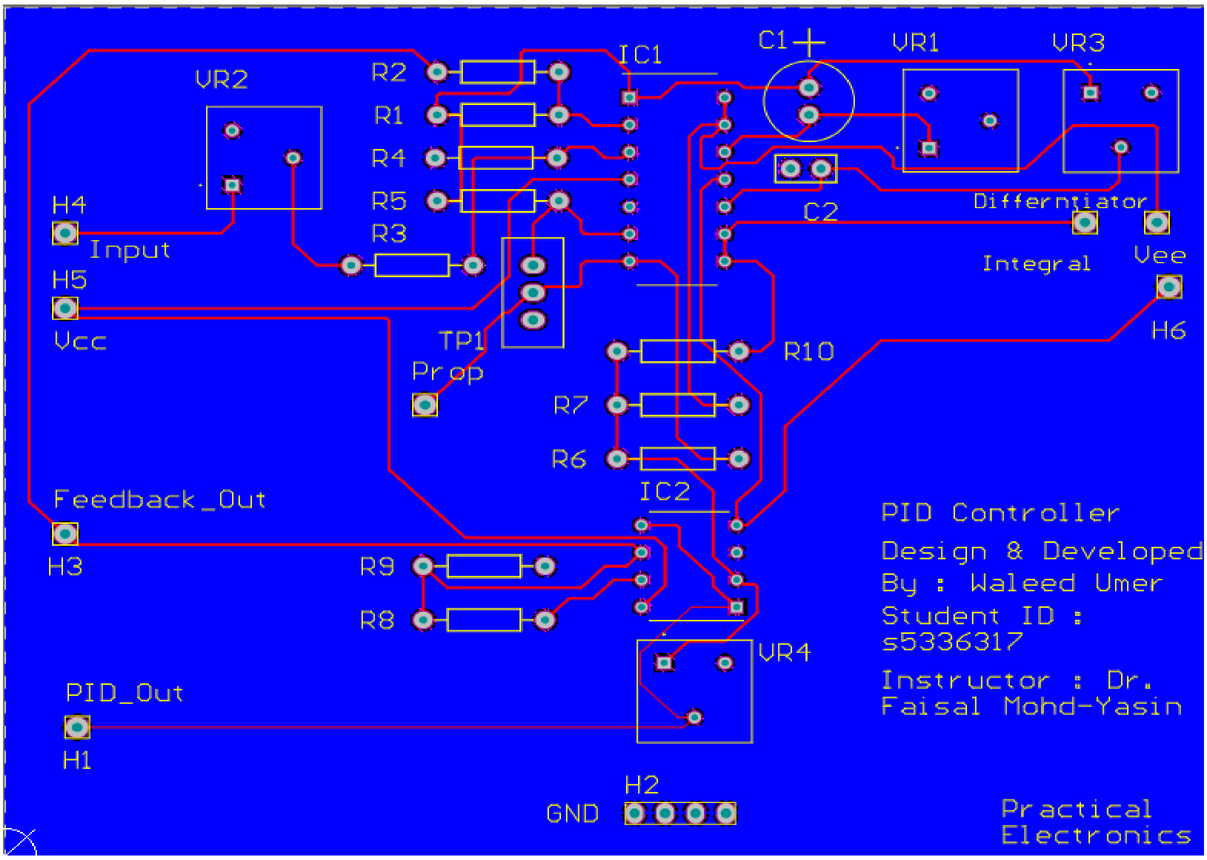

Figure 3.5 PCB Manufacturing Script of PID

4.0 – System Design Characteristics & Analysis

The system design underwent thorough testing and analysis on both breadboard and PCB platforms, yielding valuable insights. An additional Proportional stage was introduced in the PCB circuit as a modification. The results of various controller circuit behaviours were categorized and explained, highlighting the benefits and drawbacks of each approach.

Throughout the analysis, it became evident that while alternative circuits showed promise in certain scenarios, they were not preferred over a full PID controller. The drawbacks of these circuits, such as limited control accuracy or instability, were identified and solutions were proposed. These findings underscored the importance of a comprehensive PID controller design for optimal performance and versatility in various control applications.

Breadboard Results

The response of this circuit measured by the oscilloscope is shown below *(Figure 4.2)*. The reference signal (yellow) and the PID signal (green) at different gain values for Kp , Ki and Kd. The figure below is taken from the pre-liminary design powerpoint where I explained the behaviour of the circuit.

Key Takeaways from Breadboard Demonstration:

- The left PID output demonstrates high stability, achieved by suppressing steady-state error and overshoot through circuit tuning with the potentiometer.

- Conversely, the right output exhibits overshoot, indicating a need for tuning the integral value to optimize performance.

- -The middle circuit, however, shows balanced gain values, as evidenced by the absence of significant overshoot, or undershoot. This indicates that it effectively incorporates the functionalities of all PID elements.

- As demonstrated in the lab, without fine-tuning the circuit for a given signal, the output can become distorted.

- A square wave signal was chosen for demonstration due to its abrupt changes, offering a clear illustration of the circuit's response. The same cannot be said for sinusoidal and triangular signals, which do not provide as distinct a demonstration of the circuit's behaviour.

Figure 4.1 Breadboard results at different Tuning Values (Kp,Ki & Kd)

PRINTED CIRCUIT BOARD:

The final product is visually represented in the images below. The PCB appears clean and compact, presenting a professional appearance. Most connections are tidy and precise, contributing to the overall neatness of the assembly. Moreover, the PID controller operates as anticipated, demonstrating its functionality and reliability.

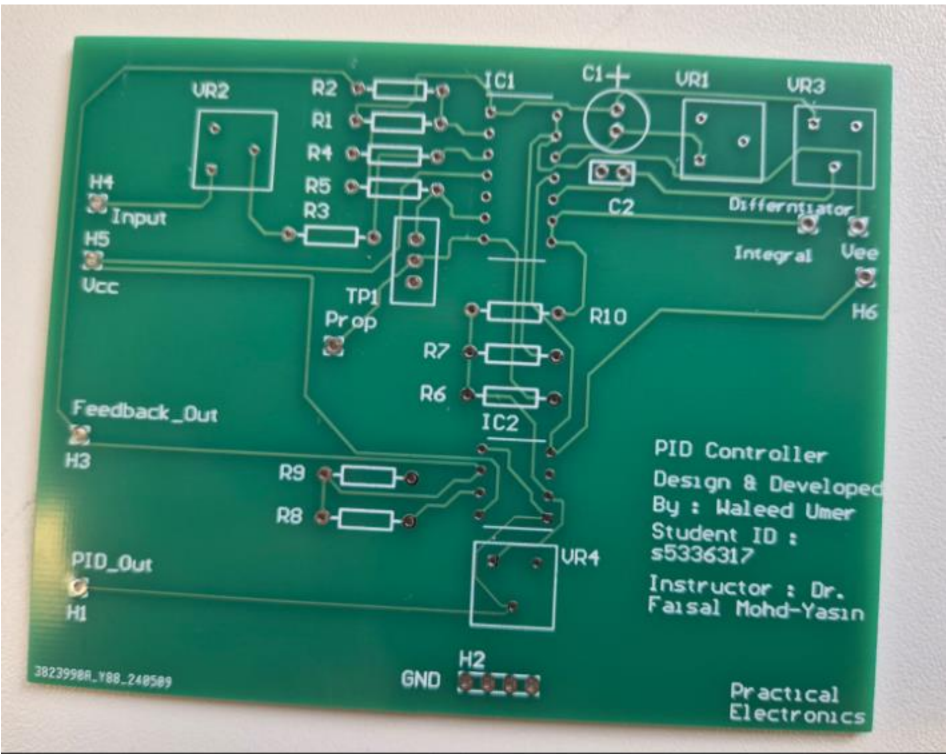

Figure 4.2 PCB prior to soldering components

In figure 4.3 we can observe the top view of PCB after soldering.

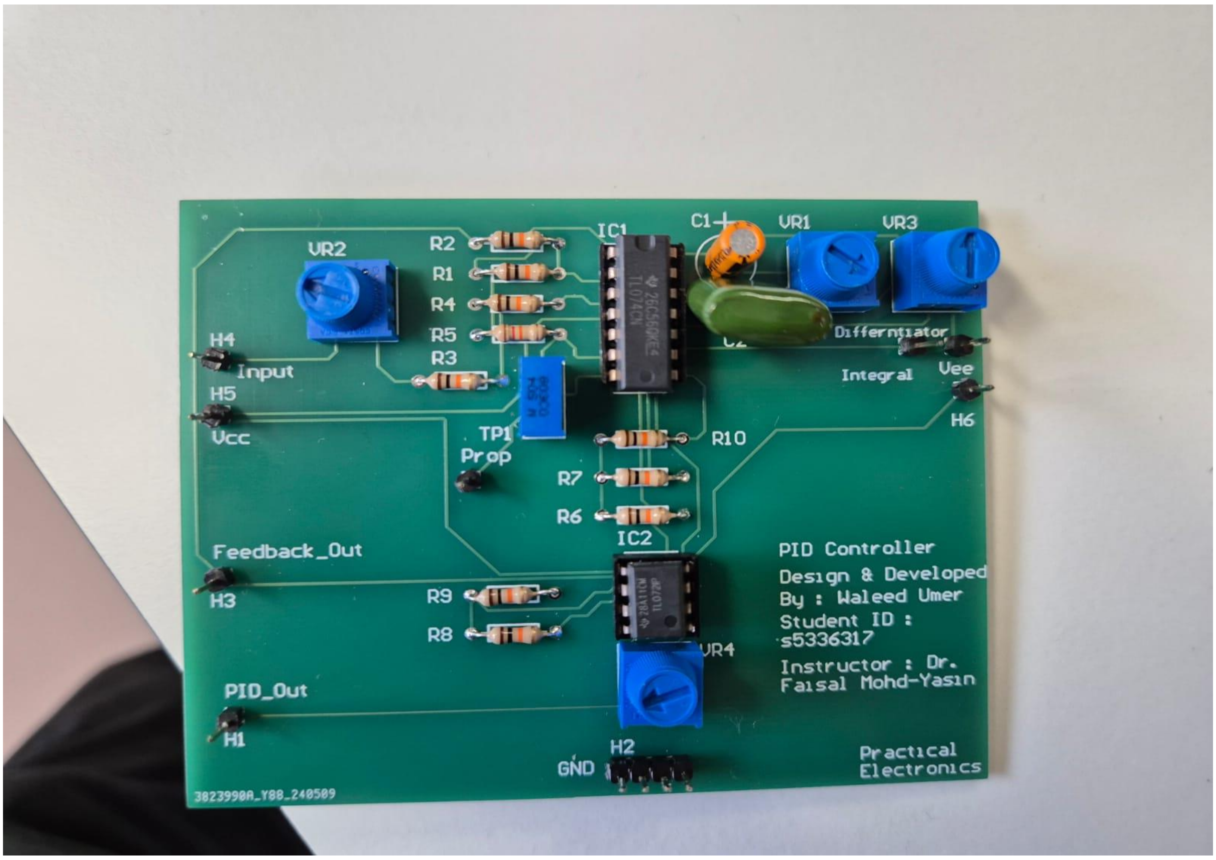

Figure 4.3 PCB Top View after Soldering Components

PCB RESULTS & ANALYSIS :

In this section, I conducted an in-depth analysis of PID controllers, specifically focusing on the modification of adding a Proportional stage in front of the PID output stage to further refine the output. Below, you will find a detailed analysis of the behaviours of P, PI, PD, and PID circuits, along with explanations of why the full PID controller is preferred over each of these individual control circuits.

Proportional Behaviour:

Proportional component of the circuit is known for reacting to current errors .What we observe in the figure 4.4 below is a manifestation of P trying to correct current error (e) thus leading to oscillations as there is no other component active we get an uncontrollable oscillations along the length of the signal.

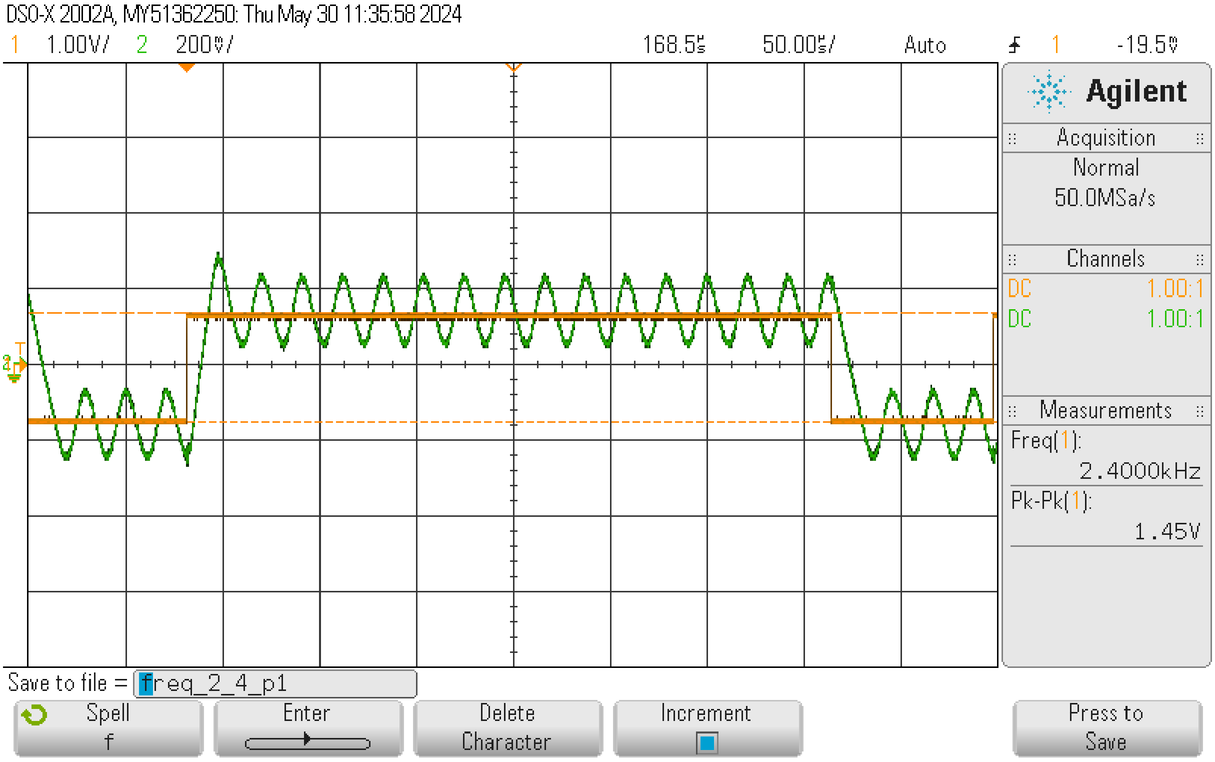

Figure 4.5 Proportional Behaviour

P-I Circuit Behaviour:

In this circuit, the integral component reacts to the accumulation of errors over time. Compared to the circuit in Figure 4.4, it is evident that errors persist in this circuit, but they are gradually reduced as the integral action works to correct past errors. However, if the integral action is too aggressive, it can lead to high amplitude overshoots. Essentially, the proportional component addresses current errors, while the integral component averages those errors over time, resulting in progressively shorter oscillations. In summary, the integral component ensures steady-state accuracy.

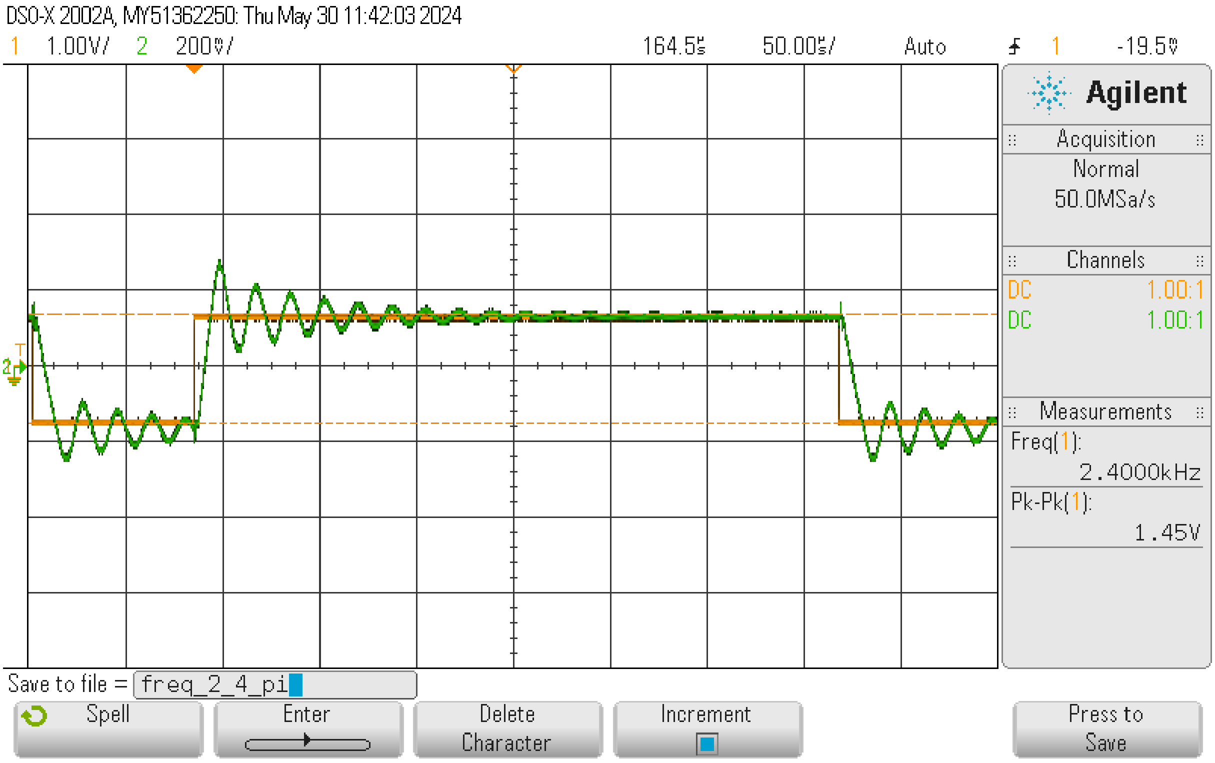

Figure 04.4 PI Behaviour

P-D Circuit Behaviour:

The PD circuit has behavior similar to the integral circuit as both address their errors over time. The integral component accumulates errors over time, while the differential component reacts to the rate of change of error, damping the system. Since the differential component aims to counteract the effects of the proportional component, it can cause deep undershoots.

Over time, the system suppresses all oscillations as the rate of change of error approaches zero. However, if the differential action is too aggressive, it can lead to over-damping and instability in the system.

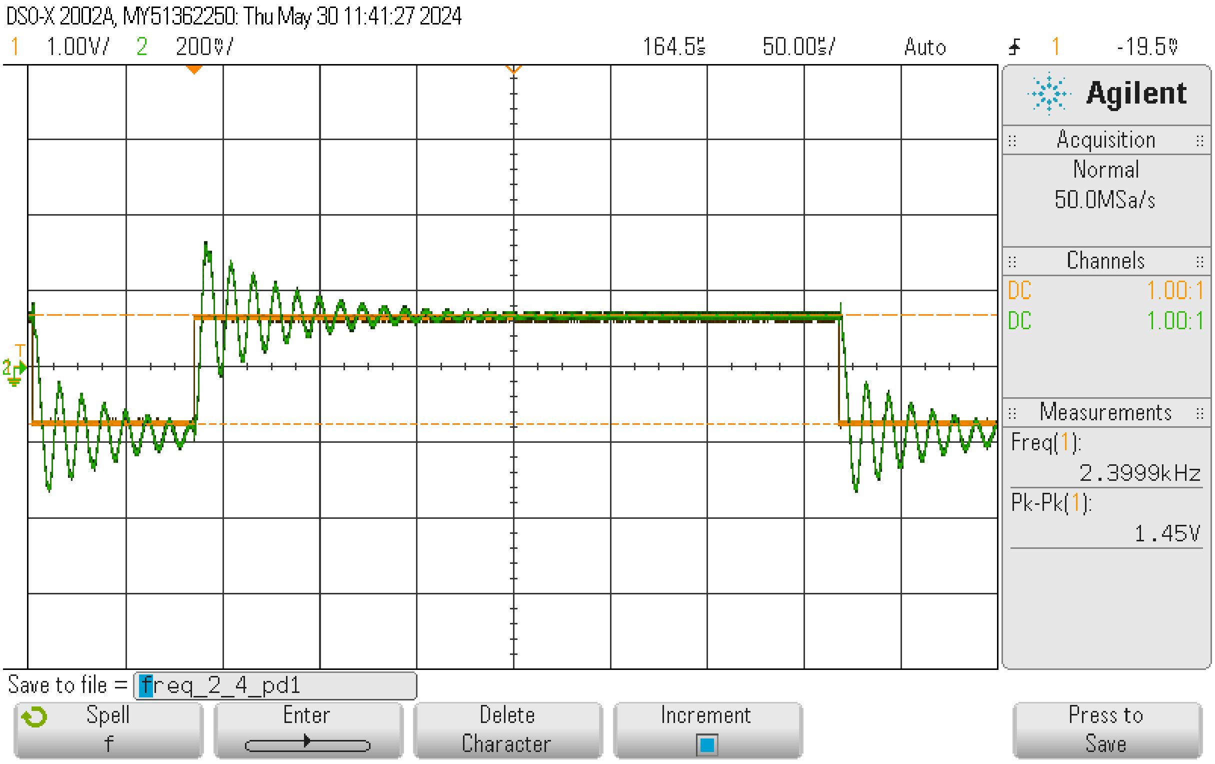

Figure 4.5 PD Behaviour

PID-P Circuit Behaviour (Modified PID):

In the PCB design, I added an extra Proportional layer and removed the gain from the summation stage to preserve the integrity of signals from each P, I, and D stage. This adjustment was made to achieve finer control over the system and to make up for the gain not ntroduced in the derivative and integral stages. As shown in Figure 4.7, the system error approached zero after a single pair of undershoot and overshoot.With enhanced stability, a quicker response, fewer overshoots, and better handling of sudden changes, the PID controller proves to be more effective than the P, PI, and PD circuits.

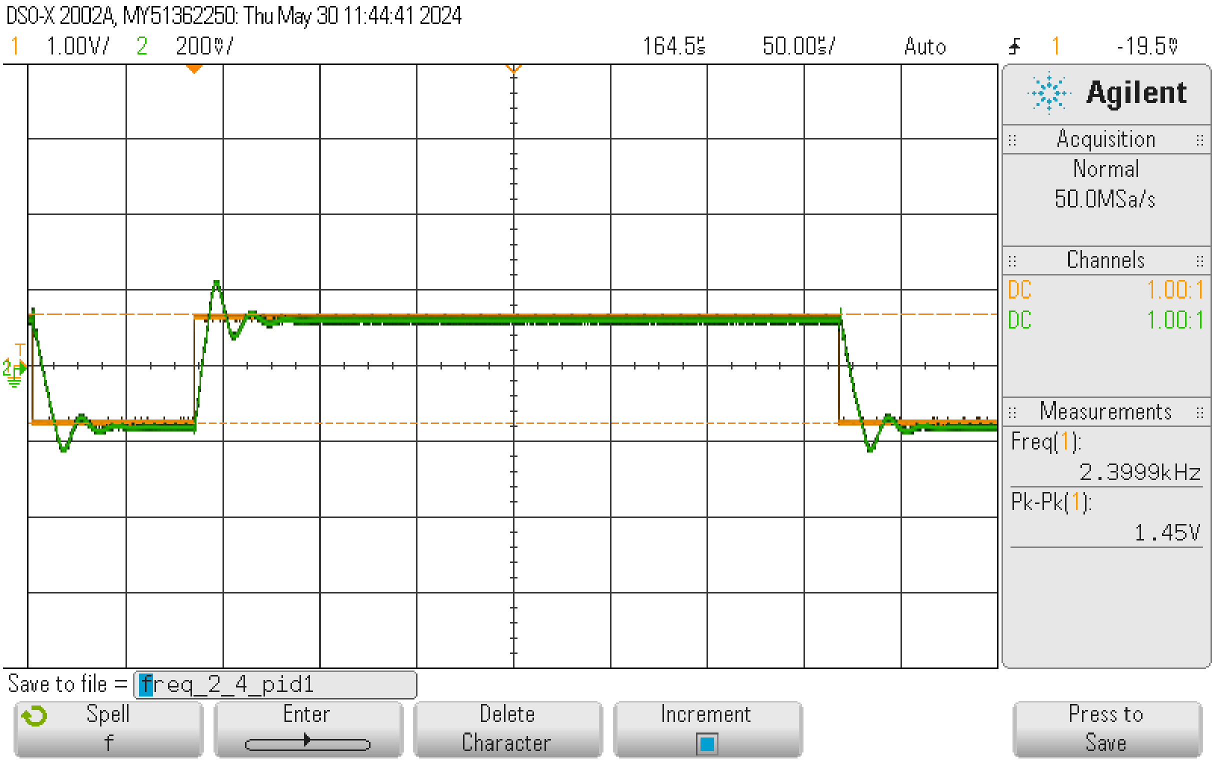

Figure 4.6 PID Behaviour

Comprehensive Analysis :

In Figure 4.8, I compare the behaviors of the P, PI, and PD controllers to illustrate how each system suppresses errors. I recorded CSV data from the oscilloscope and plotted the response of each component against the input reference signal. For clarity, I removed the reference signal from the chart.

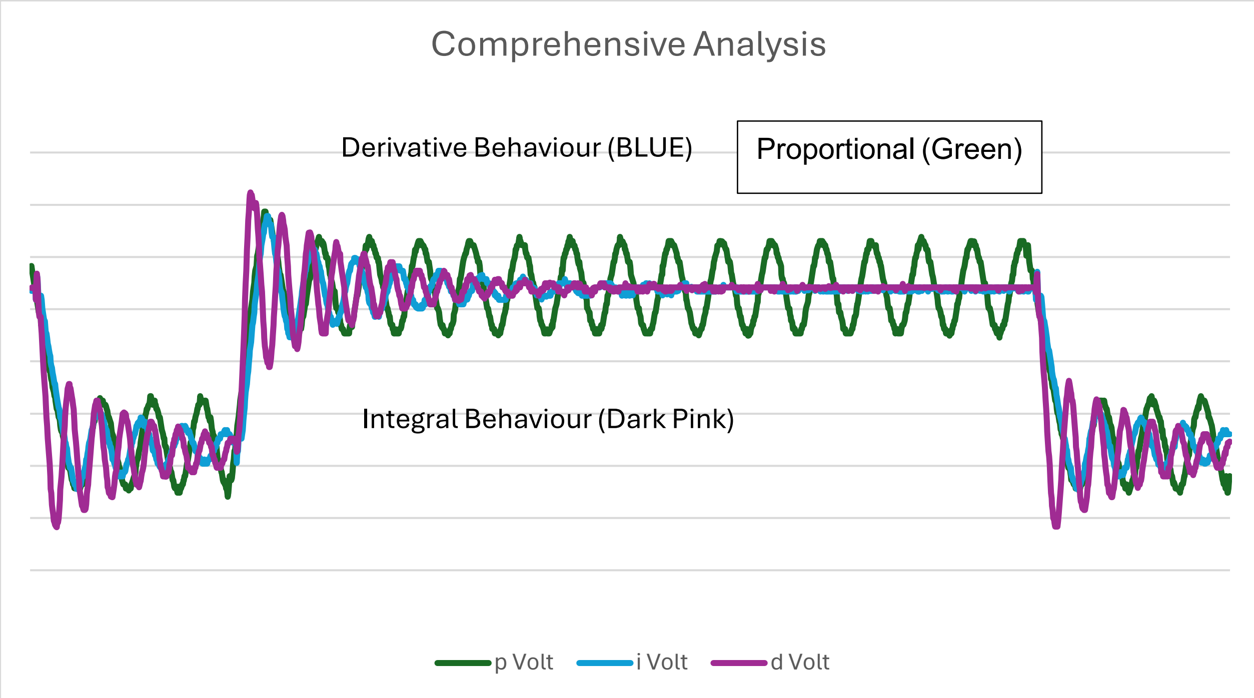

Figure 4.7 P , PI & PD Behaviour

In figure 4.9 I showed a comparison between PID and P outputs .

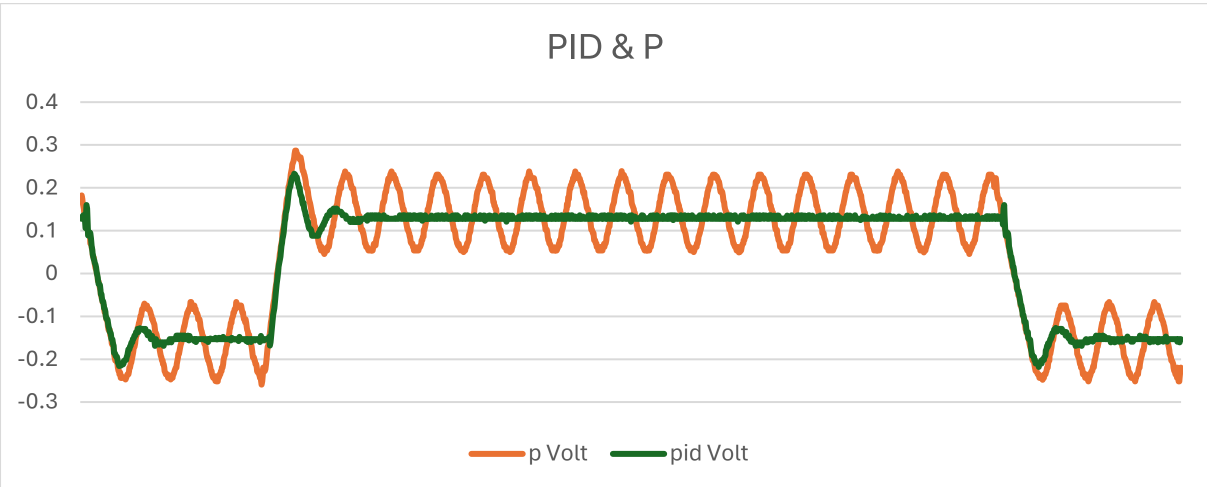

Figure 4.8 PID & P Comparison

In figure 4.10 I showed a comparison between PID and PD outputs. This is quite evident why PID is preferred over PD as we get a system that has no uncontrollable overshoots. A close look at figure 4.10 shows clear difference between amplitudes of undershoots in PID & PD.

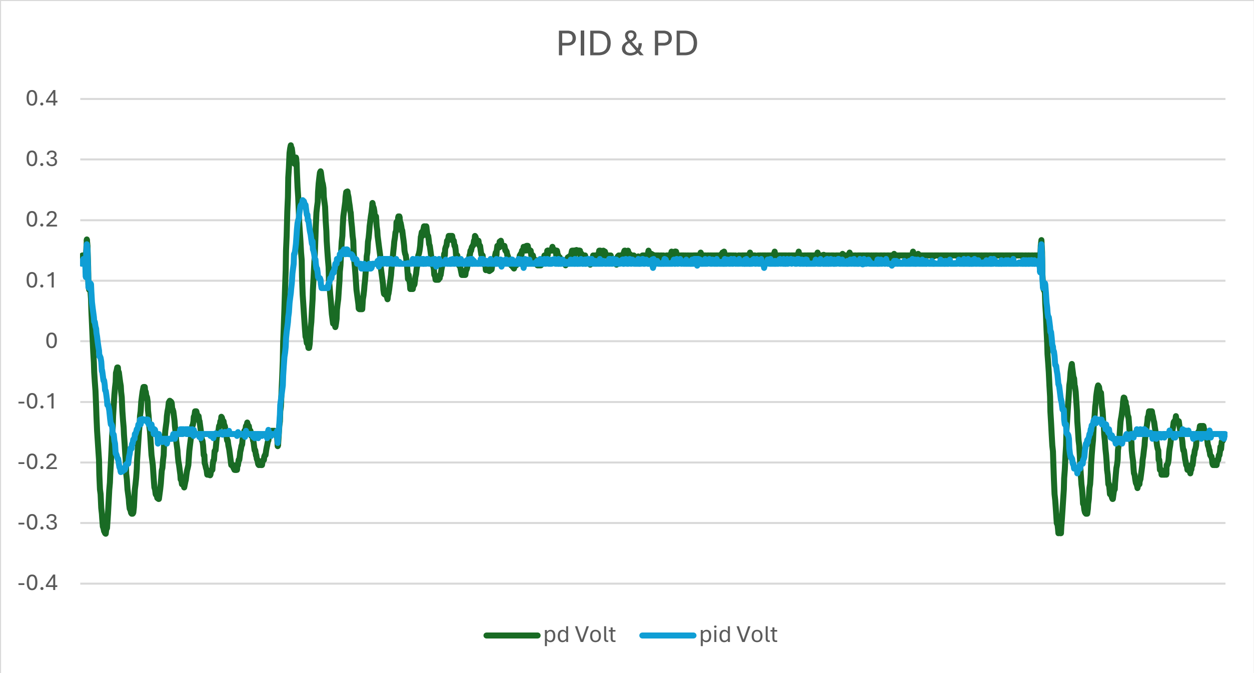

Figure 4.9 PID & PD Comparison

In Figure 4.11, I show a comparison between PID and PI behavior. The PD controller results in overshoots, while the PI controller also exhibits overshoots. This figure clearly distinguishes the amplitude differences between PID and PI overshoots. Increasing the integral effect can make the system's behavior more unstable, resembling that of the PI controller.

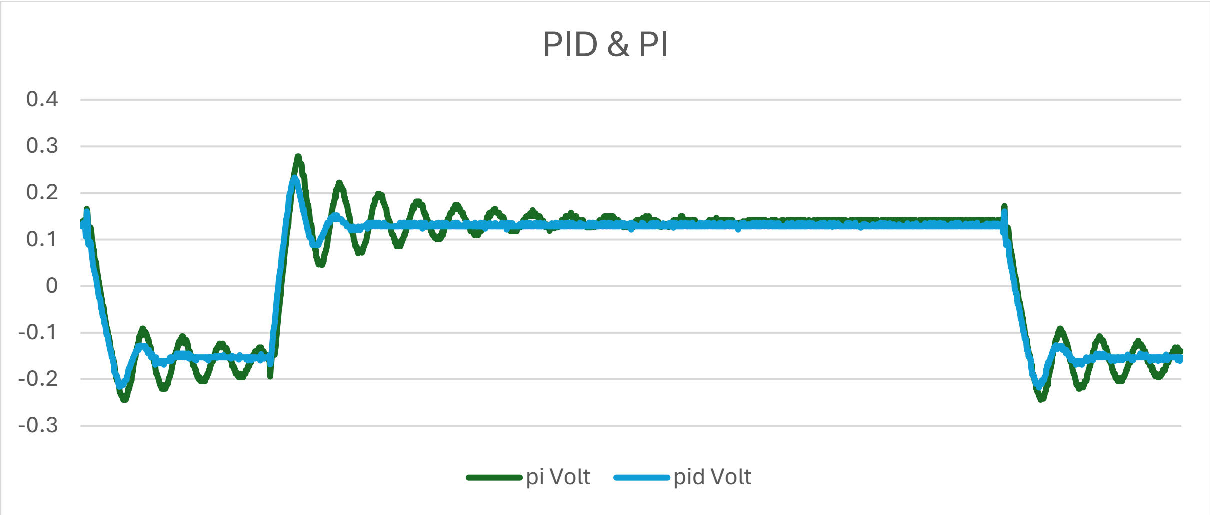

Figure 4.10 PID & PI Comparison

SOME LIMITATIONS :

KEY Takeaways

• Frequency limitations: In the final PID controller circuit, it was noted that the circuit's frequency response ranged from as low as 5 Hz to as high as 20 kHz. At lower frequencies, a peculiar observation was made: when the signal dropped below a certain frequency threshold, the circuit exhibited behaviour akin to a Proportional controller. This investigation aimed to assess the circuit's performance close to DC (0 Hz). Figure 4.12 illustrates that while the output matches the input at DC, only its amplitude can be controlled. This phenomenon suggests that the derivative and integral circuits do not engage in this response due to their relatively faster response times, likely attributed to their higher capacitance.

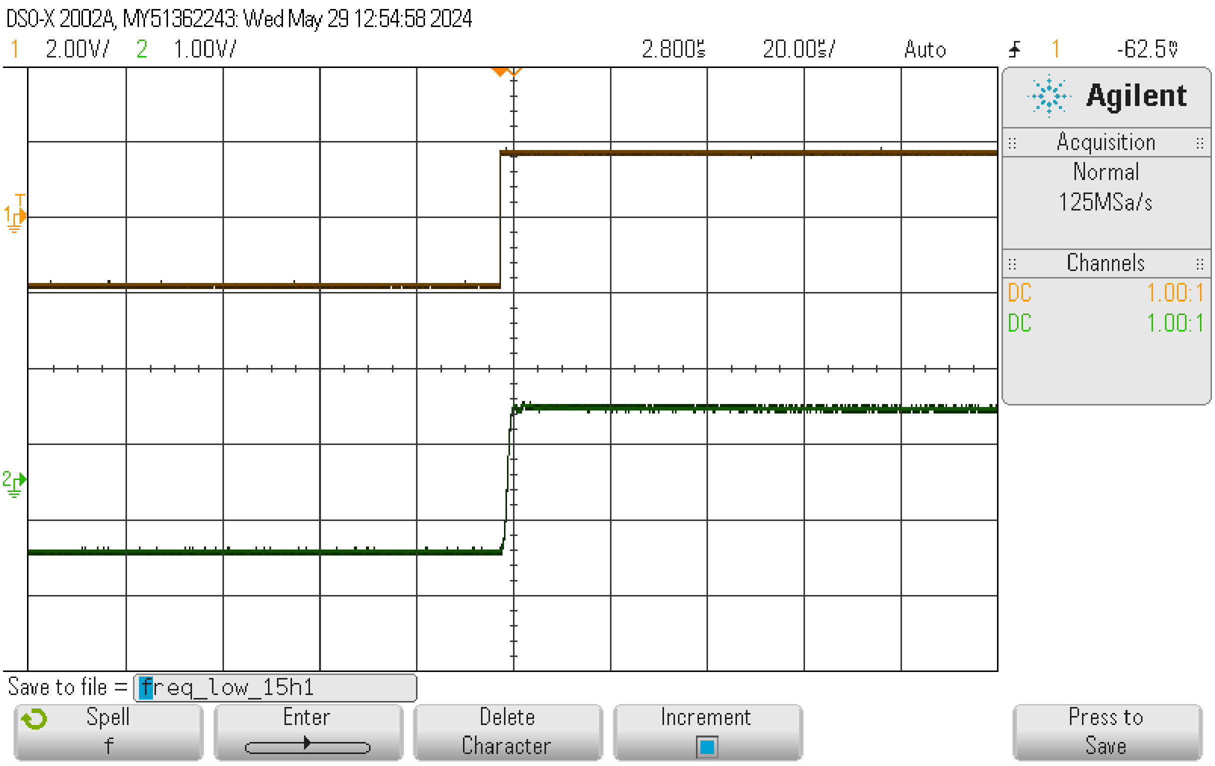

Figure 4.11 Low Frequency PID result

• Triangular & Sinusoidal: The frequency limitation threshold appears higher for triangular and sinusoidal signals. These signals exhibit the behavior mentioned earlier until approximately 300 Hz. Beyond this frequency, the effects of integral and derivative actions begin to manifest. For reference, a triangular wave is included in Figure 4.13 to illustrate this phenomenon.

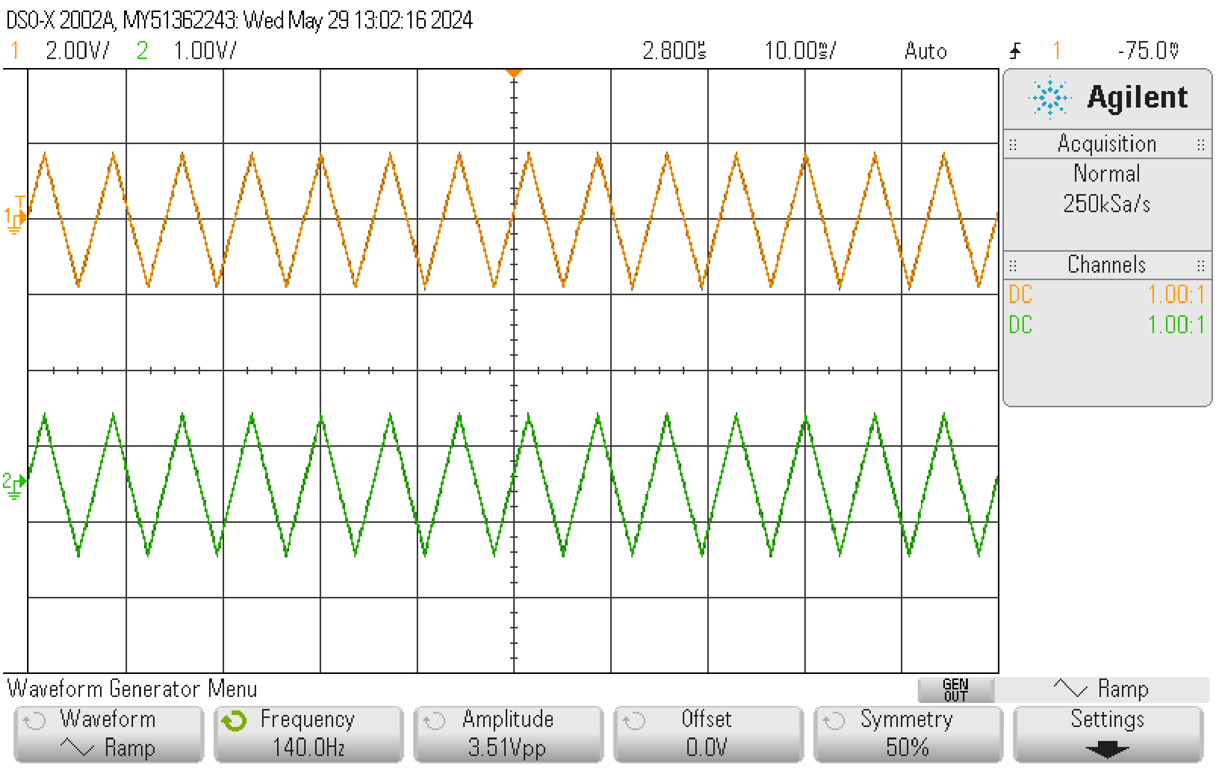

Figure 04.12 Triangular wave Output

• Overall, the PID results show promise for practical application. However, some modifications may be necessary to accommodate the specific needs of the specified application.

5.0 – CONCLUSION

In conclusion, the PID controller operates as intended, with modifications made to accommodate changes resulting from the transition from conventional integral and derivative circuits to passive circuits. These modifications effectively addressed the vacuum created by the zero gain in the integral and derivative stages.

For future iterations of the design, improving the frequency range can be achieved by incorporating high-order integral and derivative circuits. Additionally, the use of capacitors and inductors can enhance the response of each stage. While this may introduce challenges in troubleshooting, it lays a solid foundation for potential commercial applications.

However, since no load implementation was conducted for the output, commercial use is not recommended. Nonetheless, the design provides valuable insights into the theoretical behaviour of a PID controller and areas for improvement. It is essential to thoroughly test the design with different loads before considering it for commercial use.

REFERENCES

[1] K. J. Åström and R. M. Murray, *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton, NJ: Princeton Univ. Press, 2008.

[2] K. J. Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*. Research Triangle Park, NC: Instrument Society of America, 1995.

[3] Texas Instruments. (2020, November). TL07xx Low-Noise FET-Input. Retrieved from Texas Instruments: https://www.ti.com/lit/ds/symlink/tl074.pdf

[4] T. Hägglund and K. J. Åström, "Revisiting the Ziegler-Nichols step response method for PID control," *Journal of Process Control*, vol. 14, no. 6, pp. 635-650, 2004.

[5] K. Ogata, *Modern Control Engineering*, 5th ed., Upper Saddle River, NJ, USA: Prentice Hall, 2010.

[6] W. L. Luyben, "Practical Distillation Control," *AIChE Journal*, vol. 48, no. 5, pp. 889-894, 2002.