HVAC Hardware Modeling Using Programmable Automatic Controller

A Senior Project
presented to
the Faculty of the Electrical Engineering Department
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In Partial Fulfillment
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Bachelor of Science

by

Panthil Patel, June 2022
Lumanti Tuladhar, June 2022

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Abstract

The primary purpose of this project is to use the donated programmable automatic controllers (PAC) previously known as programmable logic controller (PLC) from Schneider Electric to develop experiments for a future lab class at Cal Poly. Our goal as the first group working on this project is to develop an experiment where the PLC can control the HVAC system based on temperature and humidity sensors and user inputs to maintain a desired consistent temperature. The PLC will be controlled using Unity Pro XLS/Control Expert software for simulations. The overall purpose of the experiments will be to demonstrate the potential of the PLC to minimize manual intervention while operating electrical devices. The end result of the project was that we successfully emulated an HVAC system utilizing DC Brushless Motor computer fans and the PLC. Much of the project also involved learning how to use the Unity Pro XLS/Control Expert software, designing a Functional Block Diagram in Control Expert based on the logic we want the PLC to act upon, designing the hardware setup with the drivers and temperature sensors, constructing the system, and ultimately implementing the PLC with the HVAC.

Chapter 1: Introduction

As industries continue to expand, automation is becoming ever more prevalent. "Commercial building and industrial facility rely on the automation of their mechanical and electrical systems. This trend only increases, especially as larger, smarter, more complex systems and buildings are constantly under construction" [7]. Control systems for such innovative and complex organizations need advanced logic controllers rather than traditional relays. With solid-state electronics, Programmable Logic Controllers (PLCs) have come into the control system industry.

PLCs have been around since 1968; however, it was only in the early 2000s when the Modicon Quantum Programmable Automation Controllers (PACs) was released that PLCs finally gained embedded web server capabilities. This new generation of PLCs paved the way for more robust implementations commercially and industrially with PLCs controlling electrical operations in large compounds through the internet [1].

PLCs are a small computer used commercially and industrially to minimize manual intervention while operating electrical devices. Before PLCs, the operating system control was carried out via relays. Each relay is monitored based on dedicated inputs and outputs; the PLC system has inputs and outputs hardwired into it. The manipulation of physical wiring results in each change in control system operation. PLCs consist of three main components: information, work, and CPU. The essential process of a PLC is to perform a pre-programmed output, depending on the input signal, by following a set of rules. The PLC completes its essential operation under stages such as Input scan (detect the state of the inputs), Program scan (Check current status), Execute program logic (Implementation of what the rules state), Updates Output (Updates the output to new operation settings) & Housekeeping (Self-diagnostics, communication, and reporting).
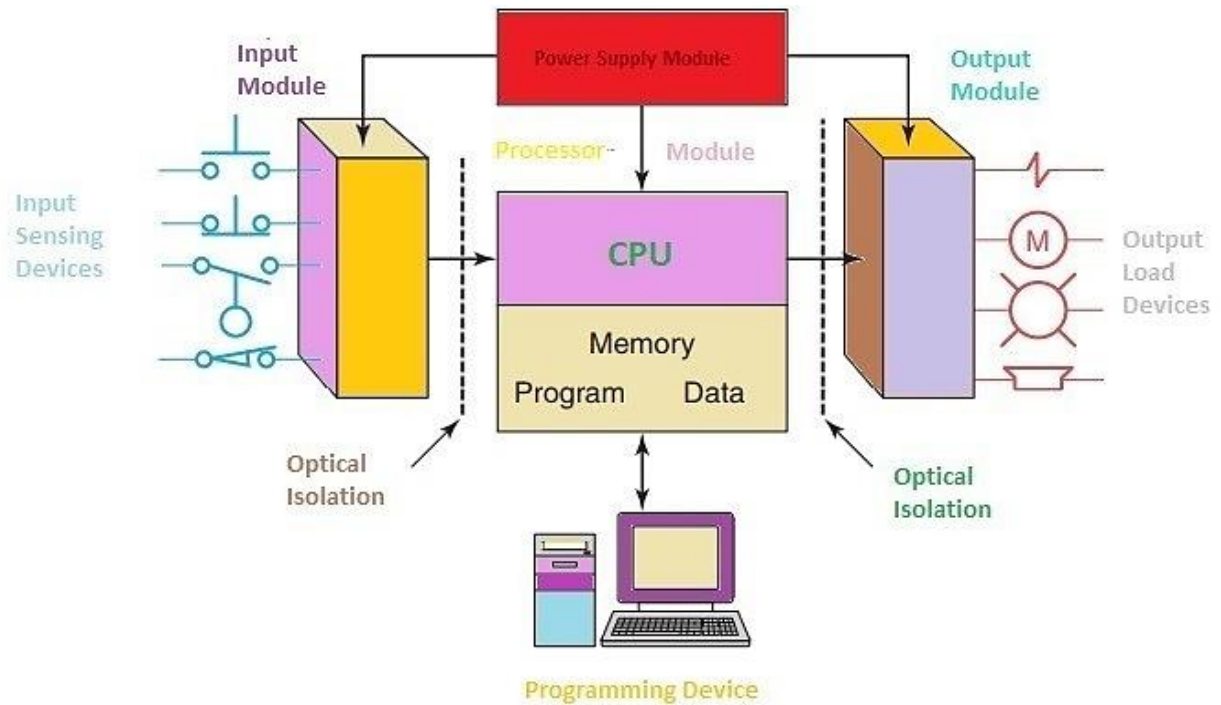
Figure 1-1 : Block diagram of the Programmable Logic Controller in integrated development systems [2]

Most PLCs can be controlled using both digital and analog values and can accept both voltage and current inputs. There are several acceptable I/O ranges which allow PLCs to be very flexible in their implementation as they can be added or removed from a system with little change to the pre-existing architecture.

Out of many commercial applications of PLC, controlling HVAC systems is one of the important sectors where we can benefit from automated ventilation systems in commercial buildings. HVAC is a vital component in every residential and commercial building that ensures air filtration, ventilation, and stable indoor temperature based on the user's direction. The HVAC associated with PLC can control desired indoor temperature via ethernet connection to any electronic device.

Chapter 2: Background

In today's world, everything we own as a whole or part of it has involved automation in some way during the manufacturing process. Automation is everywhere and has taken a pivotal role in today's industrial age making many companies dependent on PLCs and PLC-trained personnel [4]. PLC is the brain behind the operation or controls the timing, temperature, level, speed, etc. Even though industry standards demand electrical engineers to know PLC, the Cal Poly Electrical Engineering (EE) department does not offer any PLC-related courses designed especially for electrical engineers. Several classes cover some automation skills such as microcontroller and microprocessor, but regarding industrial automation for large-scale production, these trim level controllers transpire as impractical and inefficient. The growing manufacturing automation demands advanced and powerful industrial digital computers such as PLC [1]. Although a basic microcontroller and PLC is a computer with automation capabilities, it requires many I/O choices when designed to work with industrial sensors. The basic microcontroller will need external I/O pins, which turn into complicated and ineffective regulators. Instead, PLCs have inbuilt ports for I/O pins that offer wide versatility for commercial automation [5].

Currently, there is a plan to offer a new course based on automation design for EE students to address this concern. The course will consist of lab experiments with hardware implementation of Modicon M580 and simulation via Unity Pro XLS software [4]. The course has been listed as EE435 in the current Cal Poly's catalog. The outcomes of the newly added course aim to prepare EE graduates to broaden their skills in PLC-related fields. As the demand for control engineers increases, the skillset of having PLC operate would create an electrical engineer to compete well in job markets.

We are basing our goals around and expanding upon two prior works. The first is a senior project at Cal Poly SLO from Spring 2019, a direct prequel to our project [4]. The goal of their project was to develop PLC lab experiments for a future lab course at Cal Poly. Our project directly relates to this, as we attempt to pick up where they left off while making a few adjustments. The members of this project were able to set up the PLC benches and install the software necessary to interface with the PLC. The second project we are drawing inspiration from

is another senior project at Cal Poly SLO, from Spring 2020 [3]. This project aims to use the PLC benches in building 20 room 150 from the Spring 2019 project to interface an HVAC system, emulated through computer fans, with the Modicon M580 PLC. Unfortunately, due to the COVID-19 pandemic, this group had to halt the hardware implementation aspect of their project and could not effectively integrate the PLCs with the computer fans. Our goal is to complete the work of the Spring 2019 project by designing the remaining experiments for the course and testing all the hardware in a lab setting.

The objective of our project involving the Modicon M580 PLC is to explore its capabilities and develop lab experiments that showcase its primary functions and utilization in the industry. Currently, we have set a goal of thoroughly testing and planning two of the experiments to be used in the future lab course. Ultimately, the end goal is for students who take the lab course to understand PLC specifications sheets and architecture and the utility of PLCs in communications relays. Also, it focuses on understanding the importance of the Modicon M580 model in developing more robust cybersecurity systems and demonstrates PLC project creation, troubleshooting, and interfacing.

Chapter 3: Design Requirements

The design exemplifies the replication of commercial HVAC systems into a simple laboratory experimental form illustrated by using Modicon M580 to control the Panaflo FBA08T12L Fan based on the temperature-driven thermistor, and pre-scheduled program in the PLC. Figure 3-1 demonstrates the level 0 block diagram for the aimed HVAC system. Input modules consisting of Manual Control, Power supply, and Temperature sensor. The Manual control specifies the Programming with International Electrotechnical Commission(IEC)'s standard language (Ladder Diagram, Instruction List, Function Block Diagram, Structured Text, and Sequential Function Chart) and Human Machine Interface (HMI). The negative temperature coefficient (NTC) thermistor is used to provide the input temperature status. The power supply of 120 V AC rms, 60 Hz is supplied via a standard room outlet. The thermistor monitors the state of nearby temperature, which communicates with Modicon M580 to make a logical decision based on pre-programmed code in CPU to control the output temperature via speed control of fans and give status to the number of fans in motion simultaneously through HMI.
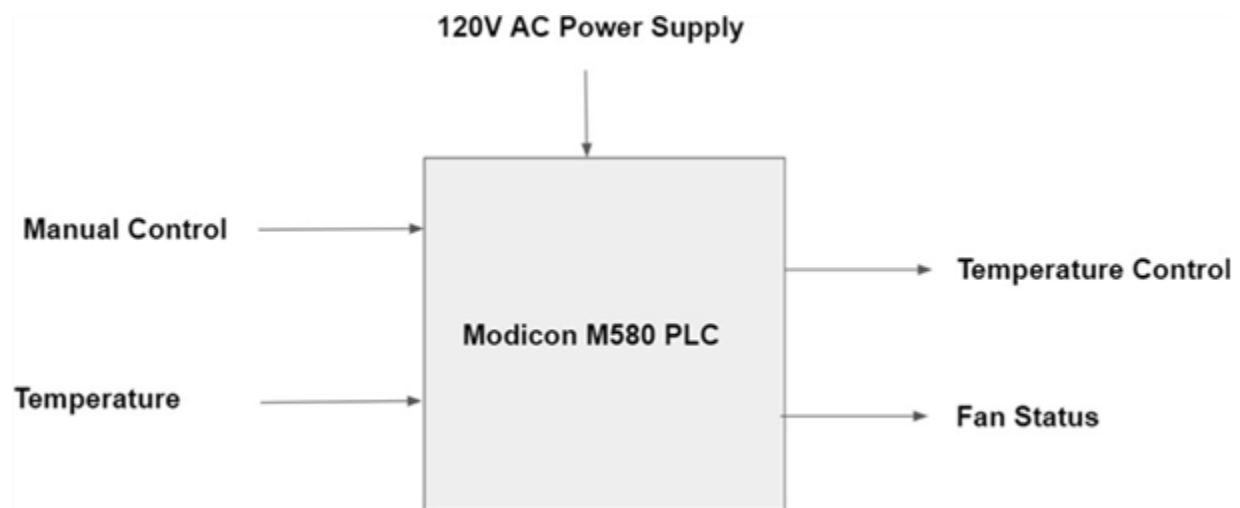

Figure 3-1: Level 0 Block Diagram
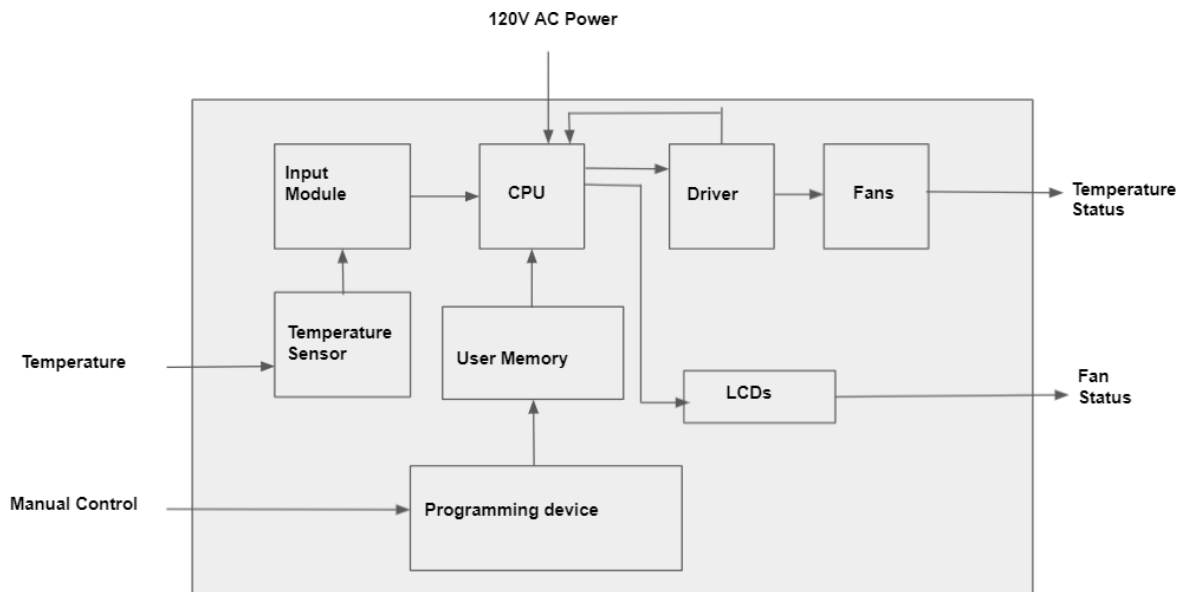
Figure 3-2 : Level 1 Block Diagram

Figure 3-2 demonstrates the Level 1 Block Diagram for this project. The temperature sensor detects the temperature variation of the surrounding environment as potential changes over resistive load (low-ohmage heat element); Agilent/HP E3649A provides an input voltage to the thermistor. The input module's output includes temperature input status to PLC through an NTC thermistor connected to its I/O pins. In the meantime, the instruction from the programming device is fetched into the CPU as the User memory Stores program information or the control logic. The CPU processes the pre-programmed code and outputs accordingly. The current from the driver, instruction on CPU, and temperature status operate the fan speed. The LCDs provide Human Machine Interface (HMI) showing Fan status after the signal from CPU has been processed. The temperature status (fan speed) concurrently syncs with fan status (HMI), illustrating the physical working observation of automation control using Modicon M580.

Table 3-1: Summary of Design Requirements

Requirement	Engineering Requirement
Agilent/HP E3640A Power supply	● Maximum power: 30 W ● Voltage range: 0 - 8V or 0 - 20V ● Current range: 1.5 - 3amps
Nichrome Wire	● Diameter: 24 Gauge / 0.51mm ● Length: 100 ft ● Resistance: 1.6089 ohms/ ft ● Melting temperature 1400 ℃
Temperature Sensor (NTC Thermistor)	● Resistance @ 25°C: 47kΩ ● Thermal dissipation constant: 1.5mW/°C ● Maximum power: 7.5mW
Circuit Breaker (BMXCPS3500)	Typical PSU input current: ● 1.104Arms @115Vrms ● 0.1As @115Vrms ● 0.15As @230Vrms ● Breaker rating: 1P, 1.6A, ~277V, 50/60Hz
Circuit Breaker (ABL8REM24950)	● Mounting support: 35 x 7.5 mm symmetrical DIN rail ● Max input current: 2.8A ● Breaker: 1P, 3A, ~277V, 50/60Hz
Touch Panel HMI (HMISTU855)	● Display resolution: 320 x 240 pixels QVGA ● Power consumption - 6.8 W ● Integrated connection USB 2.0 type A ● Supply voltage limits 20.4...28.8 V
Modicon M580 ePAC	● Primary voltage: 100-240V ● Local digital I/O processor capacity:1024 I/O ● Local analog I/O processor capacity: 256 I/O
AH5775 Driver	● Operating voltage: 2.5 - 18V ● "Applications: 5V/ 12V / 15V min. BLDC cooling fan ● Maximum continuous output current: 300mA
Panaflo FBA08T12L Fan	● Operating voltage: 7-13.8V ● Rated current: 79 mA ● Nominal speed: 2000 rpm
Unity Pro XLS	International Electrotechnical Commission's standard language: ● Ladder Diagram ● Instruction List ● Function Block Diagram

| | ● Structured Text, and |
| | ● Sequential Function Chart |

Chapter 4 : Design

  Chapter 4 will detail the theoretical design setup to interface the fans with the PLC utilizing a temperature sensor as well as the logic circuit that the PLC will use to determine what speed the fans should be set to in addition to how many fans will be turned on.
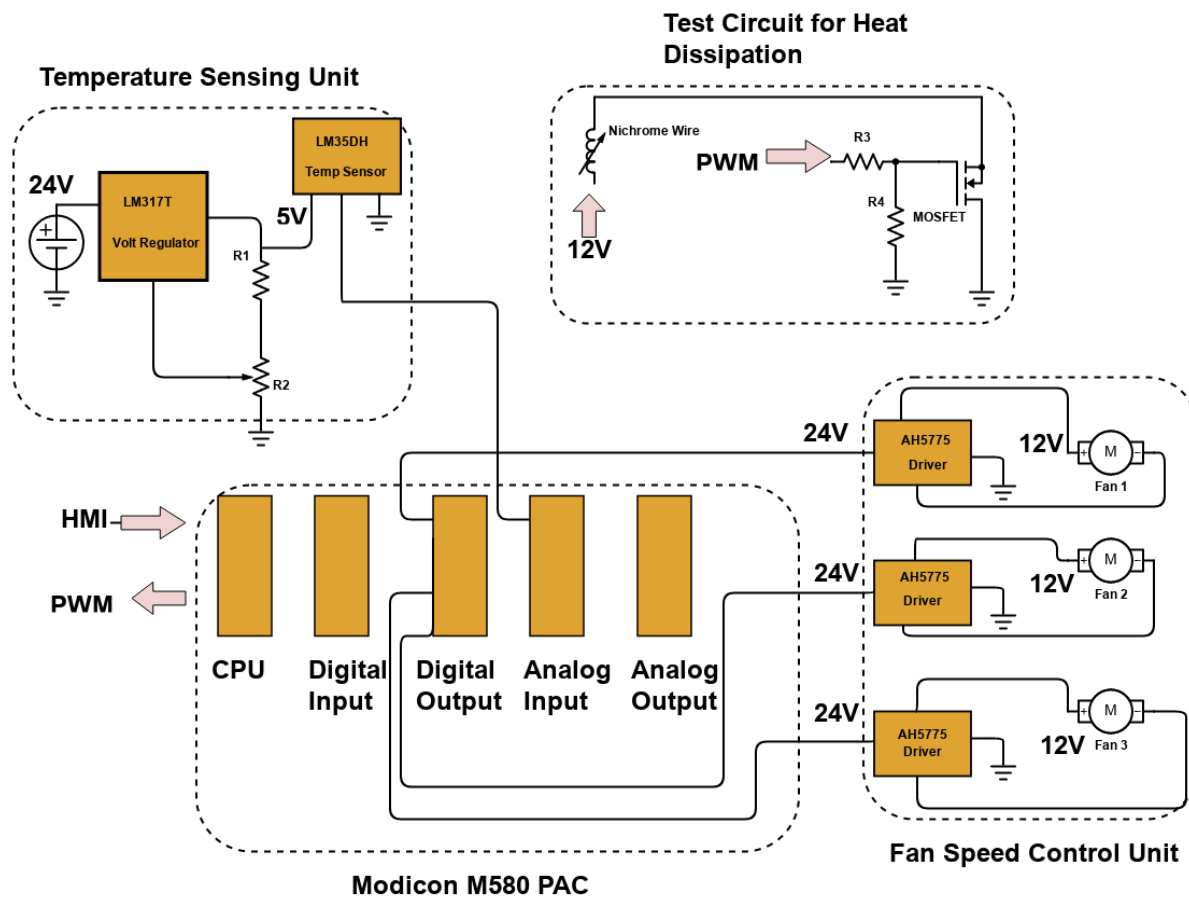
Figure 4-1 : Hardware Design of Fan Speed Control by Modicon M580 PAC

     The HVAC fan speed control system's design consists of four sections: the Temperature Sensing Unit, the Test circuit for Heat Dissipation, Modicon M580 PAC, and Fan Speed Control Unit. Each unit works in the synchronous mode, where Modicon M580 PAC controls constant communication between sections. Figures 4-1 provide a brief description of each section. A further explanation of each designed section is presented below.
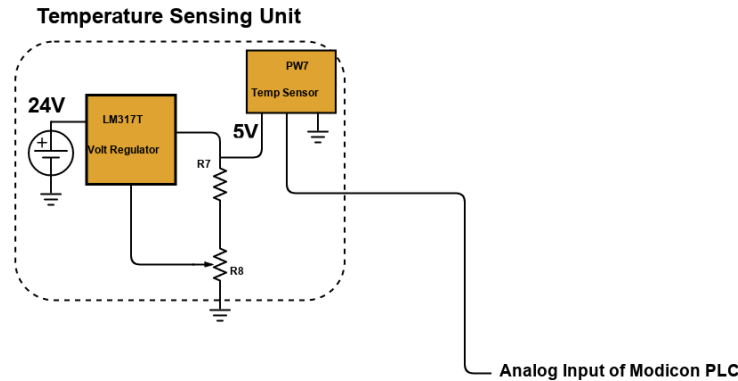
Figure 4-2 : Temperature Sensing Unit

The Temperature sensing unit is the initial step in the design of this system. It reads the nearby room temperature through the NTC resistor, fed into the Analog Input of PLC. The procedure involves the system's response to the variation of room temperature ranging from 20^oC to 110^oC. The heat dissipation unit is designed to create an ideal room temperature in the desired range. The NTC resistor has an operating voltage of 5V. In contrast, the input voltage available in the PLC unit is 24V, for which the circuit consisting of a voltage regulator is used to provide optimum voltage to the Temperature sensor. The circuit consists of an input voltage of 24V, which is fed into the LM317T voltage regulator, whose output is voltage divided between resistor R1 and R2. The LM317T is a variable voltage regulator and can output 5V as per the resistor varied in potentiometer R2.

Figure 4-3 : Test Circuit for Heat Dissipation

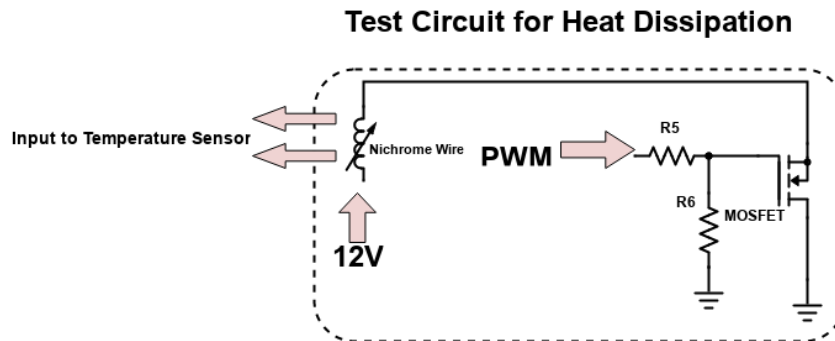Pulse-Width Modulation (PWM) provides absolute control over the heat-dissipating element. The dissipating element used in this project is a 24 AWG Nichrome Wire with a resistance of 1.6089 Ω/ft. In the controlled output voltage from PWM, the voltage across the Nichrome Wire varies resulting in the heat being dissipated. The placements of the test circuit are close to the temperature sensing range of the thermistor, allowing real-time temperature reading. The MOSFET provides the pathway current flow to the nichrome wire based on the duty cycle of the PWM. The duty cycle output from the digital input of the PAC determines the current passing through the nichrome wire, which regulates the amount of heat-dissipating from the nichrome wire. The MOSFET is attached to a heat sink to protect from excessive heat dissipation. The MOSFET used in this project is STFH18N60M2 N-channel Enhancement Type. Also, the MOSFET acts as a Digital to Analog Converter (DAC).
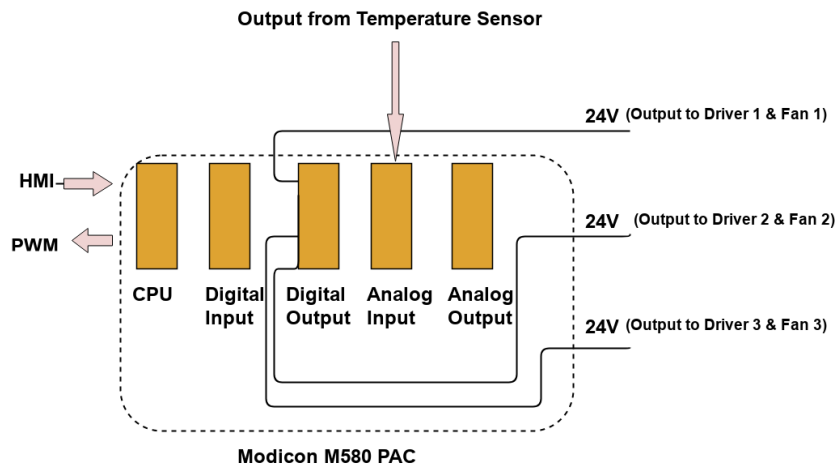
Figure 4-4 : Modicon M580 PAC

The Modicon M580 consists of ridge circuitry and doesn't require further design in its internal components whereas the wiring in digital I/Os and analog I/Os constitute parts of the design process. The exact inputs and outputs we will be using are detailed below.

- Digital Input : HMI
- Digital Output : 24 volts - 3 outputs to motor driver, PWM
- Analog Input : Temperature to voltage FROM Temperature sensor
- Analog Output : None
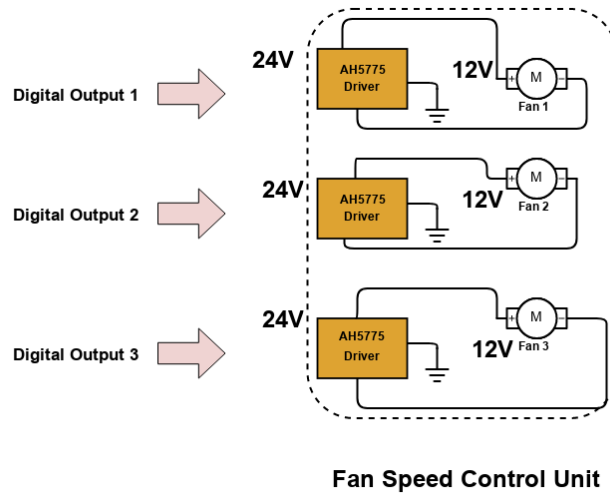
Figure 4-5 : Fan Speed Control Unit

The Fan Speed Control Unit is also called Driver Circuit which consists of three AH5775 fan drivers for three output 12V DC Brushless Motors. The inputs to the fan drivers are the 24V outputs from Digital output pins of Modicon M580. The fan speeds will be controlled by the logic circuits programmed into the Modicon M580.

Simulations:
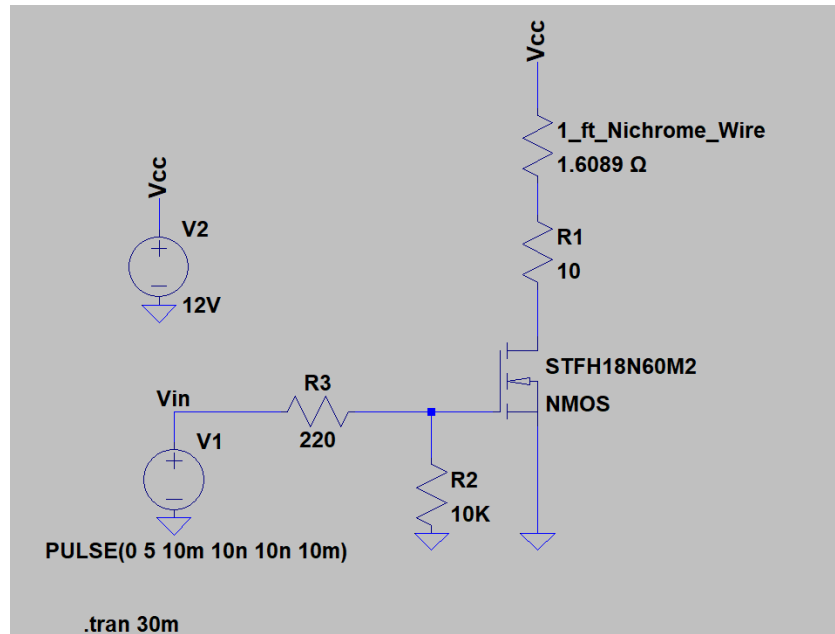
Figure 4-6 : Schematic showing the Test Circuit for Heat Dissipation

Figure 4-6 shows the LTspice schematics of the test circuit for heat dissipation. The design accounts for the operating conditions of the MOSFET based on the datasheet. The voltage divider with a pulse input voltage of 5V provides the operating gate voltage for MOSFET. The R1 resistor with a resistance of 1ft nichrome wire facilitates the MOSFET performance under its recommended temperature range.
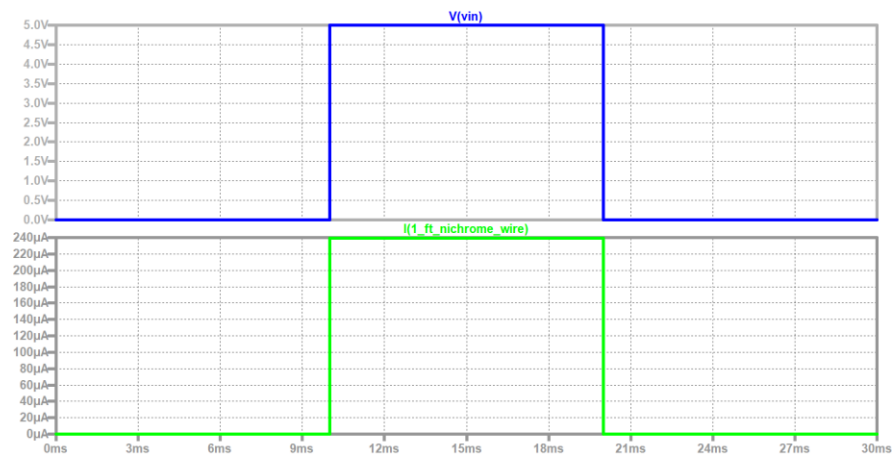
Figure 4-7 : Simulation showing the Input voltage of PWM at 50% duty cycle and current across Nichrome Wire

Figure 4-7 shows simulation results, including the input voltage of PWM and across the nichrome wire. Table 4-1 explains the necessary criteria for MOSFET operation.

R_{DS}	**0.280Ω**
Rthj-amb (Thermal resistance junction-ambient)	**62.5 °C/W**
Operating Temperature of MOSFET	**-55°C** to **150°C**
Current Across MOSFET	(I) = 12V / 11.6089Ω = **1.034 A**
Power Dissipation	(P) = $I^2 * R_{DS}$ = $(1.034A)^2$ * 0.280Ω = **300mW**
Temperature of MOSFET during operation	= Rthj-amb * P = 62.5 °C/W * 300mW = **18.70°C**

Table 4-1: Datasheet of STFH18N60M2 N-channel Enhancement Type

Figures 4-8 through 4-10 detail the variable, address setup, and logic circuit setup that will be used in standard mode to interface the fans with the PLC [1].
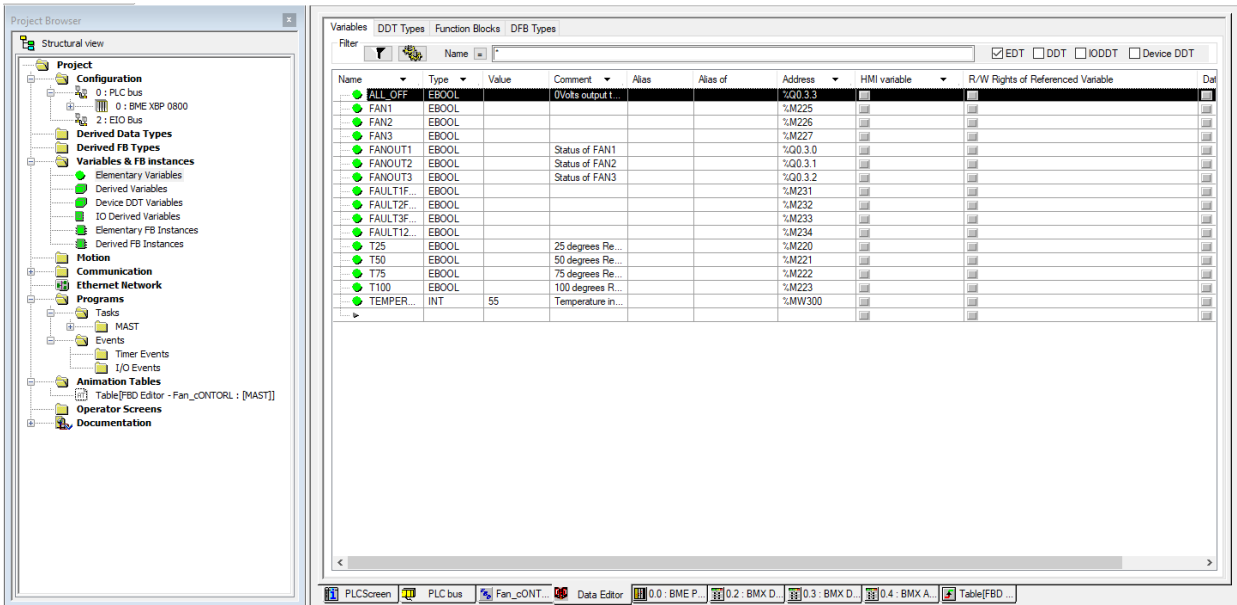
Figure 4-8 : Diagram showing Digital I/Os and Analog I/Os and their topological addresses [1]

The figure 4-8 shows that at the topological addressing of each module in the PLC rack. The addresses ranging from %Q0.3.0 to %Q0.3.3 represent the one bit digital outputs for three drivers. The bit 1 is 24V and bit 0 is 0V. The bit 1 is the operating voltage of functional DC brushless motors and bit 0 is the stopping voltage in case of fault detection in any of the fans. The analog input is the output of the temperature sensor which is inscribed at the address with word (16 bits)of %IW0.4.0.
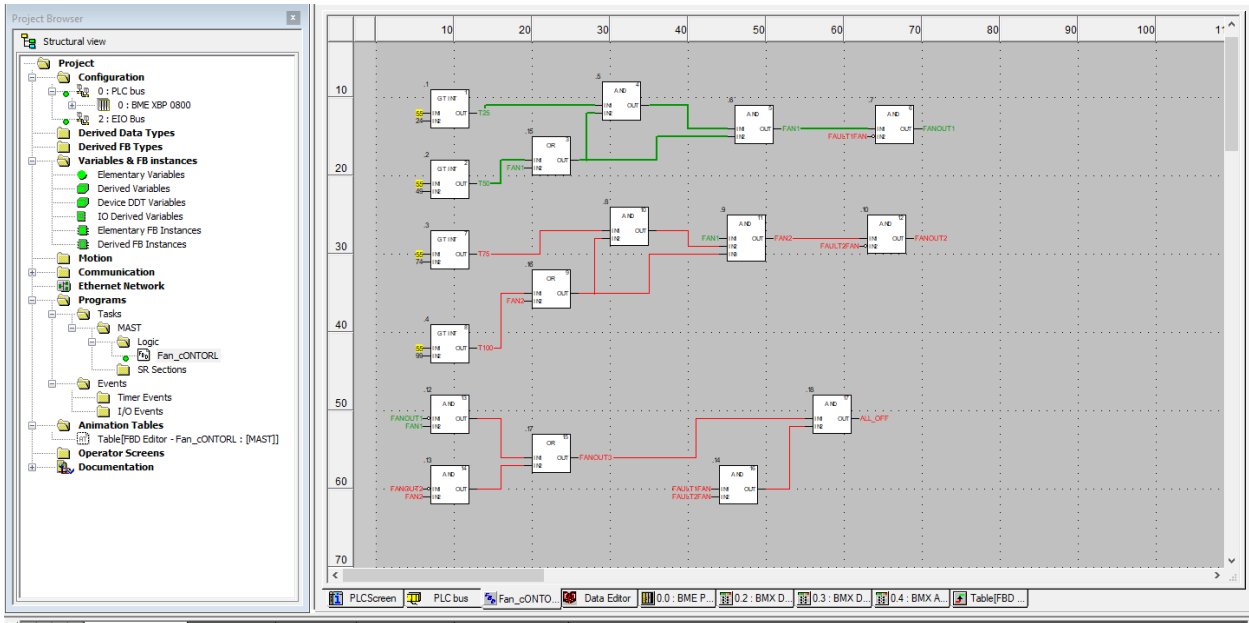
Figure 4-9 : Simulation of FBD with input temperature of 55^oC [1]

In the figure 4-9, the standard mode simulation at analog input of temperature 55^oC shows that Fan 1 is fully functional at high speed with supply voltage of 12V indicated by the bold red route in block diagram 1 and 2.
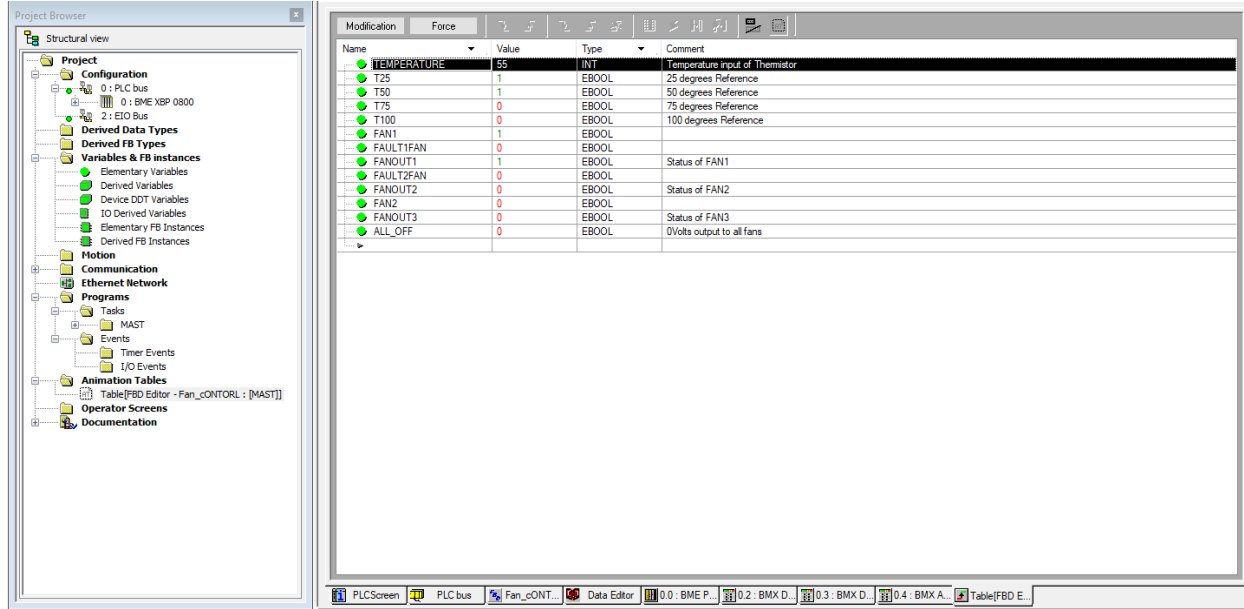
Figure 4-10 : The Animation Table showing real-time response based in simulation

Fan 1 rotates at low speed with supply voltage of 6V from the driver at the temperature below 50^oC and above 25^oC. Fan 2 is not being used, as the input temperature is below its operating temperature of 75^oC (low speed) and 100^oC (high speed). Fan 3 is a back-up fan and is operational only in the case of detection in faulty conditions of Fan 1 or Fan 2. Since, there is no fault detected in either of the Fans, Fan 3 is nonoperational.

Table 4-2: Bill of Materials

Item	Description	Supplier	Manufacturer	P/N	Quantity	Unit Cost ($)	Total Cost ($)
Micro USB Cable	PC-PLC Connection	Amazon	Amazon Basics	N/A	1	7.67	7.67
24 AWG 100 ft Nichrome	Used to simulate various temperatu	TEMCO Industrial	TEMCO Industrial	RW0407`	1	8.03	8.03

80 Resistance Wire	res						
MOSFET	Test circuit for heat dissipation and switch for PWM	Digikey	STMicro electronics	STFH18 N60M2	1	2.76	2.76
Voltage Regulator	Stabilize the voltage to ensure the fans don't switch between speeds or turn on and off constantly	Texas Instruments	Texas Instruments	LM117	1	18.83	18.83
Temperature Sensor	Detect External Temperatures	Texas Instruments	Texas Instruments	LM35	1	28.43	28.43
Fan Drivers	Reduce input voltage to 12V so fan can function	Digikey	Diodes Incorporated	AH5775	10	6.24	6.24
DC Brushless Motors	Computer fans simulating HVAC system	Cal Poly EE Department	Allegro Microsystems	A4915	3	N/A	N/A
Total							71.96

Table 4-3: Component Datasheets

MOSFET	Https://www.st.com/resource/en/datasheet/stfh18n60m2.pdf
Nichrome Wire	Https://temcoindustrial.com/24-awg-100-ft-nichrome-80-resistance-w
Voltage Regulator	lt://www.ti.com/lit/ds/symlink/lm117.pdf?HQS=dis-dk-null-digikeymc sf-pf-null- vwe&ts=1650987021844&ref_url=https%253A%252F%252Fwww.ti.c 52Fgeneral%252Fdocs%252Fsuppproductinfo.tsp%253FdistId%253D 526gotoUrl%253Dhttps%253A%252F%252Fwww.ti.com%252Flit%2 n%252Flm117
Temperature sensor	https://www.ti.com/lit/ds/symlink/lm35.pdf
Fan Drivers	https://www.diodes.com/assets/Datasheets/AH5775.pdf
DC Brushless Motors	https://datasheetspdf.com/pdf-file/613208/ETC/FBA08T12L/1

Chapter 5 : Hardware + Simulation Tests & Results

Chapter 5 will cover the individual hardware components that interface with the PLC in order to emulate the HVAC system, the simulation results/FBD on Control Expert, and the final assembly of the emulated HVAC system connected to the PLC.

5-1: Individual Hardware Components
- Temperature Sensing Unit/LM35 Chip
- Current Sensing Unit/ACS712 Chip
- PWM
- Fan Drivers
- DC Fans/Brushless Motor
- L7805 Transistor
- LM7805C Transistor
- 9V Battery

- 10Ω Resistor

5-2 : Procedures for Hardware Connection
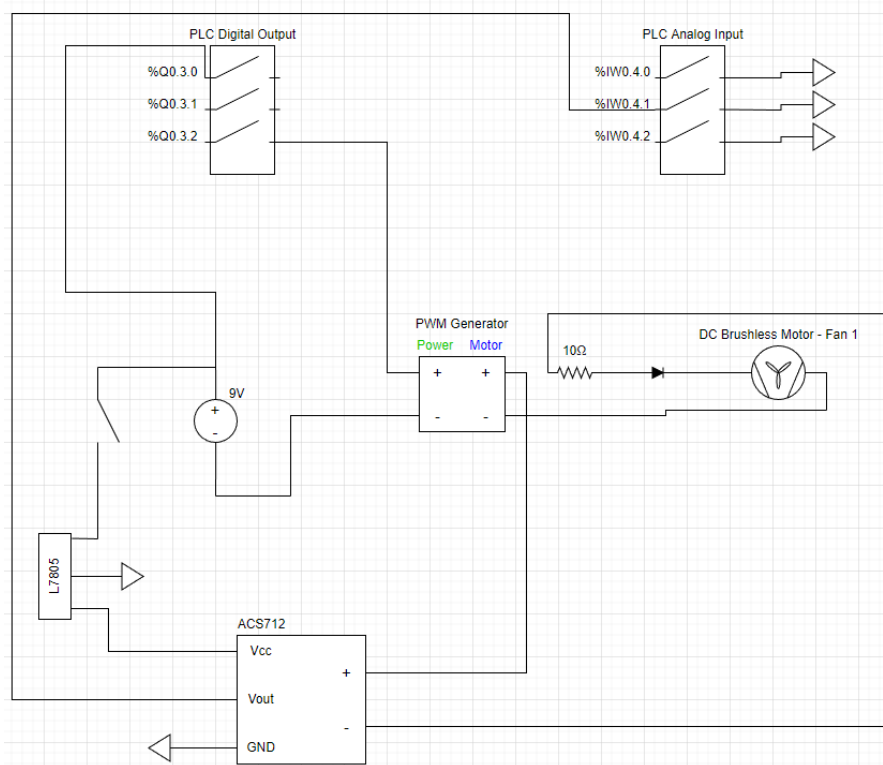## 5-2-1: Circuit connection of the Fan 1

Figure 5-1: Fan 1 Connection

1. Digital and Analog inputs and outputs of PLC act as a switch.
2. The connection is made from the positive terminal of the battery to the Q0 port in digital input, which in Control Expert software indicates the address by %Q0.3.0. The 'Q' refers to outputs in PLC, whereas 'I' specifies inputs. The connection from Com0 to the positive terminal of the power section of the PWM Generator circuit is built. When the PLC activates the Q0 as per the applied commands to the software, the relay connection is made between Q0 and Com0, indicating a closed circuit.
3. PWM Low Voltage Motor Speed Controller controls the voltage supply to a DCmotor by adjusting its Duty Cycle in the range of 0%-100%. The power section of the PWM controller is fed with output from the Q0 port of digital output. In contrast, the motor section of the controller is connected to a 12V Panaflo DC brushless motor followed by 10 Ohms resistor and LED connected in series to indicate the status of Fan 1.
4. The 5V hall-effect current sensor is connected between the PWM controller and DC fan, giving the real-time status of the current flowing through the circuit. The output of the hall-effect current sensor is fed into the analog input of the Modicon M580 PLC.

5. The switch between the 9V battery and current-sensor is a replica of the fault in the circuit controlling fan 1, mimicking the zero current flowing through circuit 1. The indication of zero current flowing through fan 1 activates the fault in fan 1 signal to the analog input (Ui1) of the plc with address of %IW0.4.1.
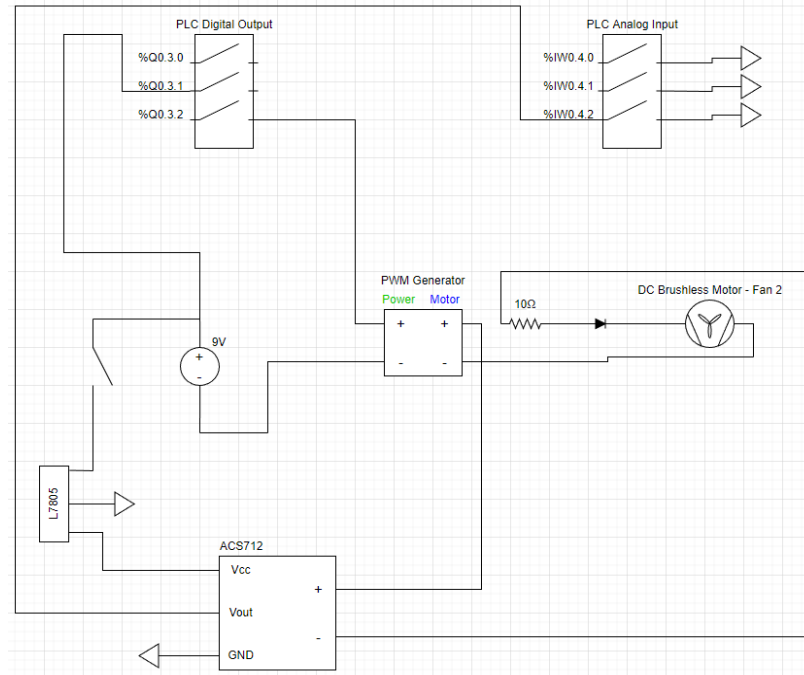
5-2-2: Circuit connection of the Fan 2

Figure 5-2: Fan 2 Connection

The hardware connection of Fan 2 follows the same way as Fan 1, whereas the port connection in digital output and analog output varies. The Digital output connection is made through the Q1 port and Com1, and port Ui2 in analog input links the output from the current sensor.

5-2-3: Circuit connection of the Fan 3

Figure 5-3: Fan 3 Connection
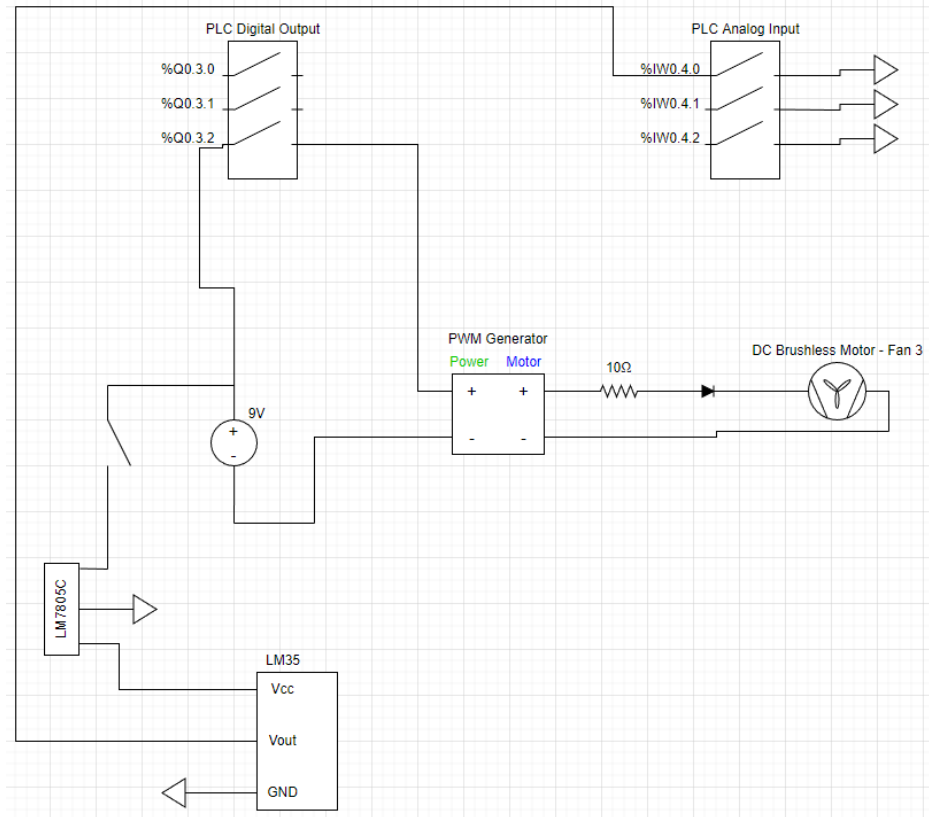
In the hardware connection of Fan 3, the LM35 temperature sensor replaces the 5V hall effect sensor used for Fan 1 and Fan 2. The digital output consists of port Q2 and Com2, whereas port Ui0 is a bridge between the analog input and work from the current sensor.

5-3: Result of Standard mode hardware simulation at varying temperature
5-3-1: At 25.4^0C, no fault in Fan 1 and Fan 2

Figure 5-4: Control Expert Simulation at $25.4^0 C$

Figure 5-4 showcases the logic ladder in control expert whenever the system detects a temperature of 25.4 degrees Celsius and none of the fans have been turned on yet, meaning a temperature exceeding the initial threshold value to turn on the first fan, 49 degrees Celsius has not been detected yet. This check can be seen in the logic at block 15 which is holding up blocks 6 & 7 from turning on fan 1. If fan 1 was already on and a temperature of 25.4 degrees Celsius had been detected, fan 1 would stay on as it is still greater than the requisite 24 degrees Celsius to keep the system running. The speed however will change based on the PWM implemented through hardware explained in Figure 5-1.
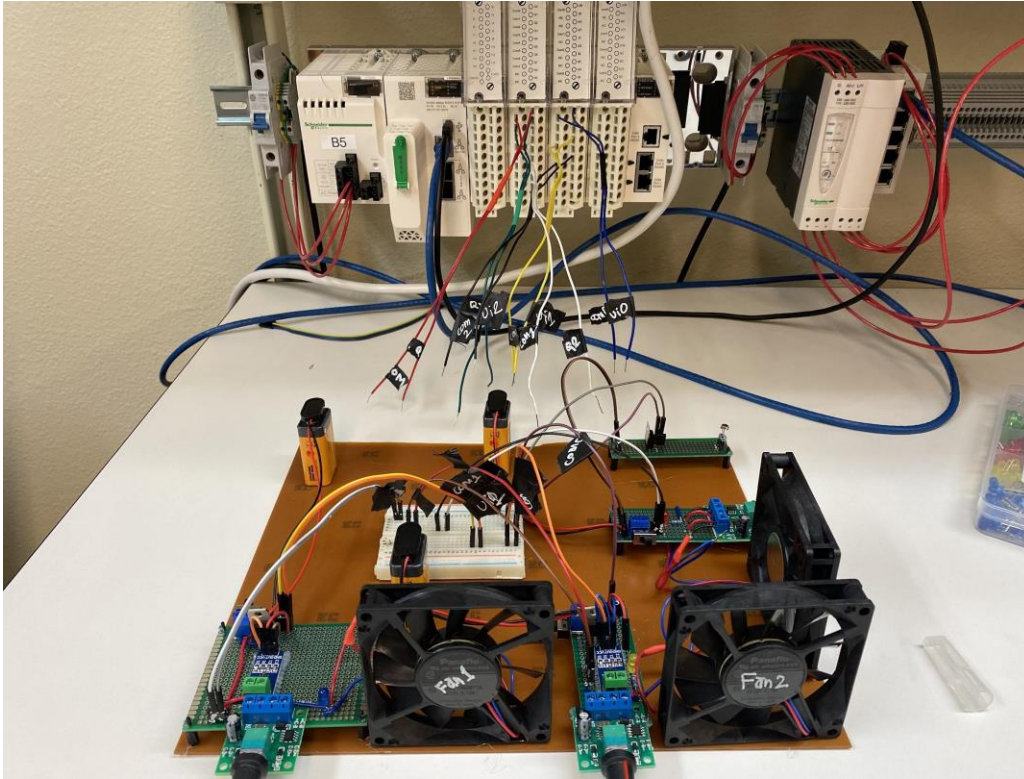
Figure 5-5: System Status at $\underline{\mathbf{25.4^0C}}$ before reaching initial threshold

Figure 5-5 showcases the system with none of the fans turned on while registering a temperature of 25.4 degrees Celsius. All of the fans are off because a temperature exceeding the initial threshold value of 49 degrees Celsius has not been detected yet.

5-3-2: At 107.4^0C,no fault in Fan 1 and Fan 2
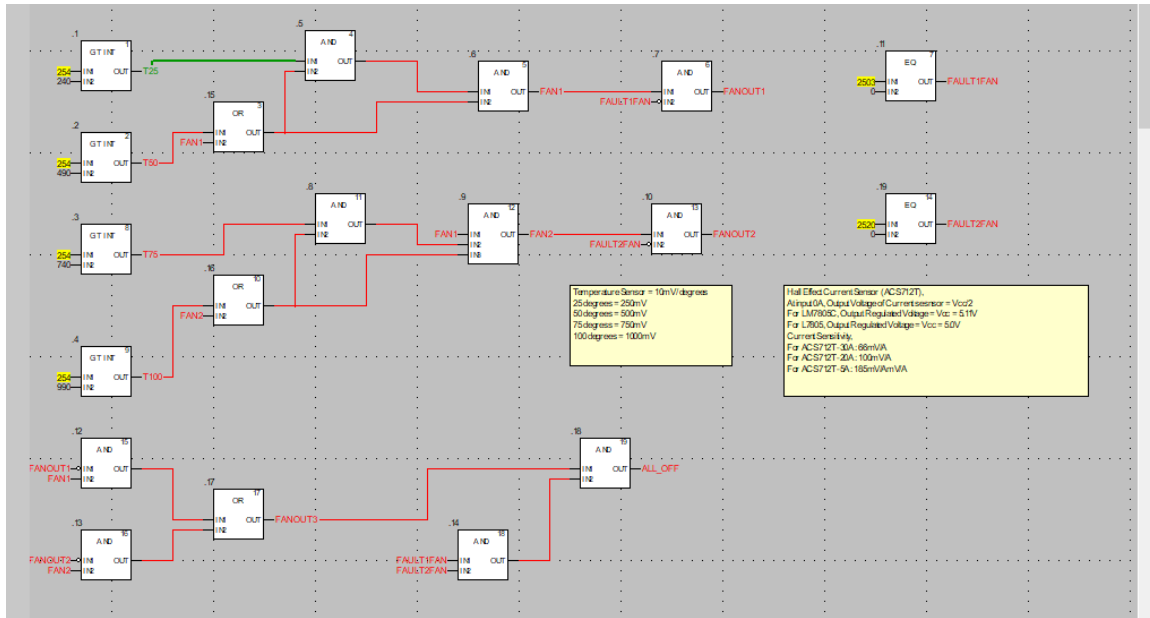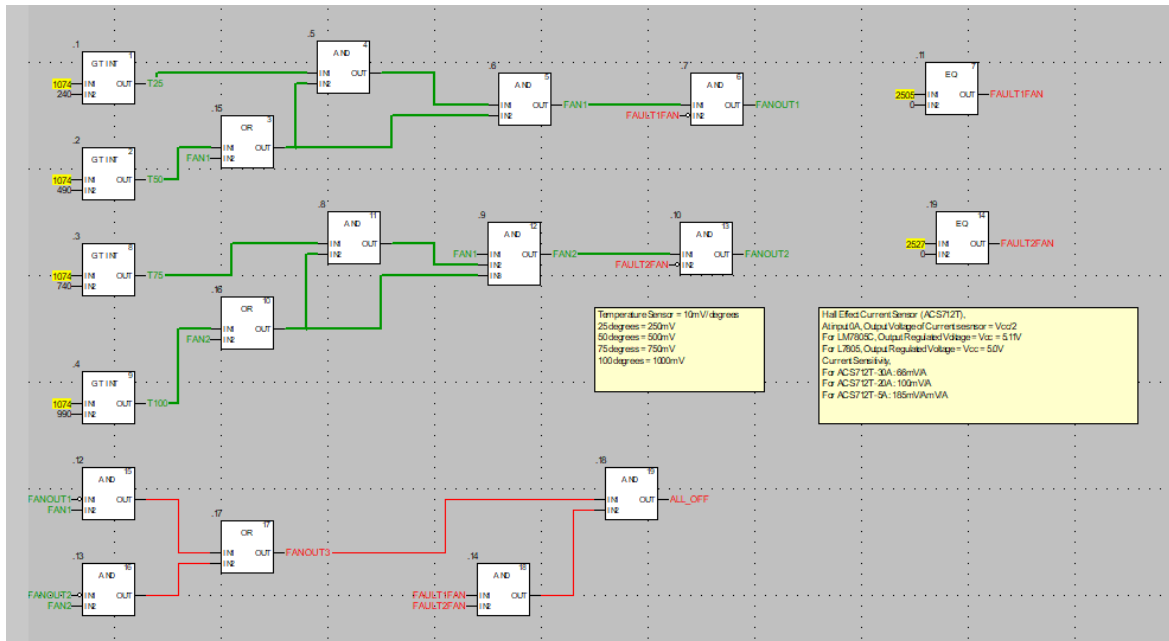

Figure 5-6: Control Expert Simulation at $\underline{107.4^0C}$

Figure 5-6 showcases the logic ladder in control expert whenever the system detects a temperature of 107.4 degrees Celsisus. In this case it does not matter whether Fans 1 or 2 were already on or not as the detected temperature exceeds the threshold value for fan 2, 99 degrees Celsius. At 107.4 degrees fans 1 and 2 should both turn on.

Figure 5-7: System Status at $\underline{\mathbf{107.4^0 C}}$

Figure 5-7 shows the LEDs next to fans 1 & 2 lit up, indicating that both fans are spinning when the detected temperature is 107.4 degrees Celsius. The speed of the fans are variable based on the adjusted duty cycle from the PWM.

5-3-3: At 121.4^0C, fault in Fan 2
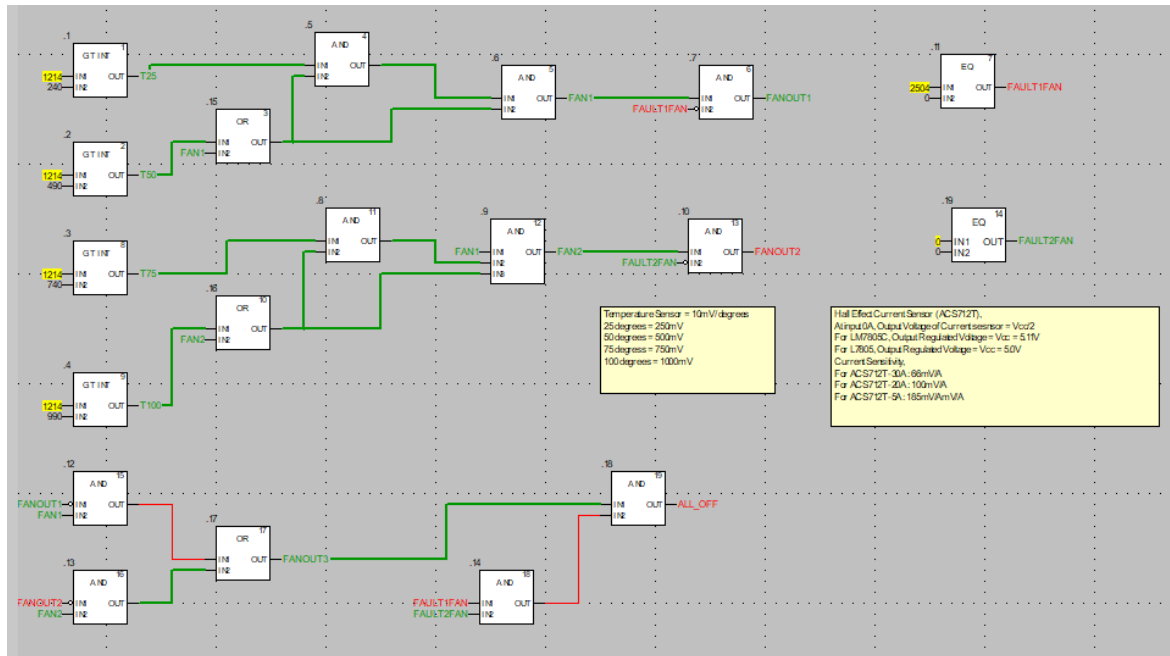
Figure 5-8: Control Expert Simulation at 121.4^0C

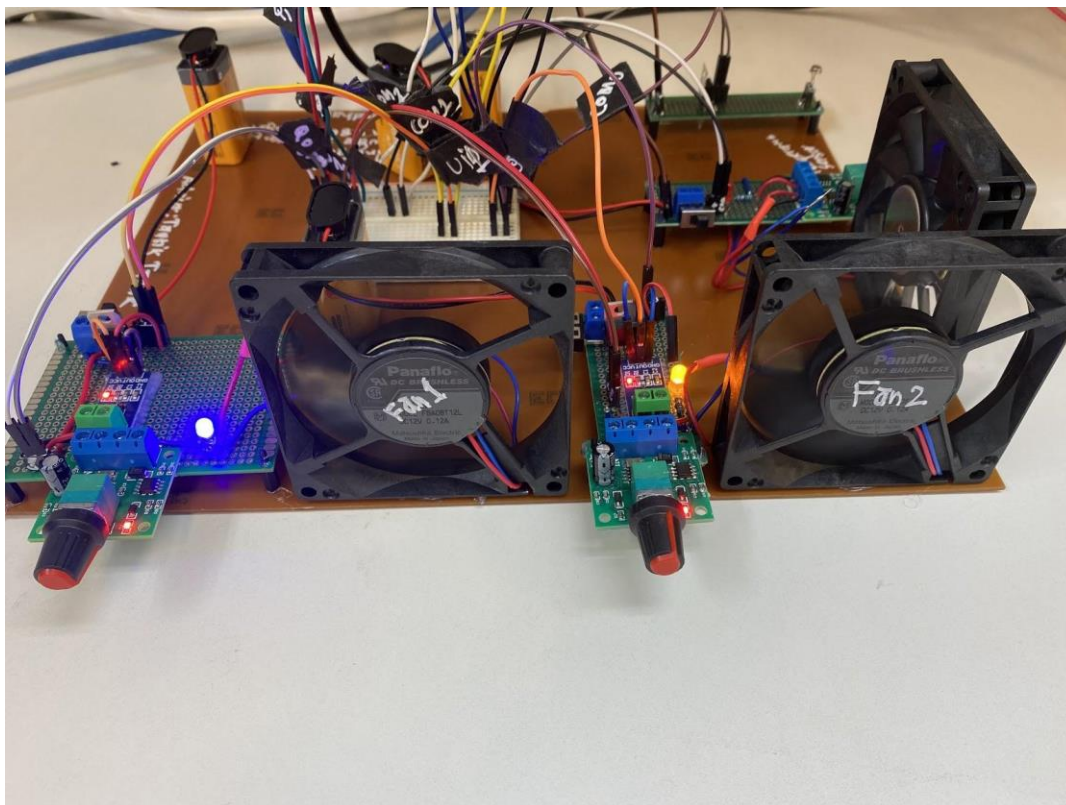Figure 5-8 showcases a scenario where fan 2 experiences a fault. Fan 3 exclusively exists in cases where either fans 1 or 2 experience faults. Control Expert uses toggles in conjunction with AND blocks to essentially create an XOR gate. Blocks 12 & 13 can effectively be treated as XOR gates that pass the signal when a fan should be turned based on the detected temperature but in reality the fans are not on. In this case, a temperature exceeding 99 degrees celsius has been detected, but fan 2 is experiencing a fault so fan 3 is turned on in order to compensate.
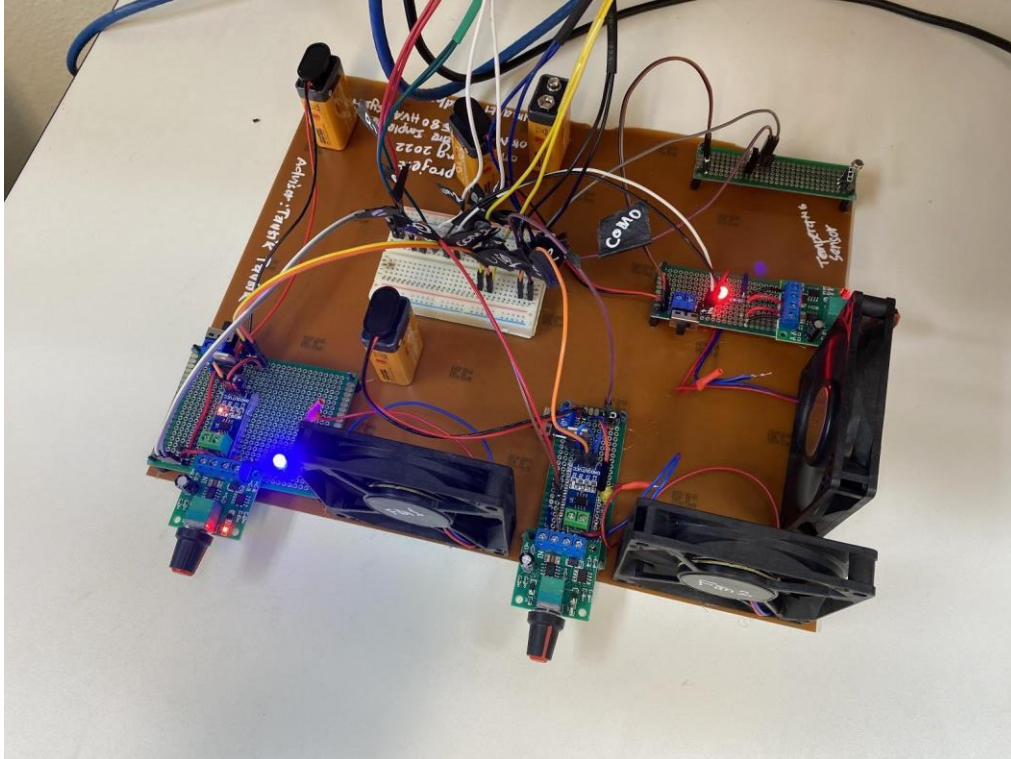
Figure 5-9: System Status at $\underline{\mathbf{121.4^0 C}}$

Figure 5-9 shows the system in an instance where fan 2 is experiencing a fault. As indicated by the LEDs fans 1 and 3 are on at a temperature of 121.4 degrees Celsius.

5-3-4: At $\mathbf{99.3^0 C}$, fault in Fan 1

Figure 5-10 showcases a scenario where fan 1 experiences a fault. The detected temperature is 99.3 degrees celsius so fans 1 and 2 should both be on as the detected value is greater than the upper threshold value of 99 degrees celsius. However, fan 1 is experiencing a fault so it will not turn on and fan 3 will turn on in its stead.
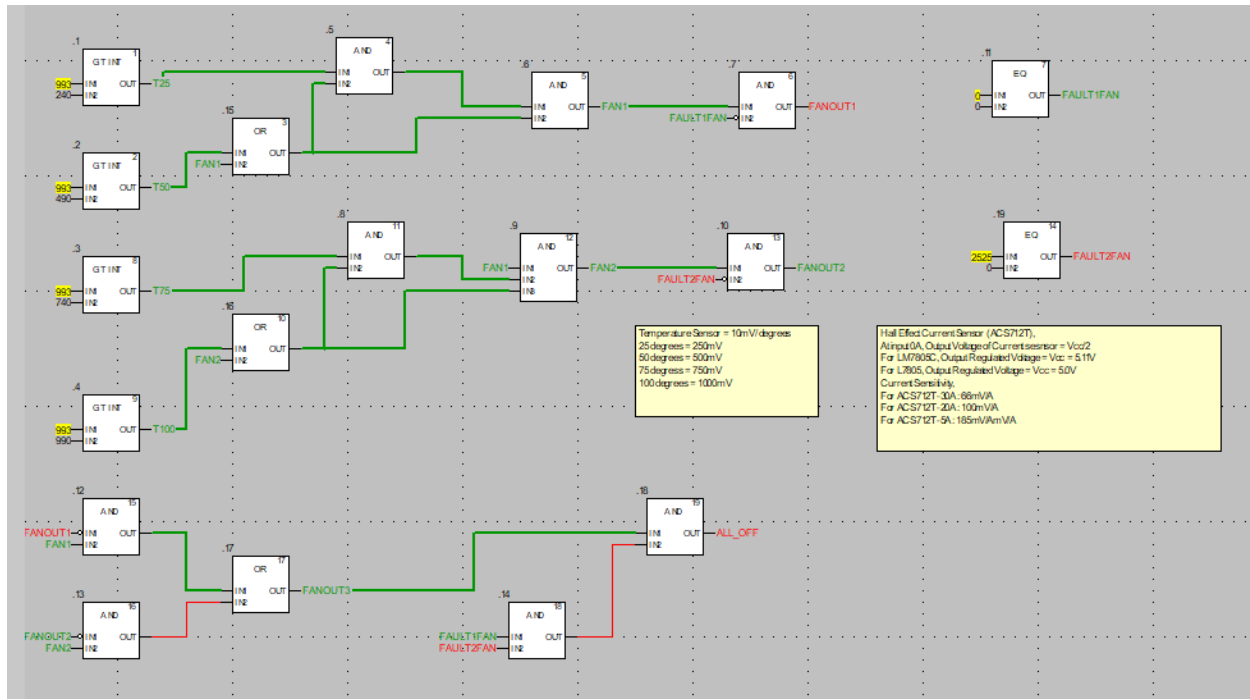
Figure 5-10: Control Expert Simulation at 99.3^0C
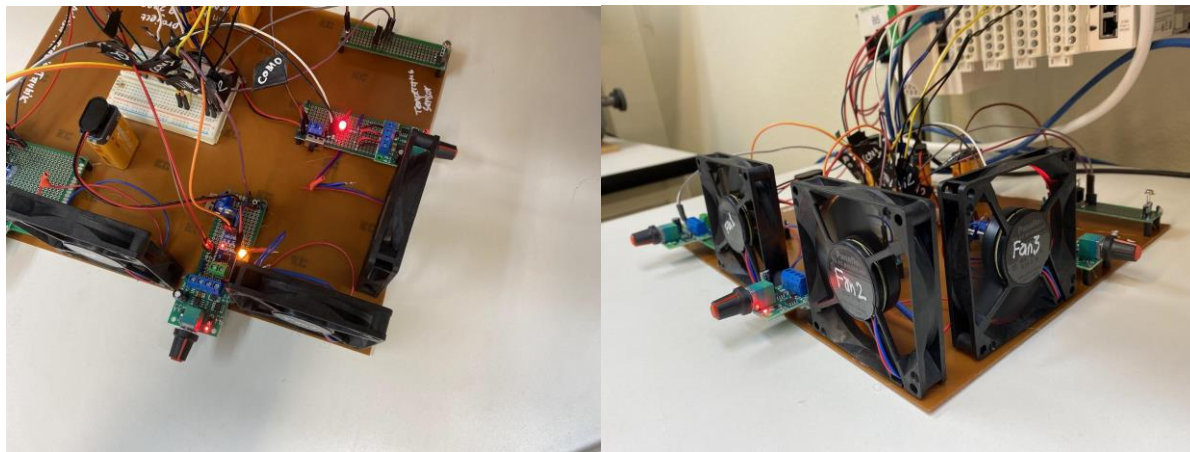
Figure 5-11: System Status at 99.3^0C

Figure 5-11 showcases when fan 1 is experiencing a fault and the detected temperature is above 99 degrees celsius. In this instance, fans 2 & 3 have turned on as indicated by the lit LEDs with fans spinning at a variable speed as determined by the PWM.
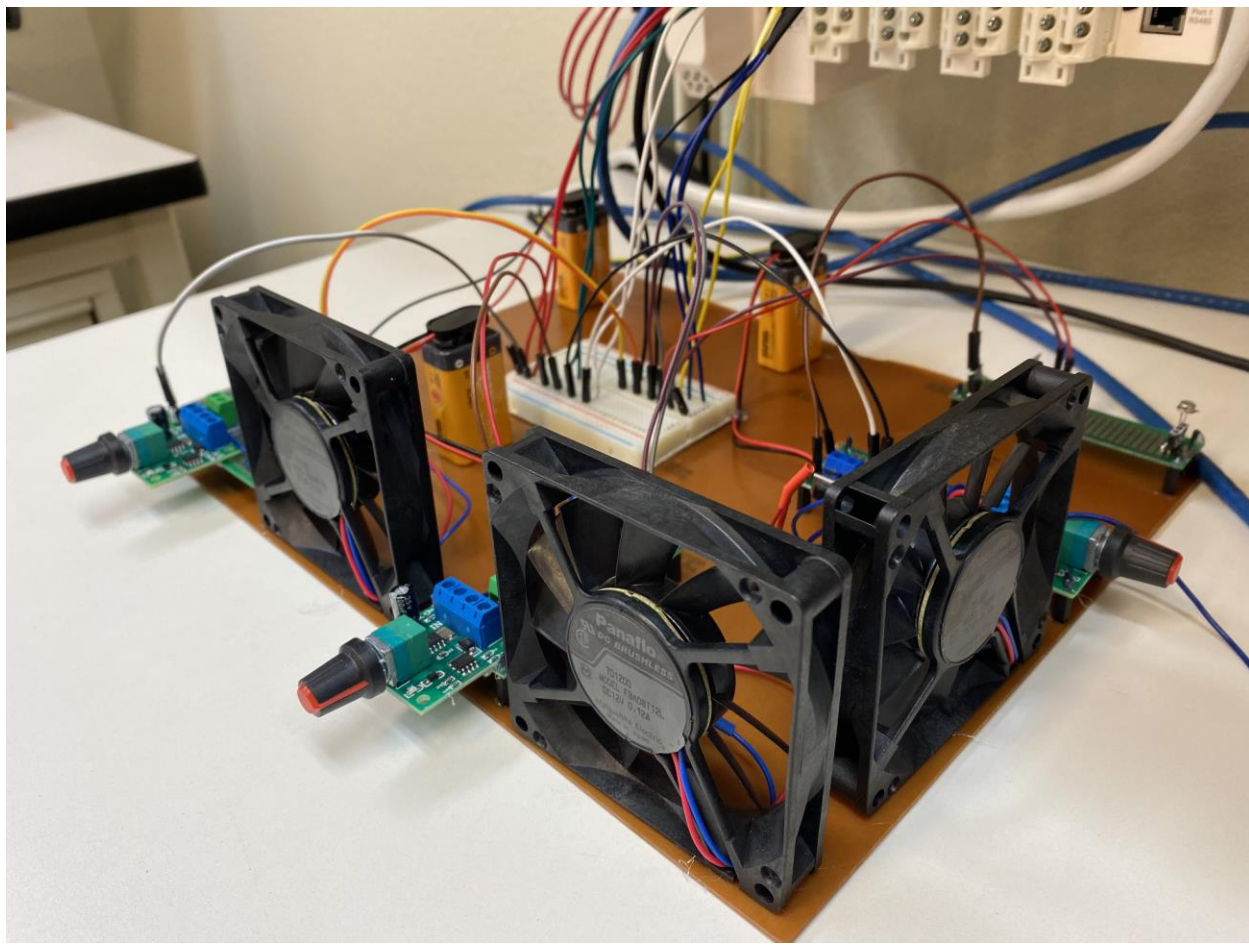
Figure 5-12: Full Hardware Assembly Angle 1

Figure 5-12 showcases the completely assembled system focusing on the front of all 3 fans.
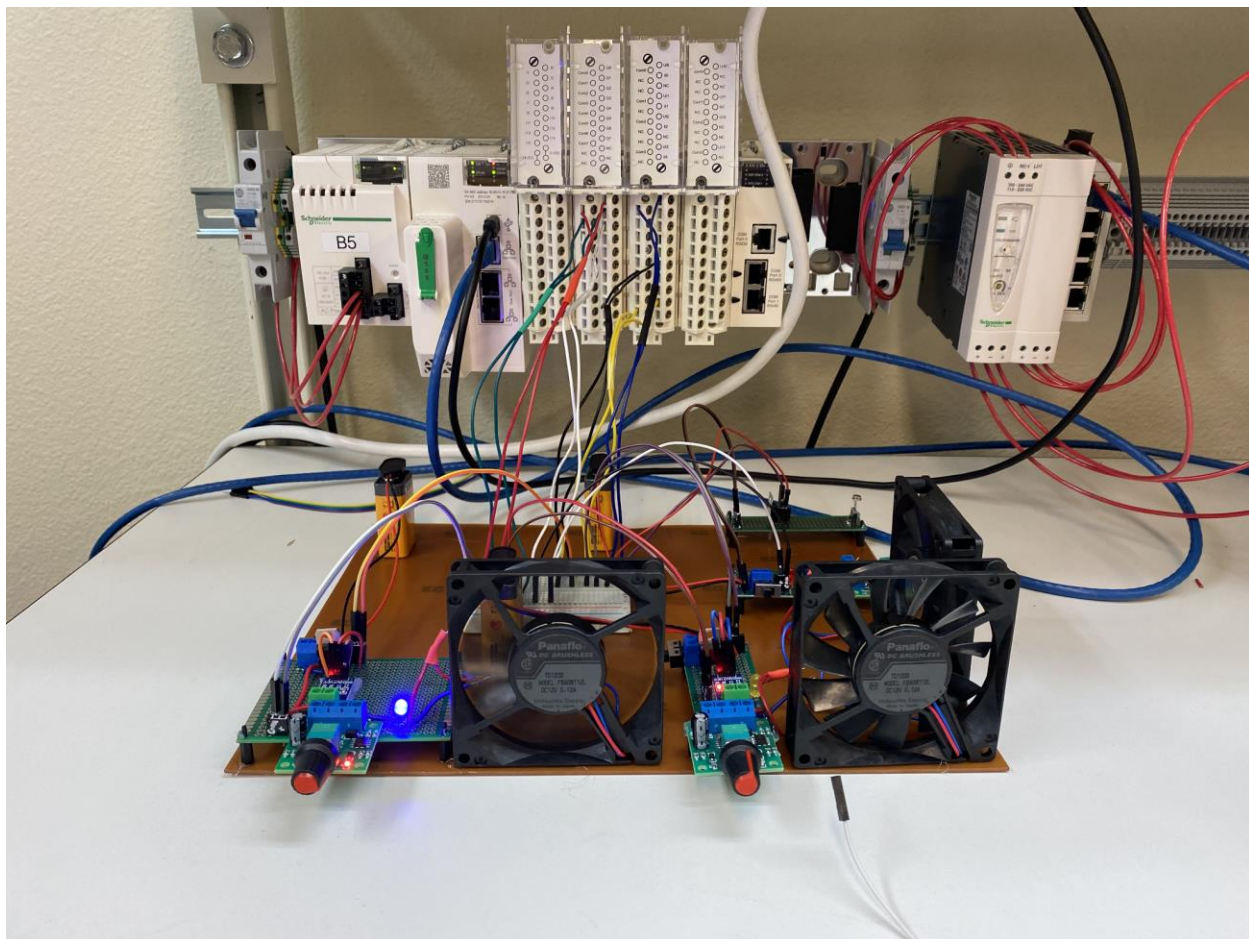
Figure 5-13: Full Hardware Assembly Angle 2

Figure 5-13 displays another angle of the completely assembled system with Fan 1 on.
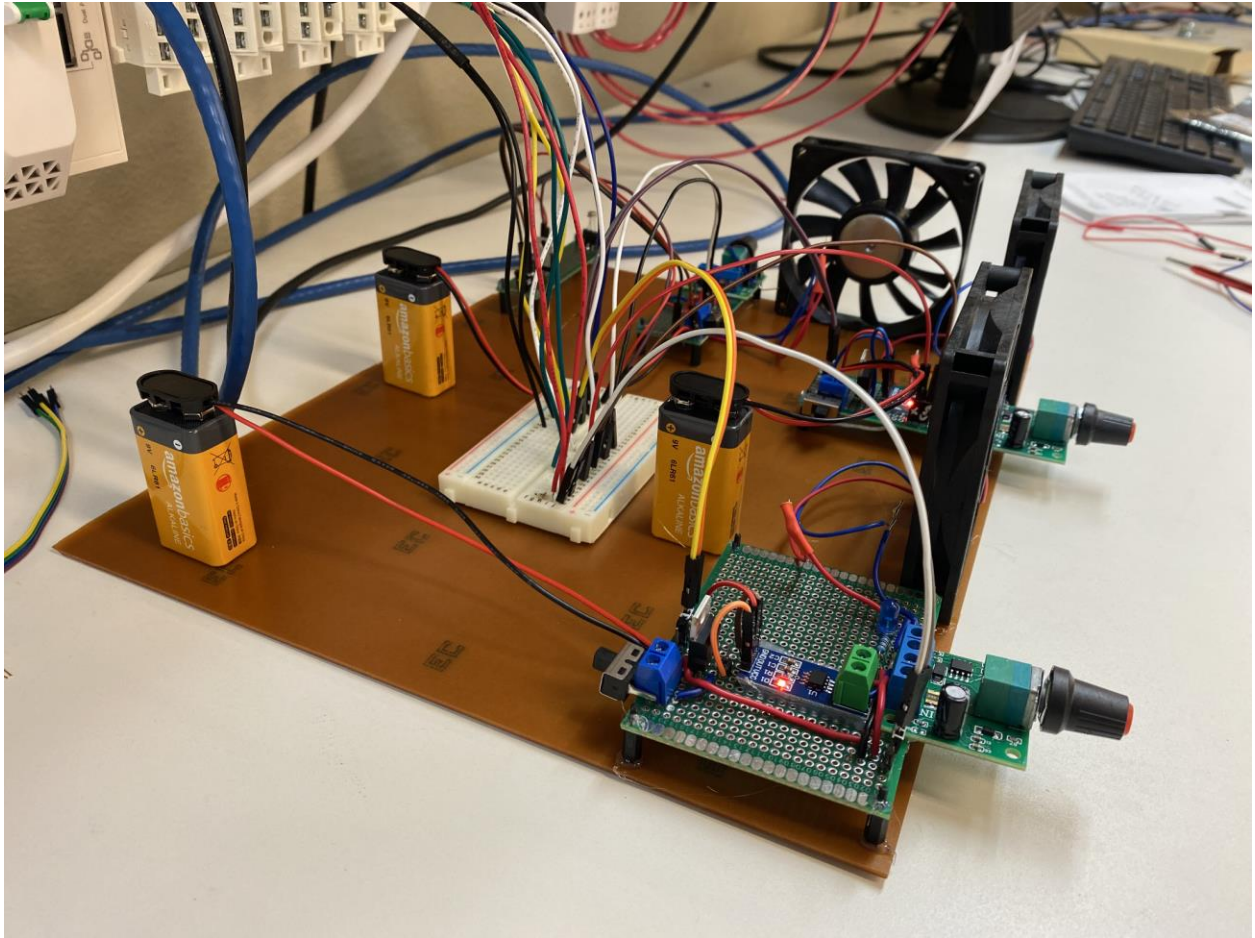
Figure 5-14: Full Hardware Assembly Angle 3

Figure 5-14 shows a third angle of the fully assembled system, focusing on the backside and the connection between all the hardware components.
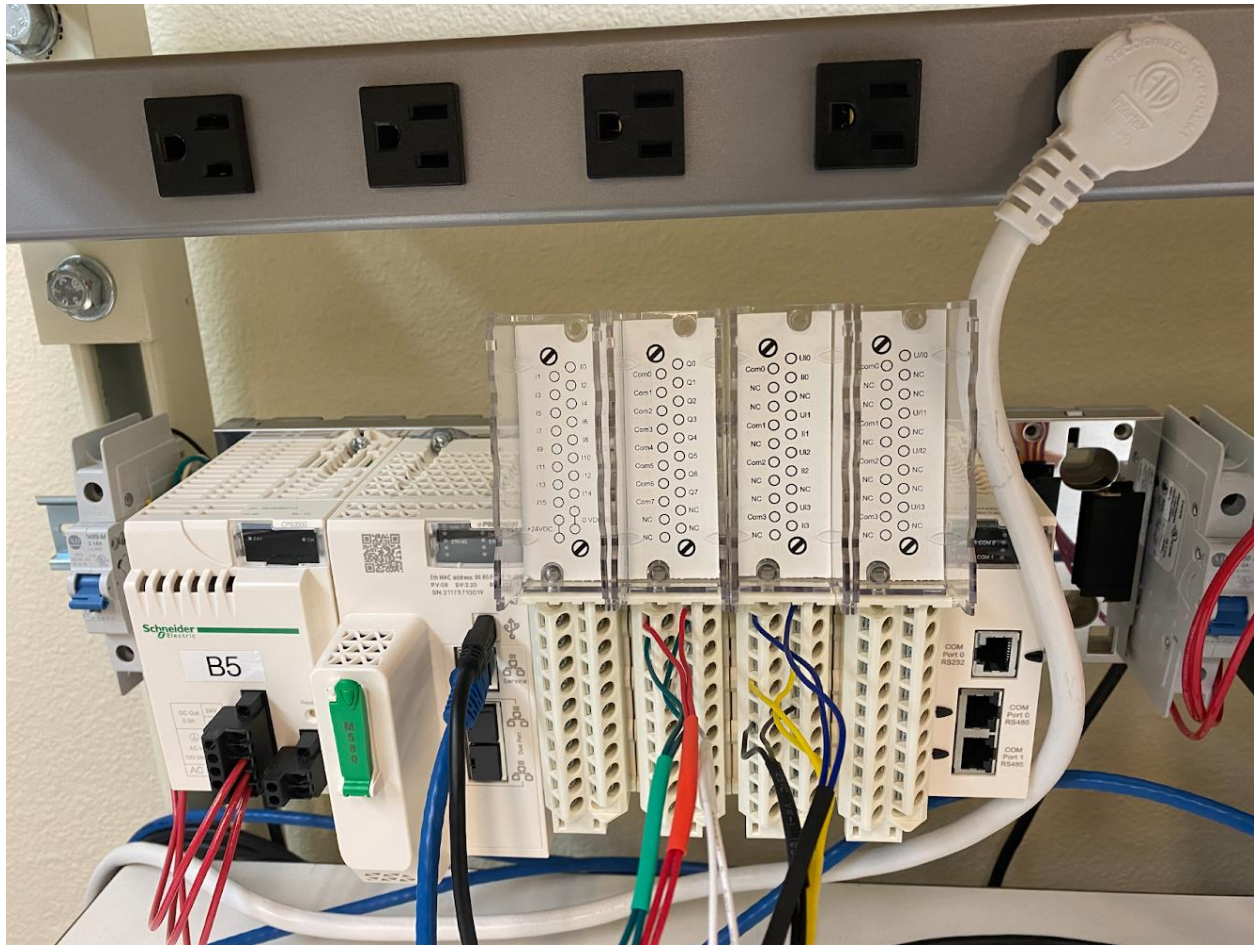
Figure 5-15 : Wire connection in Digital inputs and Analog outputs

Figure 5-15 shows all of the digital output and analog input connections to the PLC for all 3 fans.

The assigned variables with their type and address before the animation table is initialized as shown in Figure 5-16. The result after the animation table has been initialized with a temperature of 25.6 degrees Celsius. Figure 5-17 indicates the real time status of all variables given specific temperature conditions.

Figure 5-16: Animation Table Pre-Initialization

Figure 5-17: Animation Table Post-Initialization

Chapter 6: Conclusion

The initial purpose of this project was to familiarize ourselves with the PLCs and develop a greater understanding of how to use them in an industrial setting. Ultimately, this was done by expanding upon a prior senior project that did not have the chance to do any hardware implementation due to the COVID-19 pandemic. The project involves using the Modicon M580 PLC to emulate an HVAC system using DC motor fans, fan drivers, a temperature sensor, a current sensor, and a pulse width modulator. By learning from what our predecessors left behind, trained professionals, and our own personal research we were able to update and understand the Control Expert software, develop solutions to have variable fan speeds, and successfully construct the whole system in a way that fulfills the initial goals.

One of the major problems we ran into early on was how little documentation there was for interfacing with the Modicon M580 PLC model specifically. All PLCs behave in mostly similar ways; however, when initializing and coding for them there are slight differences that are extremely difficult to discern without having spent an immense amount of industry time working with PLCs. Luckily, we had an expert on the Modicon M580 controller give us advice from time to time. However, even though we were taught generally how it should work for several cases, figuring out minute things like how to name addresses and when variables should be tied to addresses gave us a lot more trouble than we expected. While our predecessors were able to simulate some of their ideas and we were meant to expand upon their simulations, the setup in simulation mode ended up having several differences between actual implementation in standard mode. The biggest thing definitely being the variable address assignment mentioned earlier. Understanding addresses are key to utilizing the PLC and there was little to no mention of them in earlier works. Another initial problem we ran into was setting up the IP addresses on the PLC so they could actually connect to the computers. It was a build-up of several of these barriers that unfortunately made some instances in the project a bit more frustrating than they probably should have been. Once we had our design completely set up, the actual hardware construction and implementation went extremely smoothly. The sensors, motor, and PWM all worked without too many problems on the first or second try after properly mapping out our schematics on paper. In

regard to optimization, there are certain aspects in the hardware that could be more efficient which will be discussed in the future improvements section.

The recommendations for future work include designing the circuit in PCB layout software which enables signal integrity and minimizes leakage current in Hall-effect current sensors. As the current sensor is sensitive to a slight change in current status, having a stiff circuit board design gives a well-performing system. The Heat testing unit used in this project comprises hot nichrome wire, which can be improved with a safe heat source such as a hot air dryer, potentiometer across the temperature sensor to vary its output voltage. The circuit for all the fans consists of an individual power supply of 9V, which is 75% the potential of a 12V DC Brushless motor. Also, using a 12V power supply to power the entire circuit is cost-effective, and the performance of the fans is much better as the 12V supply up to a duty cycle of 100%.

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Appendix A: Scheduling
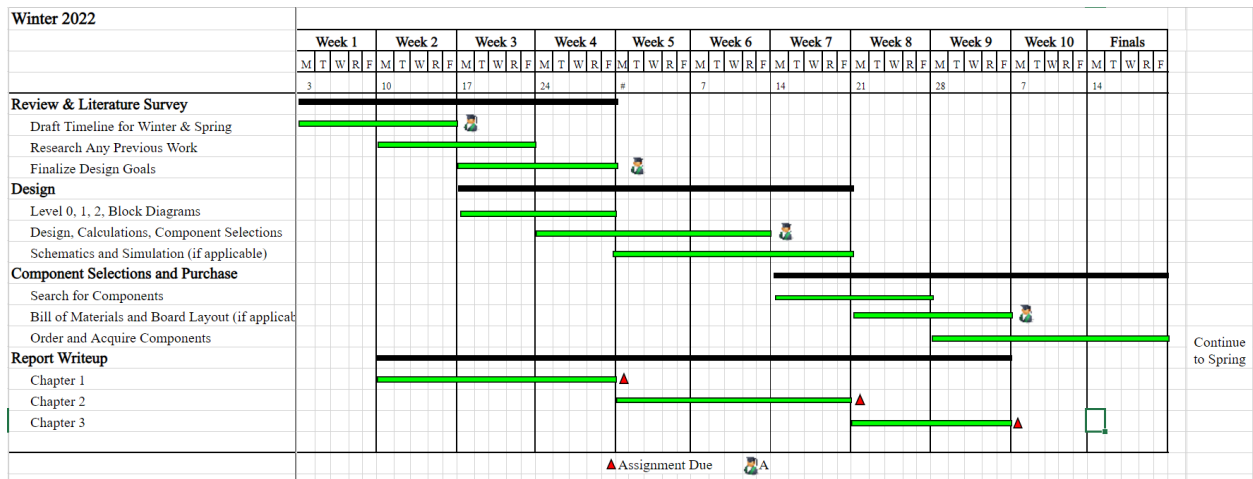
Figure A-1: Winter 2022 Gantt Chart
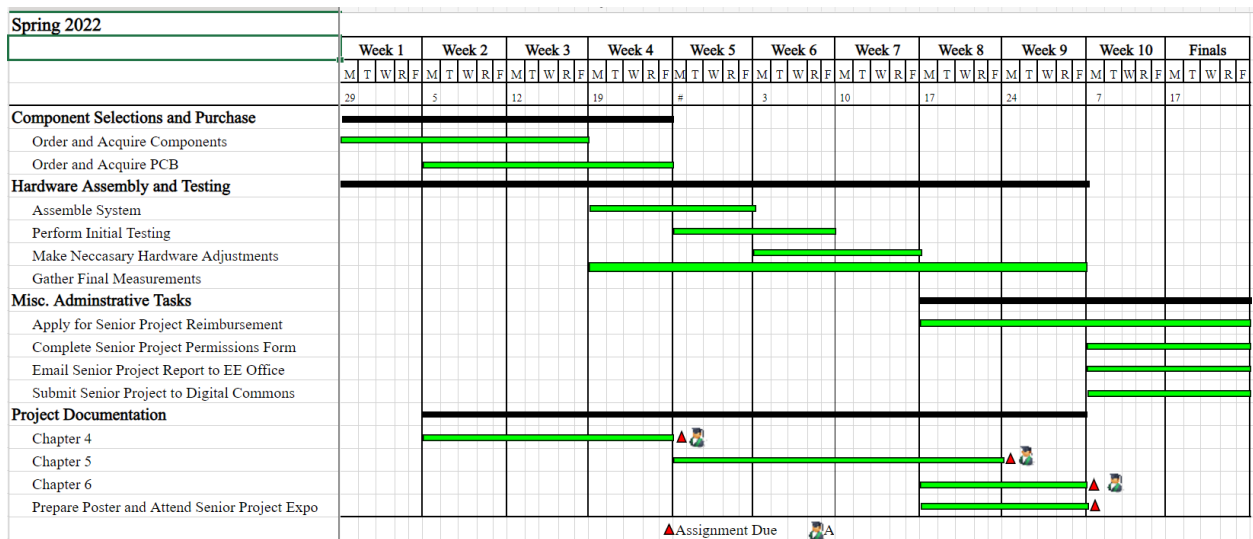
Figure A-2: Spring 2022 Gantt Chart

Appendix B: Bill of Materials

Item	Description	Supplier	Manufacturer	P/N	Quantity	Unit Cost ($)	Total Cost ($)
Micro USB Cable	PC-PLC Connection	Amazon	Amazon Basics	N/A	1	7.67	7.67
24 AWG 100 ft Nichrome 80 Resistance Wire	Used to simulate various temperatures	TEMCO Industrial	TEMCO Industrial	RW0407`	1	8.03	8.03
MOSFET	Test circuit for heat dissipation and switch for PWM	Digikey	STMicroelectronics	STFH18N60M2	1	2.76	2.76
Voltage Regulator	Stabilize the voltage to ensure the fans don't switch between speeds or turn on and off constantly	Texas Instruments	Texas Instruments	LM117	1	18.83	18.83
Temperature Sensor	Detect External Temperatures	Texas Instruments	Texas Instruments	LM35	1	28.43	28.43

Fan Drivers	Reduce input voltage to 12V so fan can function	Digikey	Diodes Incorporated	AH5775	10	6.24	6.24
DC Brushless Motors	Computer fans simulating HVAC system	Cal Poly EE Department	Allegro Microsystems	A4915	3	N/A	N/A
Total							71.96

Table B-1: Final Bill of Materials

Appendix C: Analysis of Senior Project Design

1. **Summary and Functional Requirements**

The function of the HVAC Control System is to have control over Heating, Ventilation, and Air Conditioning as per the desired temperature of the surrounding based on pre-programmed code [1]. HVAC controller is capable of logically controlling the rotational speed of fans, automatically turned off/on. It acts as Liquid Control (liquid for cooler with PID control), Air Quality Control (via Ventilator), Room Sensor (detects surround temperature), & Climate Control (Humidity Control, Room temperature control).

2. **Primary Constraints**

The primary Constraint of this project is some of the material unavailability. For instance, having access to an HVAC outlet nearby the workspace might be an issue. In addition to material availability, the required software to operate the Modicon M580 might be another issue since it cost over $1000. The number of hours to complete this project is also a potential constraint, as 3 hrs./week is insufficient. Materials are not allowed out of the lab to work on this project; thus, all the work needs to be taken care of inside the control laboratory at the EE building, but I was only able to work there 3hrs/week.

3. **Economic**

(i) Human Capital - The certified individuals will be required to set up the connection for the whole PLC system as part of the hardware. On the other hand, trained personnel should know how to use the software necessary to facilitate the operation.

(ii) Financial Capital - Schneider Electric donated all the hardware equipment, and
The Cal Poly EE department provides programming Software and Laboratory. Based on the financial requirements to complete, this project is only limited to labor cost. In cases of possible losses from unexpected risk, the EE department will appeal to cover the loss based on provision funding for Senior Projects.

(iii) Manufactured or Real Capital - The project's end product enables the development of a prototype of the HVAC system that can be controlled from a far distance. This project also helped assist in creating laboratory experiments based on PLC.

(iv) Natural Capital - The equipment required to complete the project contains metals used in almost all components, plastics used in PLC controllers, liquid for the cooler, etc. The mentioned materials use limited resources available on the planet.

The total costs required for equipment and labor to complete the project bring down the cost to $7000. These costs have not covered the maintenance cost to support the project's productivity. The maintenance cost will mostly be spent on batteries, cooler, fans, switches, programming devices, etc. The cost to maintain the device's productivity is considered so that it does not exceed the price to buy a new device.

To complete this project, the inputs such as trained individuals, a laboratory, and hardware equipment will be required. The Cal Poly EE department covers the cost required for the project.

4. **If manufactured on a commercial basis**

The Project Programmable Logic Controller (PLC) focuses on industrial, residential, and commercial automation. The implementation of PLCs has a broader scope as every sector worldwide is getting into a more innovative system where a compelling logic controller is a must. The PLCs are vital components for industrial manufacturing and smart grid; due to this, PLCs are supplied as commercial and industrial products.

Based on the devices sold globally which operate HVAC systems, the number of devices sold per year is around 6 million (hardware and software). As per the purchase price of each device, cost varies for software and hardware used in the product. The total cost for software with a 1-year license comes out to be $1000+ which does not include yearly renewal fees. On the other hand, hardware cost ranges from $200-$1000.

With respect to purchase price of ~$2000/ device and number of devices sold; the yearly profit is estimated 9 billion (= 6 million * $2000/device). The yearly profit is based on the global statistics of PLC manufacturing companies all over the world. The information on manufacturing cost per device of Madison 580 PLC is not released by manufacturer (Schneider Electric). The operating cost of the device is $3150/individuals based on the amount of time spent to design the product working around 3 hours per week for 6 months [1].

5. **Environmental**

Under the consideration of the impact of manufacturing the product in the environment, the by-product and the types of materials used might indirectly and negatively affect the environment when the production is carried out in wide range. Regardless of its effect on the environment, a product manufactured is not enough to cause significant damage to the environment.

The use of limited earth resources and electricity to power the device are indirect ways the environment gets affected. The primary purpose of this project is to develop small scale experiments based on PLC controllers; due to this reason; the end product is less likely to be used commercially. The time to perform the experiment using this device is negligible compared to commercial operation, where it might operate 24/7. During the manufacture of the product, no harm is caused to any ecosystem and biosphere directly.

6. **Manufacturability**

The materials required to manufacture the PLC are readily available and accessible. The accessible material requirements and demand of PLC controllers in the current world market make it non-problematic when manufacturing on a large scale. The production of PLC controllers in today's market estimates billions of dollars, infers it as a booming industry with no issues. The software to operate PLC costs more than the hardware requirements which indicates that most of the development in the system converse to software expansion. For this project, the hardware and software have already been provided with Schneider Electric and the Cal Poly EE department; there is no actual manufacturing of any of the materials required. All the equipment is readily available in the Cal Poly Control Laboratory.

7. **Sustainability**

The estimated material lifetime of the Modicon M580 PLC used for the development of the HVAC Control System is 20 years. The M580 is an integral unit of the whole system; its long life enables ecological sustainability as products with limited earth resources last for years. Once all the equipment is set up to form a completed design, there is no need to connect and disconnect the setup frequently. There is little to no challenge in maintaining the complete system, as the setup is stored indoors where it is unable by the external climatic condition.

8. **Ethical**

Although there is minimal effect on the environment and human lives during the manufacture of Modicon M580, its disposal might cause environmental hazards. In this sense, it can be said that the ethical dilemma might arise with the disposal of the PLC controller. Modicon M580 follows the same level of harm caused by the dumping of traditional semiconductors, electronics. The materials such as lead, hexavalent chromium, etc., used in manufacturing this device contain toxins when they come in contact with the external environment and may forecast health hazards such as respiratory discomfort and lead poisoning.

Based on the goal of this project, which is to create an HVAC control system, the end product benefits the majority of the population around the globe. Other than the issue with disposal, the product has no additional adverse effects compared to other electronic devices. As the impact and benefits weigh out to give more favorable outcomes, it is enough to support the moral framework of Utilitarianism (i.e., the greater good for the more significant number). Since no electronics could have been manufactured without having adverse effects on the environment and health of human beings as of the present day, the possible solution to create a sustainable and ethical manufacturing industry needs to be considered in future designs.

9. **Health and Safety**

The power supply (120 V AC rms, 60 Hz), operating voltage (0-20V), and current used in this device do not cause harm to the user. The possible health issue might arise from the external equipment such as liquid control, air quality control, climate control, etc. being controlled by Modicon M580. The extended use of air conditioning might result in dehydration leading to headaches and migraines. The cooling agent used in liquid control produces fluorinated hydrocarbon (Freon), which negatively affects the respiratory system. The pieces of equipment controlled by the climate controller maintain a humid environment which might promote the growth of dust mites and mold.

The potential privacy issue might arise within the device as the device consists of a programmable device and has web assets. Keeping in mind that any programmable device has possible malware threats, it is our responsibility to present a design with minimal malware issues. Hence, the software program Unity Pro XLS is a trustable software platform used in designing the HVAC system.

10. **Social and Political**

This project's stakeholders are Product Designers, Advisor, Schneider Electric, & Cal Poly EE Department. During the product's design process, the individuals will spend minimal time experimenting with exposed environments, which is considerable compared to when used commercially 24/7. The issue of disposal of Modicon M580 on nature is a severe environmental conservation concern. The Environmental Protection Act 1990 presses a charge care on the authority concerned with handling waste, including the rules and regulations to dispose of harmful electronics waste [9].

Based on the government's appeal to regulate E-waste, infliction is placed as a duty to protect the environment and living society. Due to this reason, the disposal of material involved in this project design will have to follow protocol implemented by the government, which protects the residential area and surrounding environment. With the duty of care implemented by Act 1990, the personal moral belief should respect the well-being of the social life. The goal of a sustainable environment and functional society needs to be protected at any cost regardless of stakeholders' pursuit.

11. **Development**

In addition to completing this project, the trained individual will further develop the functionality of the PLC controller in fields such as pressure control, lighting control, etc. The variation on frequency and inputs will help experiment with the possible future of PLC controllable systems. Further knowledge of the system interface will be required to understand the project's scope entirely. Working in PLC-related projects aids the development of new skills in control systems related to HVAC. It exposes new software and hardware equipment which broadens the scope of an electrical engineering career.