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DESIGN AND DEVELOPMENT OF A PLC-BASED CONTROL SYSTEM FOR PLASTIC EXTRUSION MACHINE

FYP-20-10

Final Year Project Report

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Declaration

We hereby declare that the work contained in this report is original; researched and documented by the undersigned students. It has not been used or presented elsewhere in any form for award of any academic qualification or otherwise. Any material obtained from other parties have been duly acknowledged. We have ensured that no violation of copyright or intellectual property rights have been committed.

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Abstract

This report details the design and implementation of a Programmable Logic Controller based control system for a plastic extrusion machine. The plastic extrusion process demands precise regulation of critical parameters, including temperature, motor speed, and hydraulic operations, to ensure consistent product quality and operational efficiency. The machine's original control system is non-functional, necessitating the development of a new, robust control solution. The design and implementation process encompassed the selection of appropriate sensors, actuators, and control algorithms. Temperature control was achieved using the ON/OFF method, maintaining stable and accurate thermal conditions within the extruder barrel. The extrusion motor speed was regulated using a Variable Frequency Drive, enabling precise adjustments to meet varying process requirements. Hydraulic clamping and unclamping mechanisms were managed by integrating solenoid valves, prime mover and a pump ensuring smooth and reliable operation.The system was developed and programmed using ladder logic by using a Siemens LOGO! Programmable Logic Controller.

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Nomenclature

CPU Central Processor Unit

DOL Direct On-Line

FBD Function Block Diagram

LD Ladder Logic

MCB Miniature Circuit Breaker

PID Proportional-Integral-Derivative

PLC Programmable Logic Controllers

SCADA Supervisory Control and Data Acquisition

VFD Variable Frequency Drive

1 Introduction

1.1 Background

Plastics have become integral to modern life, playing a vital role in various industries and applications due to their versatility, durability, and cost-effectiveness. Their unique properties, such as light weight, resistance to corrosion, and ability to be molded into diverse shapes, make them indispensable in sectors ranging from packaging and automotive manufacturing to electronics, medical devices, and construction materials. The global consumption of plastics underscores their importance, with annual production exceeding 380 million metric tons. This trend reflects the material's critical contribution to both industrial and consumer products [1].

Figure 1.1 [2] illustrates the extensive applications of plastics, highlighting their significance across numerous industries. Among these, the packaging industry stands out, utiliz-

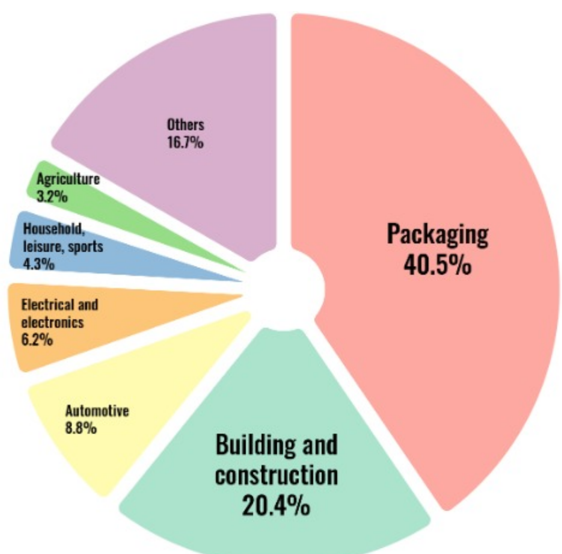


Figure 1.1: Statistic on plastics used across industries

ing plastics for containers, films, and protective materials that ensure product safety and longevity. In the automotive sector, plastics are essential for manufacturing lightweight components that enhance fuel efficiency and reduce emissions. Electronics rely on plastics for insulation, housings, and components, while the medical field uses them for sterile packaging, prosthetics, and disposable devices. Construction materials, such as piping, insulation, and fixtures, further demonstrate plastics' adaptability and importance in modern infrastructure [3].

The production of plastic products often involves advanced manufacturing processes designed to achieve precision and efficiency. Blow molding and thermoforming are particularly prominent in packaging applications, with blow molding encompassing three primary types: injection molding, extrusion molding, and injection stretch molding. Each method offers unique advantages and is chosen based on the desired product's characteristics and application [4].

Extrusion process

Extrusion is a cornerstone of plastic manufacturing, characterized by its ability to produce continuous profiles with consistent cross-sections. The process begins with the feeding of raw plastic materials, typically in the form of pellets or powders, into a hopper. This material is then channeled into the extruder barrel where it undergoes a series of transformative stages. As shown in Figure 1.2 [5], the extrusion process relies on the coordinated interaction of mechanical and thermal energy to convert raw material into finished products. Within the extruder barrel, a rotating screw plays a pivotal role. Its primary functions include conveying the material, melting it through the application of heat and pressure, and homogenizing it to ensure uniformity. The design of the screw is a critical determinant of the extrusion process's efficiency and the quality of the final product. Common screw designs include:

- **Single-screw extruders:** Known for their simplicity and cost-effectiveness, these are widely used in applications where mixing requirements are minimal.
- **Twin-screw extruders:** Featuring intermeshing or co-rotating screws, these are

employed for applications requiring enhanced mixing, such as compounding additives or processing heat-sensitive materials.

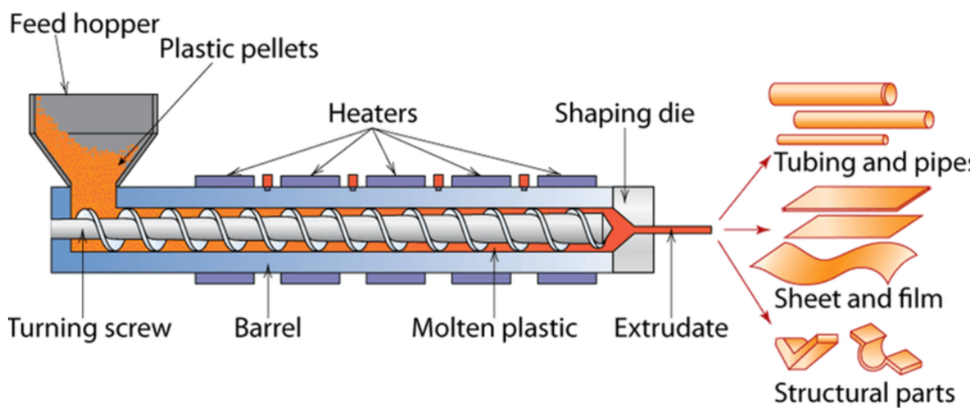


Figure 1.2: Extrusion Machine

The transformation of the plastic material within the extruder barrel occurs through three distinct zones which are feed, compression and metering zones. The feed zone is the initial stage where the material is compacted and begins to heat up. The second stage is compression zone where the material starts to melt under increasing pressure and temperature. Lastly, the metering zone where the molten plastic is homogenized and pressurized, ensuring a consistent flow toward the die.

The molten plastic is subsequently forced through a die, which imparts the desired shape to the extrudate. Die design is a highly specialized aspect of extrusion, requiring careful consideration of factors such as material flow behavior, product geometry, and the potential for post-extrusion deformation. Advanced die designs may include:

- **Flow distributors:** To ensure uniform material distribution across the die opening.
- **Adjustable lips:** For fine-tuning product dimensions to achieve precise tolerances.

Upon exiting the die, the extrudate enters a cooling phase to solidify and stabilize its final dimensions. Cooling methods vary depending on the product's size and material characteristics, ranging from air cooling for thin profiles to water baths for larger extrudates.

Secondary processing steps, such as in-line cutting, embossing, or co-extrusion, may be integrated to enhance the product's functionality or aesthetics [6].

Historical Development of Plastic Extrusion

The history of plastic extrusion dates back to the early 20th century, with foundational developments occurring in the 1930s. Early extrusion machines relied on mechanical controls, requiring operators to manually adjust parameters such as temperature, motor speed, and material feed rate. This manual approach, while innovative for its time, limited the precision and consistency of the extrusion process, posing challenges for scaling production and achieving high-quality outputs [7].

Significant advancements emerged in the mid-20th century with the introduction of electrical controls. These systems provided more precise regulation of extrusion parameters, improving both product quality and process efficiency. However, they remained relatively rudimentary compared to modern standards, lacking the capability to adapt dynamically to variations in the extrusion process [8].

The late 20th century marked a revolution in extrusion technology with the advent of microprocessors and digital control systems. These innovations enabled real-time monitoring and control of critical parameters such as melt temperature, pressure, and screw speed. This period also saw the widespread adoption of PLCs, which provided a robust platform for implementing complex control algorithms. PLCs allowed manufacturers to automate many aspects of the extrusion process, enhancing precision, consistency, and efficiency while reducing reliance on manual interventions [9].

Modern extrusion systems integrate advanced sensors, data acquisition systems, and sophisticated control algorithms to optimize performance.

1.2 Problem Statement

The existing plastic extrusion machine at the campus is currently non-operational due to its outdated control system. This has resulted in a complete halt in the production of plastic materials, depriving students and researchers of a valuable resource for practical learning and experimentation. The lack of access to a functional extrusion machine has significant consequences, including the need for outsourcing plastic production or relying on alternative methods. These limitations compromise the educational experience, as students are unable to gain hands-on training with equipment that mirrors current industrial practices. This gap in practical exposure not only restricts their readiness for the job market but also limits their understanding of contemporary manufacturing processes.

In an ideal scenario, the campus extrusion machine would be fully operational, featuring high efficiency, precise temperature control, and accurate regulation of motor and hydraulic systems. The proposed solution is to retrofit the existing machine with a PLC-based control system. Programmable logic controllers are renowned for their reliability, precision, and adaptability, making them an ideal choice for addressing the current inefficiencies and restoring the machine's functionality. This upgrade aims to enhance the machine's performance, sustainability, and productivity, transforming it into a state-of-the-art educational tool. By integrating advanced automation technologies, the project seeks to bridge the gap between academic training and industry requirements, enriching the learning environment for students and researchers alike.

Objectives

1.3 Main Objective

To develop a PLC-based control system capable of managing temperature, motor speed and direction, and hydraulic operations for a plastic extrusion machine. To achieve the above, the following specific objectives were derived:

1. To redesign the actuation components of the plastic extrusion machine to make it more efficient for use.
2. To design and develop a PLC-based controls for temperature, material extrusion rate and hydraulic system.
3. To integrate the controls into unit control system.

1.4 Justification

The design and development of a PLC-based control system for plastic extrusion machines is a critical project aimed at addressing the challenges of maintaining precise control over key operational parameters: temperature, motor speed, and hydraulic pressure. Given the increasing demand for high-quality plastic products across various industries, achieving consistent production quality is paramount. Traditional manual control methods often fall short in providing the level of precision required, leading to product defects, increased waste, and higher operational costs.

The justification for this project lies in its potential to enhance the efficiency and reliability of the plastic extrusion process. By automating the control of critical parameters, the PLC-based system minimizes the risk of human error, ensuring consistent product quality. Moreover, the real-time monitoring and adjustment capabilities of the system allow for dynamic responses to process variations, reducing downtime and improving overall operational efficiency. .

2 Literature Review

Programmable logic controllers are fundamental control components in industrial automation. They are widely used due to their adaptability, durability, and capacity to manage intricate control tasks. In the plastic extrusion process, PLCs are particularly crucial for monitoring and regulating key parameters which are extrusion temperature, motor speed, and hydraulic pressure, which are vital in ensuring consistency and efficiency in the production of high-quality plastic products [10].

A typical PLC system comprises several key components, including the CPU, power supply, input/output (I/O) modules, and communication interfaces. The CPU serves as the brain of the PLC, executing control instructions based on the logic provided by the user. I/O modules interface with sensors and actuators, allowing the PLC to monitor and control external devices. The communication interfaces, such as LAN, allow the PLC to link with other devices such as computers, extension modules, human-machine interfaces and other PLCs. Modern PLCs often include advanced features like real-time data processing, remote access, and integration with Supervisory Control and Data Acquisition (SCADA) systems [11].

PLCs operate by receiving inputs from field sensors embedded in extrusion machinery, processing this data according to pre-programmed logic, and sending output signals to actuators that adjust the process parameters in real time. This capability to automate and control multiple aspects of the extrusion process simultaneously is a significant reason for the widespread adoption of PLCs in plastic manufacturing industry settings.

PLCs are programmed using a variety of languages standardized by the IEC61131-3 standard, which include:

- Ladder Logic (LD) : The most widely used PLC programming language, modeled after electrical relay logic diagrams.

- Function Block Diagram (FBD) : A graphical language that represents control algorithms as blocks.

2.1 Temperature Control in Plastic Extrusion

Temperature control in plastic extrusion is responsible in achieving the temperature profile in the barrel to ensure good quality and consistency of the final product. The extrusion process involves heating the material to its melting point and maintaining a stable thermal profile throughout the barrel to achieve homogeneity and efficient material flow. Plastic extrusion machines typically feature multiple heating zones along the barrel, each equipped with independent control mechanisms to establish a precise temperature profile.

Maintaining an accurate and consistent temperature profile is essential for several reasons:

- Melting

  The material, usually in pellet form, must reach its melting point to transition into a uniform molten state suitable for extrusion. If the temperature is too low, there can be incomplete melting resulting to uneven flow, poor surface finish, and structural defects in the final product. Excessive temperatures can lead to thermal degradation of the material, resulting in discoloration, loss of mechanical properties, and an overall decline in product quality [12].

- Material flow

  Temperature influences the viscosity of the molten polymer which affects the flow characteristics of the molten plastics through the die to the die. A stable temperature profile ensures that the material flows uniformly, preventing issues such as warping, uneven thickness, or voids.

- Efficiency

  Energy efficiency and equipment longevity are enhanced when the system operates within optimal temperature ranges.

2.1.1 Methods of Temperature Control

Various methods are employed to regulate the temperature in plastic extrusion, ranging from ON/OFF control to PID algorithms. Each approach has its advantages and limitations, which are discussed below.

1. **ON/OFF Control**
   ON/OFF control is the method of temperature regulation where the heating element is switched on when the temperature falls below the set point and switched off when it exceeds the set point. While cost-effective and easy to implement, this method often leads to significant temperature fluctuations, known as hunting and overshooting as shown in Figure 2.1 [3]. Such fluctuations can compromise the precision required in high-quality extrusion processes [10].

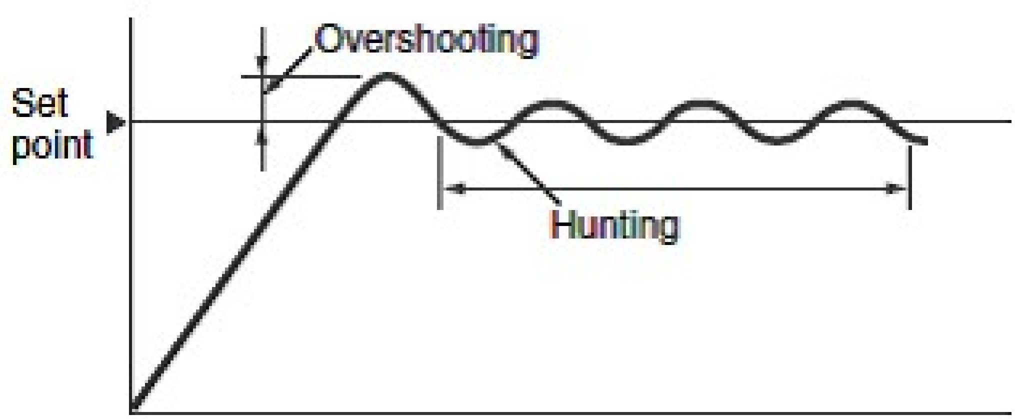


Figure 2.1: Hunting and overshooting in ON/OFF control.

2. **Analog Control**
   Analog control offers a more nuanced approach by varying the power supplied to the heating elements in proportion to the deviation from the set point. This continuous adjustment reduces temperature swings compared to on/off control but may still

exhibit challenges like overshoot and longer settling times. Analog control is suitable for applications requiring moderate precision [13].

3. **PID Control**

   PID control is widely regarded as the most effective method for temperature regulation in plastic extrusion. A PID controller calculates the heating element's output by considering:

   - Proportional control: The current deviation from the set point.
   - Integral control: The accumulated error over time.
   - Derivative control: The rate of change of the temperature.

   This comprehensive approach minimizes overshoot and ensures a fast response to temperature deviations, providing the precision necessary for demanding extrusion applications. However, tuning PID parameters can be complex, requiring expertise to optimize the controller for specific materials and production conditions [11].

2.2 Motor Control in Plastic Extrusion

Motor speed and direction control in the plastic extrusion process directly influences the material flow rate, the uniformity of the extrusion, and the dimensional accuracy of the final product. PLC-based systems provide the precision and flexibility required to maintain consistent motor speeds under varying load conditions, thereby ensuring high-quality output.

The motor in a plastic extrusion machine drives the screw, which transports and mixes the molten material before forcing it through the die. The screw's rotational speed determines the extrusion rate, which in turn affects the product's thickness, diameter, and overall consistency. Also motor rotation contributes to the heating of the plastics in the barrel through friction. Fluctuations in motor speed can lead to non-uniform flow, resulting in defects such as thickness variations or structural weaknesses. Consistent motor speed is particularly critical in applications requiring tight tolerances, such as medical tubing or high-performance films [14].

Maintaining precise motor speed also improves process efficiency by reducing material wastage and enhancing product uniformity. Furthermore, controlling the motor's acceleration and deceleration minimizes mechanical wear, prolonging the equipment's operational life.

2.2.1 Methods of Motor Speed Control

Different techniques are used to regulate motor speed in plastic extrusion, each offering unique benefits. These techniques are:

1. **Direct On-Line (DOL) Starters**

   DOL starters are among the simplest and most cost-effective solutions for motor control. They connect the motor directly to the power supply as shown in Figure 2.2 [15], allowing it to operate at full voltage. While suitable for smaller motors and less demanding applications, DOL starters provide limited speed control and can lead to high inrush currents during startup, potentially stressing the motor and electrical components [14].

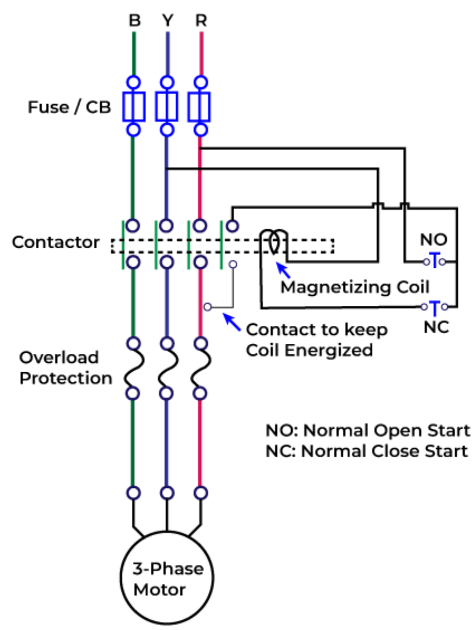


Figure 2.2: DOL starter.

2. **Star-Delta Starters**

   Star-delta starters, as shown in Figure 2.3 [15], addresses the high inrush current issue by initially connecting the motor in a star configuration, reducing voltage and current during start-up. Once the motor reaches a certain speed, the configuration switches to delta, allowing full voltage operation. This method is ideal for larger motors where reducing start-up current is essential [11].

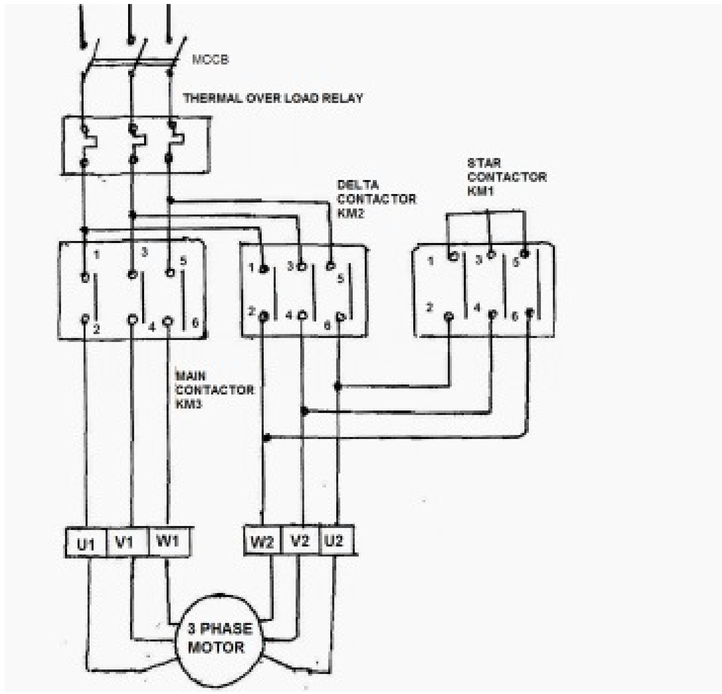


Figure 2.3: Star-delta starter.

3. **Variable Frequency Drives (VFDs)**

   Variable frequency drives method, as shown in Figure 2.4 [15], are the most advanced method for motor speed control, offering precise regulation by varying the frequency and voltage supplied to the motor. Benefits of VFDs include:

   - Smooth acceleration and deceleration.
   - Reduced energy consumption.
   - Improved process control and consistency.

   VFDs are indispensable in extrusion processes where maintaining a consistent flow rate and adapting to dynamic production requirements are crucial [11].

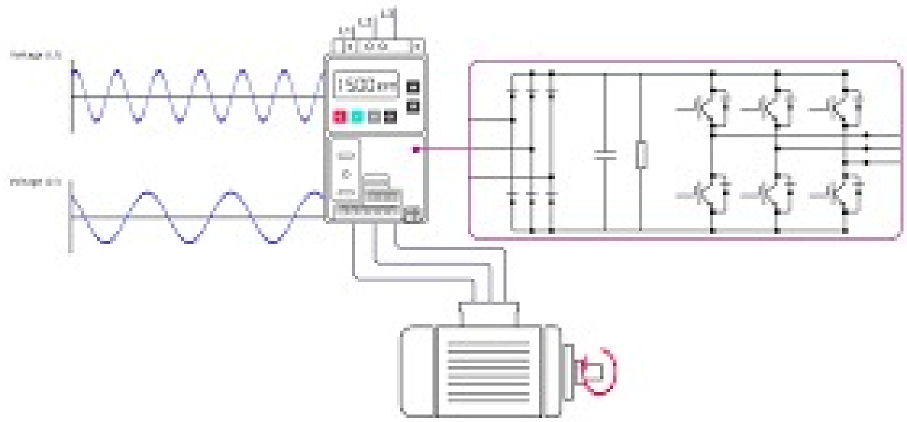


Figure 2.4: Variable Frequency Drive power circuit.

2.3 Hydraulic Control in Plastic Extrusion

Hydraulic systems in the plastic extrusion process provide the force necessary for tasks such as material feeding, clamping, and die movement. Effective hydraulic control ensures consistent performance, enhances product quality, and minimizes system wear. In extrusion systems, hydraulic control regulates the force applied during critical operations. Maintaining consistent hydraulic pressure is essential for precise die shaping and uniform material flow. Pressure fluctuations can result in defects such as uneven surfaces or structural weaknesses in the final product. Additionally, efficient hydraulic control reduces energy consumption and prevents excessive wear on system components, contributing to overall process sustainability [7].

2.3.1 Methods of Hydraulic Control

Hydraulic control in plastic extrusion involves integration of components to achieve high precision and reliability:

1. **Proportional Valves**

Proportional valves adjust the flow rate and pressure by varying the valve opening in response to electrical signals. This capability enables smoother operation and improved consistency compared to traditional on/off valves. Proportional valves are commonly used in applications requiring moderate precision [10].

2. **Servo Valves**

   Servo valves offer even greater precision by incorporating feedback loops that adjust valve positions based on real-time measurements. These valves are ideal for high-accuracy applications but are more complex and costly to maintain. Servo systems excel in scenarios requiring fine control over hydraulic parameters [13].

3. **PLC Integration for Hydraulic Systems**

   PLC-based hydraulic control systems enhance process efficiency by continuously monitoring parameters such as pressure, flow rate, and temperature. Real-time adjustments ensure optimal performance, while integration with predictive maintenance tools allows for early detection of potential issues. This proactive approach minimizes downtime and extends equipment lifespan.

2.4 Gaps in Knowledge

Despite the extensive literature on plastic extrusion, several gaps in knowledge remain. These include the need for more research into advanced control methods, such as adaptive or self-tuning PID controllers, the optimization of VFDs and their integration with other control systems, and the integration of hydraulic control systems with digital controllers. Addressing these gaps will require further research and development in these areas, as well as the validation of advanced control methods in real-world applications.

3 Methodology

The design process involved screw and barrel design, force calculation, component sizing and development of PLC control logic and programming for the extrusion process. The system's primary goal is to automate the extrusion process by controlling critical aspects: motor speed and rate of material injection, regulating extrusion temperature using thermocouples to monitor and activate or deactivate heating elements and clamping and unclamping the mold to achieve the desired product shape through hydraulic system control.

A modular approach was employed in developing the control system with motor control, temperature control and hydraulic control subsystems being developed and tested individually prior to integration and comprehensive system testing. This process encompasses the configuration, components, and operational principles of these subsystems

3.1 Design calculation

Hopper

The volume of the extruder hopper V_H was calculated using Equation (1)

$$V_H = \frac{1}{3}AH \tag{1}$$

where, A is the area of the hopper top is 70685.83 mm ^{2} and H is the height of the hopper is 300 mm. The volume of the hopper was evaluated as 7.0686 × 10 $^{-3}$ m^3. Taking the density of the PET plastic materials as 1380 kg/m^3, the mass of plastic pellets to be loaded in the hopper is evaluated to be 9.75 kg.

Extruder barrel and screw design

Extruder barrel is a metal cylinder that surrounds the screw. One end fastens to the feed throat and the opposite end connects directly to the nozzle. The extruder barrel must withstand high pressures. The internal diameter of the extruder barrel and screw ranges from 25 to 150 mm. The barrel and screw is long relative to its diameter with L/D ratios usually between 10 and 30. The higher ratios are used for thermoplastic materials, whereas lower L/D values are for elastomers [16]. The design of the screw involves calculating the screw geometry. The clearance between the barrel and screw flights is typically 0.08 to 0.13 mm. The screw diameter D $_s$ was evaluated as 35 mm with a radial clearance of 0.13 mm. The L/D ratio for optimum screw geometry was 19 giving a length of 680 mm. The helix angle (α) can be determined using the Equation (2)

$$\tan\alpha = \frac{p}{\pi D_s} \tag{2}$$

where the screw diameter (D_s) is 35 mm and the screw pitch (p) is 50 mm. The helix angle (α) is 24.45. The barrel internal diameter was evaluated as 35.26 mm. The total length of the barrel L required was calculated as 890 mm and since the barrel is cylindrical, the barrel volume V was defined by Equation (3)

$$V = \pi \times R_b^2 \times L \tag{3}$$

where R_b is the barrel internal radius and L is the total length of the barrel resulting to 0.83 m ^{3}.

Extrusion pressure

The extrusion pressure is the force required to push the material through the extrusion nozzle. The extrusion pressure was calculated using an adapted version of the flow equation for the extrusion screw, which considers the material's viscosity, the length and diameter of the screw, and the die's characteristics. The extrusion pressure (ΔP) was calculated using the flow Equation (4) adapted for the extrusion screw

$$\Delta P = \frac{2\eta L Q}{A_c^2 \cos^2(\alpha)} \tag{4}$$

where η is the viscosity of the material 800 Pa.s, A_c^2 is cross-section area of screw 9.62 $\times 10^-4$ m^2, L is the length of the screw, Q is the volumetric flow rate is $3.81 \times 10^-5 \text{m}^3/\text{s}$

and α is the helix angle of the screw. The resulting pressure of 61.6 kPa indicates the force that the motor must exert to overcome the resistance of the material as it is extruded through the nozzle.

Power requirement

The power requirements for the plastic extrusion process was determined by several factors, including the energy needed to convey material through the screw, melt the material, and overcome pressure losses within the system. The motor should deliver sufficient power to handle these tasks. The useful power requirement for the extrusion process was calculated by Equation (5)

$$P_{\text{useful}} = \dot{m} \cdot C \cdot (T_2 - T_1) + \dot{m} \cdot \Delta H_F + \Delta P \cdot V_F \tag{5}$$

where $\dot{m}$ is the mass flow rate as 0.01389 kg/s, C is the heat capacity of the material of 1300 J/Kg/°C, T_2 is the melt temperature of 270°C, T_1 is the inlet temperature 25°C, ΔH_F is the heat of fusion 56.1 J/Kg, ΔP is the pressure rise of 61.6 kPa, V_F is the volumetric flow rate of $3.81 \times 10^{-}5\text{m}^3/\text{s}$. The useful power was calculated as 4427 W. Working with a motor efficiency of 0.8 the power required for the extrusion process was evaluated as 5533 W.

Torque calculation

To ensure efficient operation, the required torque (T) must be calculated. The torque needed to drive the screw is related to the motor power and the screw speed. The optimum screw speed for the extrusion process was taken as 55 RPM and the torque was calculated using Equation (6)

$$T = \frac{P_(useful) \cdot 60}{2\pi \cdot N_m} \tag{6}$$

where P is the motor power in watts, N_m is the screw speed in RPM. The torque requirement for the process was obtained as 960.66 Nm.

Force calculation

The force produced during the extrusion process was determined using Equation (7)

$$F = \frac{T}{r_s} \tag{7}$$

where T is the torque and r_s is the radius of the screw is 0.0175 m. The force produced during the extrusion process was evaluated as 55 kN.

Motor selection and VFD sizing

A motor with power rating of 5533 W is sufficient to manage the operational demand of the extrusion process. Since most industrial application use 3-phase power supplies a three phase motor was selected for this application. The VFD must handle the motor's full load amperage, the power requirements and the operational demands of the extrusion process. The power requirement of the extrusion process is 5533 W and a motor efficiency of 0.8 and the current for a 3-phase motor was calculated using equations (8) and (9)

$$P_i = \frac{P_m}{\eta} \tag{8}$$

$$I = \frac{P_i}{\sqrt{3} \times V \times cos\phi} \tag{9}$$

where P_i is input power, η is motor efficiency, P_m is motor power, V is supply voltage of 415 V (3-phase supply voltage), ϕ is power factor of 0.9 and I is the current evaluated as 11 A. The VFD must be rated to handle a current of at least 11.1 A with a power capacity of 6916.25 W. The VFD selected should be rated slightly higher than the calculated requirement to provide a safety margin and accommodate any unforeseen load variations. Different VFD were compared as shown in Table 3.1 below.

The PowerFlex 4 was selected for this application due to its compact design, ease of use

Table 3.1: Comparison of Drives

Drive Model	Power rating (kW)	Current rating (A)	Comment
PowerFlex 4	7.5	16	Compact, versatile, easy setup
Siemens SINAMICS G120	7.5	15.5	Modular design, extensive options
ABB ACS355	7.5	14.6	Reliable, wide voltage range
Schneider ATV320	7.5	15	Rugged design, flexible mounting

and ability to handle general-purpose motor control applications. It provides adequate power and current ratings, matching the operational requirements of the extrusion process.

3.2 Motor Control System

The motor control system targets to run the motor at different speed and run in forward and reverse directions. These operations were achieved through sending commands from the PLC to the VFD which in turn modulates frequency, voltage and current to achieve different speeds and uses facilitates change in directions. The inputs to the PLC were normally open push-button to start the motor, normally closed push-button to stop the motor and a selector switch to change the direction of running the motor.

Design considerations

The design considerations for the motor control system were:

- Smooth motor operation - The motor should start smoothly and avoid inrush current that can be destructive to the PLC output module.
- Power requirement - The motor should provide a minimum of 5533 W and a motor drive that can handle current of 11 A and power of 6 kW.
- Industrial application - The power supply and components should match industrial 3-phase supplies and withstand harsh industrial conditions.

- Reverse and forward direction - The system should achieve both reverse and forward running for screw rotations.
- Safety - The system should protect both the components and the operators.

Based on the design considerations the control system was comprised of a 3-phase motor, VFD, PLC, push buttons and MCB .

Core Components of the Motor Control System

The components of the motor control system are described below.

1. **Three-phase motor**

   Three-phase motor, shown in Figure 3.1, with power rating of 11 kW was used to drive the screw. The motor was chosen for its:

   - **Suitable for industrial application:** The motor uses 3-phase power which is widely used in industries.
   - **Power rating:** The motor can deliver 5533 W power which is sufficient for the extrusion process.
   - **Energy Efficiency:** High power factor and low energy losses make it suitable for cost-sensitive operations.

Figure 3.1: Image showing the 3-phase motor

2. **Variable frequency drive**

   The VFD, shown in Figure 3.2, whose purpose is to regulate motor speed and direction smoothly.

Figure 3.2: Variable frequency drive

Its design balances efficiency with functionality:

- **Advanced control algorithms:** The VFD has inbuilt program that allow ease of use of the device.

- **Dynamic speed adjustment:** Capable of modulating output frequencies to match varying load conditions.

Motor Grounding

The drive safety ground was connected to the 3-phase power system. The motor ground was connected to one of the ground terminals on the drive.

Connecting the drive safety ground to the 3-phase power system provided low-impedance path to safely redirect fault currents therefore protecting equipment and personnel from electric shock. Grounding the motor to the drive prevents potential differences between the drive and motor, reducing the risk of electrical noise, stray currents, and damage to the motor's insulation or bearings.

It was observed that failure to properly connect the ground can result in electric shock and leakage current hence compromising the safety of the system. Figure 3.3 show the electrical circuit for the motor control system integrating all the components. The ladder logic diagram to achieve the operation is attached in the appendices of this report.

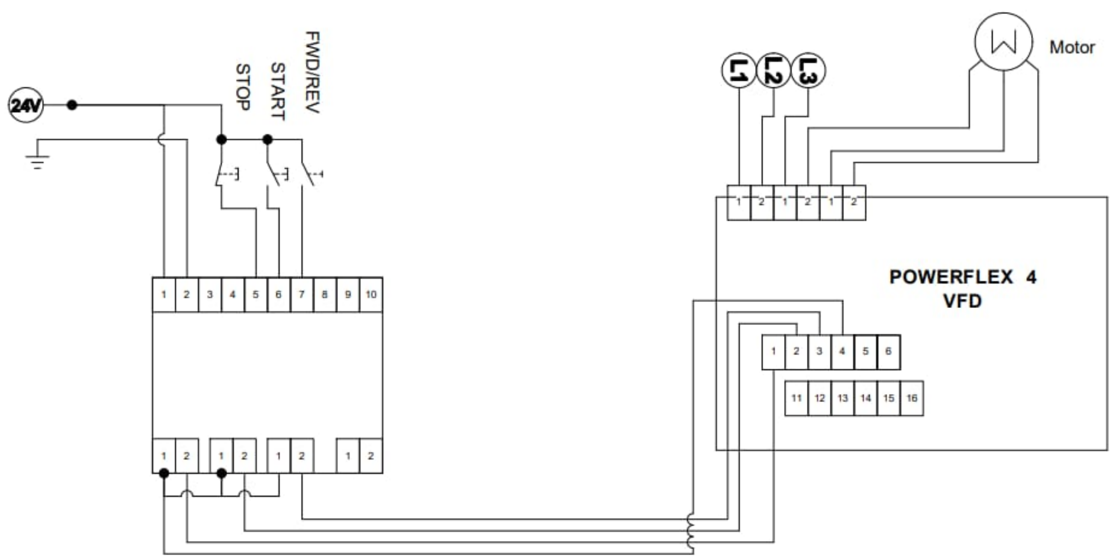


Figure 3.3: 3-Wire control circuit

Key Features of the Motor Control System

1. **Three-Wire Control Configuration**

   The motor control system employs a three-wire configuration of the VFD. The three-wire configuration connects these controls to the VFD's input terminals, translating user commands into precise motor actions. This configuration includes:

   - **Start button:** Sends an activation signal through the PLC to the VFD to initiate motor operation.
   - **Stop button:** This is used to halt motor running. Including a stop mechanism enables quick responses during emergencies.
   - **Selector switch:** Allows toggling between forward and reverse motor operation. This bidirectional capability is essential for extrusion processes requiring material repositioning.

2. **Speed Control Mechanism**

   The system integrates a potentiometer for dynamic speed adjustment:

   - **Potentiometer functionality:** By altering resistance, the potentiometer adjusts the input signal to the VFD, which then modulates the motor's operating frequency precisely controlling the motor's RPM, aligning it with material properties and production requirements. This is particularly critical in extrusion processes where material flow consistency directly affects product quality.

   The speed control mechanism allows operators to adapt to varying operational scenarios, such as changes in material viscosity or output specifications.

3. **Acceleration and Deceleration Profiles**

   Smooth acceleration and deceleration are vital for maintaining system integrity. The VFD's programmable features enable:

- **Gradual speed ramp-up:** Reducing mechanical stress during motor startup, protecting gears, belts, and bearings.
- **Controlled deceleration:** Preventing abrupt stops that could lead to material deformities or mechanical damage.

4. **Operational Logic**

   The motor control system's operational logic is designed for simplicity and efficiency:

   - **Start operation:** The Start button initiates a signal to the VFD, activating the motor. The motor operates at a predefined speed, adjustable via the potentiometer.
   - **Directional control:** The selector switch governs the motor's rotation direction, enabling forward or reverse operation as needed.
   - **Stop operation:** The Stop button halts all motor activity immediately, ensuring rapid response during emergencies.

   This logical flow ensures intuitive operation while maintaining robust performance in demanding industrial environments.

Programming an Allen-Bradley VFD

Programming an Allen-Bradley VFD involves configuring its parameters to align with the motor control system's operational requirements as guided by the codes shown in Table 3.2.

The following steps outline the process:

1. **Initial setup**

   - Wiring the the VFD in 3 wire configuration wired to the motor, power supply, and control inputs.

Table 3.2: VFD control sequence

Step	Action	VFD parameter (P)	Description
1	Reset all default parameters	P040 = 1	Factory reset
2	Set rated motor voltage	P031	Motor nameplate rated volts
3	Set Motor Frequency	P032 = 50.0	Motor nameplate rated frequency
4	Set motor rated current	P033	Rated motor current
5	Set minimum frequency	P034 = 0	Minimum frequency is 0
6	Set maximum frequency	P035 = 50	Motor rated frequency
7	Set control scheme	P036 = 0	VFD keypad for control
8	Activate stop mode for all stop sources	P037 = 0	Ramp stop mode
9	Set speed reference source	P038 = 0	Drive potentiometer for speed reference
10	Set acceleration time	P039	Acceleration for speed increase
11	Set deceleration time	P040	Deceleration for speed increase

   - **Power on the VFD:** Switch on the VFD and check for any fault indicators on the display panel.
   - **Access programming mode:** Use the keypad or connected programming software to enter the programming mode.

2. **Motor data input**

   - **Motor specifications:** Input key motor parameters such as rated voltage, current, frequency, and RPM which is 1400 RPM, 50 Hz, 17 A.

3. **Speed and direction settings**

   - **Frequency range:** Configure the minimum and maximum operating frequencies to define the motor's speed range.
   - **Direction control:** Enable forward and reverse operation if required by the process.

4. **Safety and protection settings**

   - **Overload protection:** Configuring the overload limits and response action. and actions to ensure quick diagnosis and recovery.

Benefits of the Motor Control System

The motor control system's design yields significant benefits, including:

- **Flexibility:** Adjustable speed and direction accommodate diverse materials and extrusion profiles.
- **Durability:** Smooth acceleration and deceleration enhance component longevity.
- **Safety:** Integrated protection mechanisms ensure operator and equipment safety.
- **Precision:** Real-time speed control maintains consistent material flow and product quality.

3.3 Temperature Control

Maintaining precise thermal conditions is critical for the extrusion process, as the material properties and quality of the final product depend heavily on consistent heating. The temperature control system is designed to regulate the operation of three band heaters, ensuring uniform heat distribution and stable operation throughout the process.

Key Components of the Temperature Control System

1. **Band Heaters**

   Band heaters shown in Figure 3.4 are the primary heating elements in the system, responsible for supplying the necessary thermal energy in the extruder barrel.

   Specifications:

   Each band heater is rated:

   - Voltage: 240 V
   - Power: 2400 W

Figure 3.4: Band heaters

- Temperature range: 1 - 700 °C.

Material:

Constructed using stainless steel with inner insulation comprising mica or ceramic ensuring efficient heat transfer while minimizing energy loss. These heaters are designed to withstand prolonged operation.

Placement:

The heaters are positioned along the length of the barrel in separate zones to provide uniform heating. This arrangement ensures that all material passing through the barrel receives consistent thermal energy, eliminating issues like localized overheating or under-heating.

Advantages:

- **Efficient heat transfer:** The snug fit around the barrel allows maximum heat transfer to the material.
- **Longevity:** Their robust design ensures durability even in demanding industrial environments.
- **Ease of maintenance:** Modular construction allows for quick replacement in

case of failure, minimizing downtime.

2. **Solid-State Relays (SSRs)**

   Solid state relays shown in Figure 3.5, are components used to control the power supplied to the band heaters. The SSRs were used to switch AC power to the band heaters based on the PLC's control signal, protect PLC outputs from current surges by isolating the control circuit from the load and allow the use of low-voltage DC signals from the PLC to control high-voltage AC power to the heaters.

   Current Handling: The SSRs in this system are rated for handling up to 10 amps per heater, providing adequate capacity for the load while ensuring reliable operation.

Figure 3.5: Image of contact solid state relay

Advantages over electromechanical relays:

- **Fast switching:** SSRs can switch on and off rapidly, enabling precise control over the heaters' operation.
- **Durability:** Unlike electromechanical relays, SSRs have no moving parts, reducing the likelihood of mechanical wear and tear.
- **Low electrical noise:** This ensures stable operation in industrial environments where electromagnetic interference is common.
- **Silent operation:** SSRs operate without the characteristic clicking sound of mechanical relays, which contributes to a quieter workspace.

3. **Temperature controller**

   The PLC served as the brain of the system ensuring that the barrel temperature remains within the desired range.

   Setpoint configuration: The controller is programmed to maintain a setpoint of 270 °C, which is optimal for the specific material being processed in the extruder.

   Feedback mechanism: The controller continuously receives real-time temperature data from thermocouples installed in each zone. Based on this input, it adjusts the power supplied to the heaters via the SSRs.

4. **Thermocouples**

   Thermocouples shown in Figure 3.6 are temperature-sensing devices that play a vital role in maintaining precise thermal conditions.

   Specifications:

   Each thermocouple is rated:

   - Voltage: 240 V
   - Output signal: 4 - 20 mA
   - Temperature range: 0 - 400 °C.

Figure 3.6: Thermocouple

The thermocouples were connected to transmitters to convert resistance to output signal of 4 - 20 mA. Type K thermocouples is used due to their wide operating range and compatibility with industrial processes.

Placement:

Positioned in close proximity to the band heaters, the thermocouples monitor the temperature in each heating zone.

Advantages:

- **Real-time monitoring:** Provides continuous feedback to the controller for instant adjustments.
- **High accuracy:** Ensures that temperature deviations are detected and corrected promptly.
- **Durability:** Designed to withstand harsh industrial environments and prolonged exposure to high temperatures.

5. **Contactors**

   A contactor shown in Figure 3.7 serve as auxiliary components in the system, providing an additional layer of control and safety.

Figure 3.7: Image showing contractor

Function:

Contactors are used to manage the main power supply to the system. In the event of an emergency or system shutdown, the contactors disconnect power to prevent damage.

Specifications:

Rated for high current loads, these devices are robust and capable of handling the operational demands of the extrusion process.

Advantages:

- **Enhanced safety:** Ensures power is completely cut off during faults or maintenance activities.
- **Reliability:** Provides a fail-safe mechanism to protect both equipment and personnel.

Sensor calibration

The thermocouple sensor gives output in milli-amperes while the PLC analog inputs use 0 - 10 V signal. To calibrate the temperature sensor with 4–20 mA output using the LOGO PLC's 0–10 V analog inputs, the following procedure was used:

1. Signal conversion

   The 4–20 mA signal from the temperature sensor was converted to a 0–10 V signal using 500 ohms resistor to enable compatibility with the LOGO PLC's analog input channel.

2. Scaling logic

   The input signal was scaled in the PLC program using analog amplifier function. The input signal in voltage form and in the range 0 - 10 v was represented in the range 0 - 1000 units. The signal was then mapped using 4-20 mA sensor option in the analog amplifier as shown on Figure 3.8. The signal was later mapped in 0 -

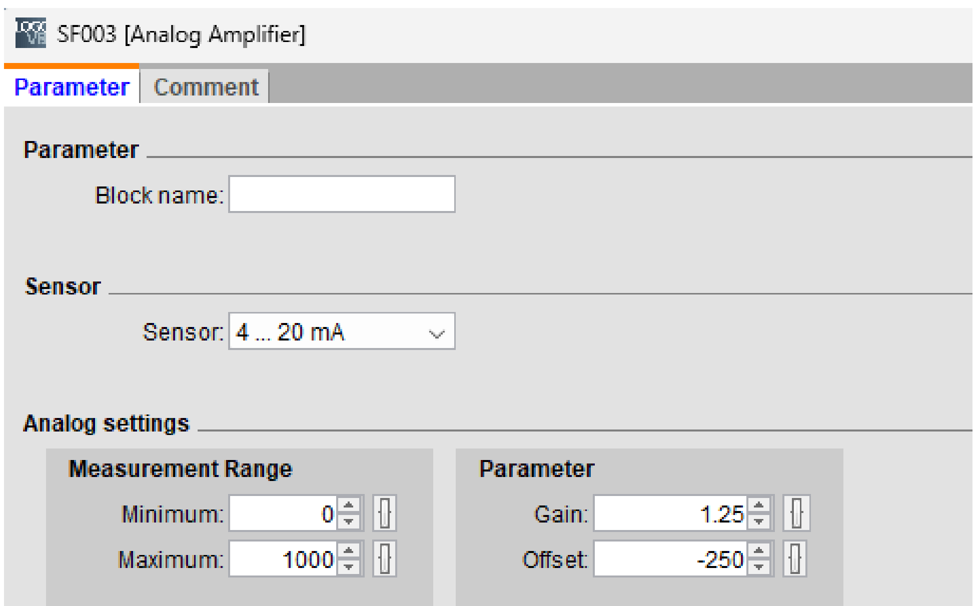


Figure 3.8: Mapping signal from 4 - 20 mA to 0 - 1000.

   400 to get the temperature in °C as shown in Figure 3.9.

Operational logic of the temperature control system

The temperature operation sequence used was turning ON heaters to raise temperature until the set temperature is achieved then turn them OFF. The logic flow chart is represented in Figure 3.10 below.

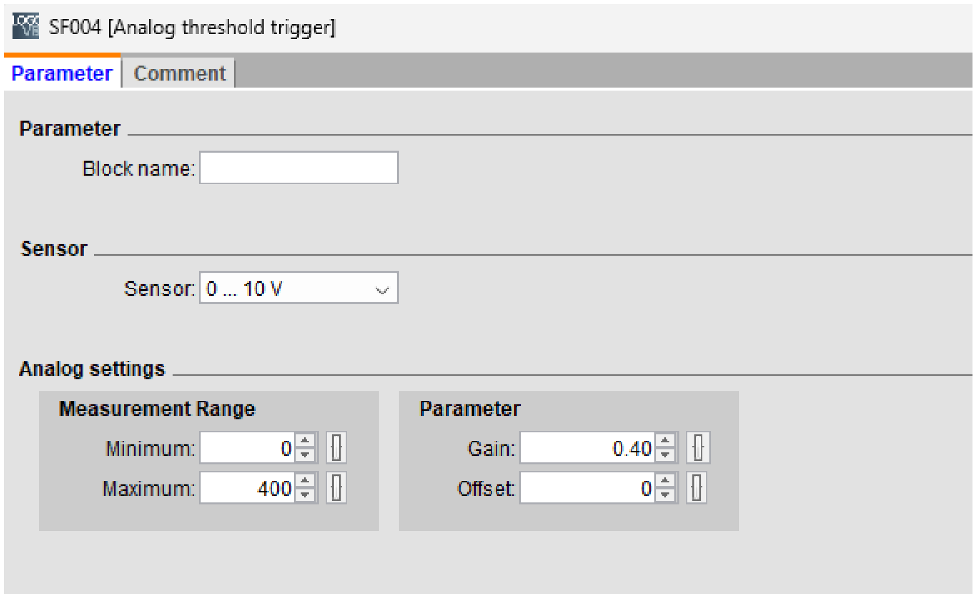


Figure 3.9: Mapping signal from 0 - 1000 to 0 - 400.

1. **Heating activation**

   When the barrel's temperature falls below the setpoint of 270°C, the temperature controller sends a signal to the SSRs to activate the band heaters. The SSRs switch on rapidly, allowing the heaters to generate heat efficiently and bring the system up to the desired temperature.

2. **Heating deactivation**

   Once the setpoint is reached, the controller signals the SSRs to deactivate, cutting off power to the heaters. This ON/OFF control strategy ensures that the temperature remains within the desired range without significant fluctuations.

3. **Hysteresis**

   The system is designed to minimize temperature fluctuations, known as hysteresis, around the setpoint. The rapid switching capabilities of the SSRs ensure precise control, reducing energy waste and maintaining consistent thermal conditions.

4. **Real-time feedback**

   The thermocouples continuously monitor the temperature in each zone and send

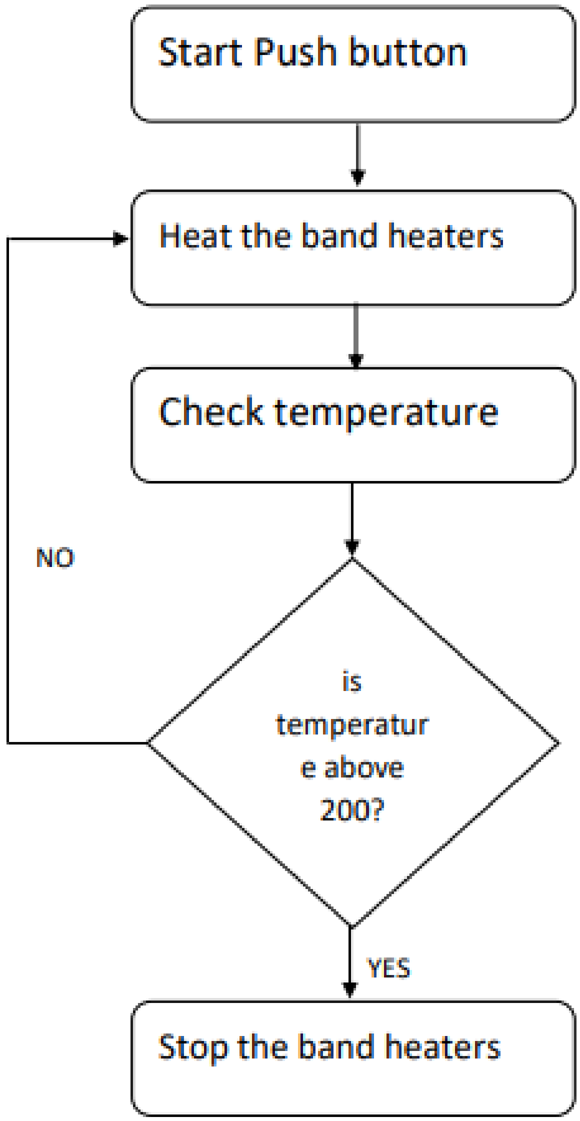


Figure 3.10: Temperature logic flow chart.

real-time data to the controller. Any deviation from the setpoint triggers an immediate response, ensuring consistent and precise temperature regulation.

Benefits of the Temperature Control System

- **Precision:**

  The closed-loop control system ensures accurate temperature regulation, critical for maintaining the material's consistency and quality.

- **Efficiency:**

  The use of SSRs minimizes energy wastage by ensuring heaters operate only when necessary, reducing operational costs.

- **Reliability:**

  Solid-state components and real-time feedback mechanisms enhance the system's durability and responsiveness, ensuring long-term performance.

- **Scalability:**

  The modular design allows for easy expansion or integration with additional heating zones, accommodating future process requirements.

3.4 Hydraulic Control System

The hydraulic control system is a vital component of the extrusion process, responsible for executing high-force mechanical operations with precision and reliability. It manages the actuation of hydraulic cylinders, which perform critical tasks such as clamping, lifting, and other force-intensive operations. This system combines mechanical, electrical, and hydraulic elements to ensure smooth, efficient, and safe functionality.

Hydraulic Power Requirements

Hydraulic power is a fundamental requirement in any hydraulic system. It is defined as the product of the flow rate and the pressure at which the hydraulic fluid is delivered. Hydraulic power P_h was calculated using the following equation (10)

$$P_h = Q \times \Delta P \tag{10}$$

where P_h is the hydraulic power in watts (W) or kilowatts (kW, Q is the flow rate in cubic meters per second (m^3/s) or liters per minute (L/min), and ΔP is the pressure difference or working pressure in pascals (Pa) or bars. Thus, the hydraulic power required is 1.2495 kW. This power is the energy needed to maintain the required flow rate and pressure within the hydraulic system.

Hydraulic prime mover sizing

The AC motor selected for the hydraulic system must be capable of providing sufficient power to drive the hydraulic pump. This power must take into account the efficiency of both the motor and the hydraulic pump. The required motor power P_m was calculated as follows

$$P_m = \frac{P_h}{\eta_m \times \eta_p} \tag{11}$$

where P_m is the motor power in kilowatts (kW), η_m is the motor efficiency, η_p is the pump efficiency. Therefore, an AC motor with a power rating of at least 1.34 kW is required to drive the hydraulic pump effectively. This ensures that the motor can meet the hydraulic system's power demands, taking into account potential losses due to inefficiencies.

Hydraulic Pump Sizing

The hydraulic pump is a critical component that must be able to deliver the required flow rate at the specified operating pressure. The flow rate Q provided by the pump can be related to the displacement per revolution and the speed of the pump by the following equation

$$Q = V_d \times N \tag{12}$$

where V_d is the displacement per revolution in cubic meters per revolution (m^3/rev) or liters per revolution (L/rev), N is the speed of the pump in revolutions per minute (rev/min). The pump displacement V_d was calculated as

$$V_d = \frac{Q}{N} \tag{13}$$

resulting to pump displacement of approximately 33.3 cm^3/rev. The pump selected must therefore have a displacement of around 33.3 cm^3 per revolution to deliver the required flow rate at the operating speed. Hydraulic cylinders, or actuators, are responsible for converting the hydraulic energy into mechanical force.

Components of the Hydraulic System

1. **Hydraulic cylinder**

   The hydraulic cylinder, shown in Figure 3.8, is the mechanical actuator in hydraulic systems responsible for converting hydraulic energy into linear motion.

   - **Design and Structure**

     The hydraulic cylinder, shown in Figure 3.11, consists of a cylindrical barrel, a piston, a piston rod, and seals. The piston divides the cylinder into two chambers, creating a differential pressure that drives linear motion. The barrel is typically made from high-strength materials like steel or cast iron to withstand high pressures.

   - **Seals and Rod Materials**

     Seals are crucial for preventing leakage and maintaining efficiency. Materials

Figure 3.11: Image showing hydraulic cylinder

such as nitrile rubber, Viton, or Teflon are commonly used for seals, depending on the operating temperature and pressure. The piston rod, which transfers motion to the external mechanism, is often chrome-plated to enhance wear resistance and prevent corrosion.

2. **Hydraulic Reservoir**

   The hydraulic reservoir in this system has a capacity of 40 liters, playing a pivotal role in fluid management.

   - **Functionality**

     The reservoir stores hydraulic fluid, ensuring an adequate supply to the system. It also allows for thermal dissipation, de-aeration (removing air bubbles from the fluid), and sedimentation of contaminants.

   - **Construction and features**

     Typically made of steel, the reservoir is designed to withstand pressure variations and prevent fluid contamination.

   - **Fluid characteristics**

     Hydraulic fluids must have properties like low compressibility, high lubricity, and thermal stability. Maintaining fluid quality is critical, as contamination can lead to inefficiencies or component damage.

3. **Prime Mover**

   The prime mover for this system is a single-phase motor which powers the hydraulic pump.

   Motor Specifications

   - Voltage rating: 240 AC power supply
   - Power rating: 3 HP
   - Speed: 1400 RPM.

4. **Hydraulic Pump**

   The hydraulic pump, shown in Figure 3.12, is powered by the prime mover to generate the pressure needed to circulate the hydraulic fluid though pipes to the hydraulic cylinders.

   Pump Types

Figure 3.12: Hydraulic pump

The choice of pump (gear, vane, or piston) depends on performance requirements:

- **Gear Pumps**: Cost-effective and reliable, suitable for low to moderate pressure.
- **Vane Pumps**: Offer better efficiency and are quieter than gear pumps.
- **Piston Pumps**: Provide high-pressure output, ideal for heavy-duty applications.

A gear pump was used for this hydraulic system as the operating pressure was low and the pump was cost effective in this application.

Pump specifications

The pump's flow rate (liters per minute) determines the system's speed, while its pressure rating (bars or PSI) dictates the maximum force.

- Flow rate: 16 L/min.
- Min. RPM: 700 RPM.
- Max. RPM: 3,000 RPM.
- Pressure: 200 bars.

Integration with the Motor

The pump was coupled using a pulley system to the single-phase motor ensuring seamless power transfer.

5. **Solenoid valves**

Solenoid valves, shown in Figure 3.13, were used for directing fluid flow in the hydraulic control system.

Construction and operation

The solenoid valve consists of a coil, plunger, and multiple ports for fluid passage. When energized, the solenoid coil creates a magnetic field that moves the plunger, opening or closing specific fluid pathways.

Types and Configurations

Figure 3.13: Image showing solenoid valves

- **Two-way valves**: Allowing or blocking fluid flow in a single line.
- **Three-way valves**: Directs fluid between three ports for supply, exhaust, or actuator control
- **Four-Way Valves**: Manages bidirectional actuator movement by directing fluid to extend or retract the actuator. The valve selected was a four way valve suitable for extention and retraction of the hydraulic cylinder

6. **Control mechanism** Solenoid valves receive signals from a PLC. The PLC uses electrical signals to precisely control the valve's actuation, enabling complex operations.

   Advantages

   - **Fast response**: Quick switching times enhance system efficiency.
   - **Durability**: High resistance to wear and tear.
   - **Flexibility**: Suitable for diverse hydraulic circuit designs.

System Implementation

1. **Hydraulic Circuit**

   The system integrates all components into a hydraulic circuit and powered through and electric circuit and controlled through the PLC. The pump draws fluid from the reservoir, pressurizes it and directs it through solenoid valves to the cylinder. Filters and pressure relief valves are incorporated to ensure safety and reliability. The hydraulic circuit is shown in Figure 3.14. It consists of a prime mover, hydraulic pump, solenoid valves and two double acting cylinders. The electric prime mover was connected to the hydraulic pump through a pulley system. The pump was then connected to the solenoid valves and reservoir though pipes. The cylinders were connected to the ports the valves though piped. The cylinders pistons were connected to the clamping mechanism of the machine.

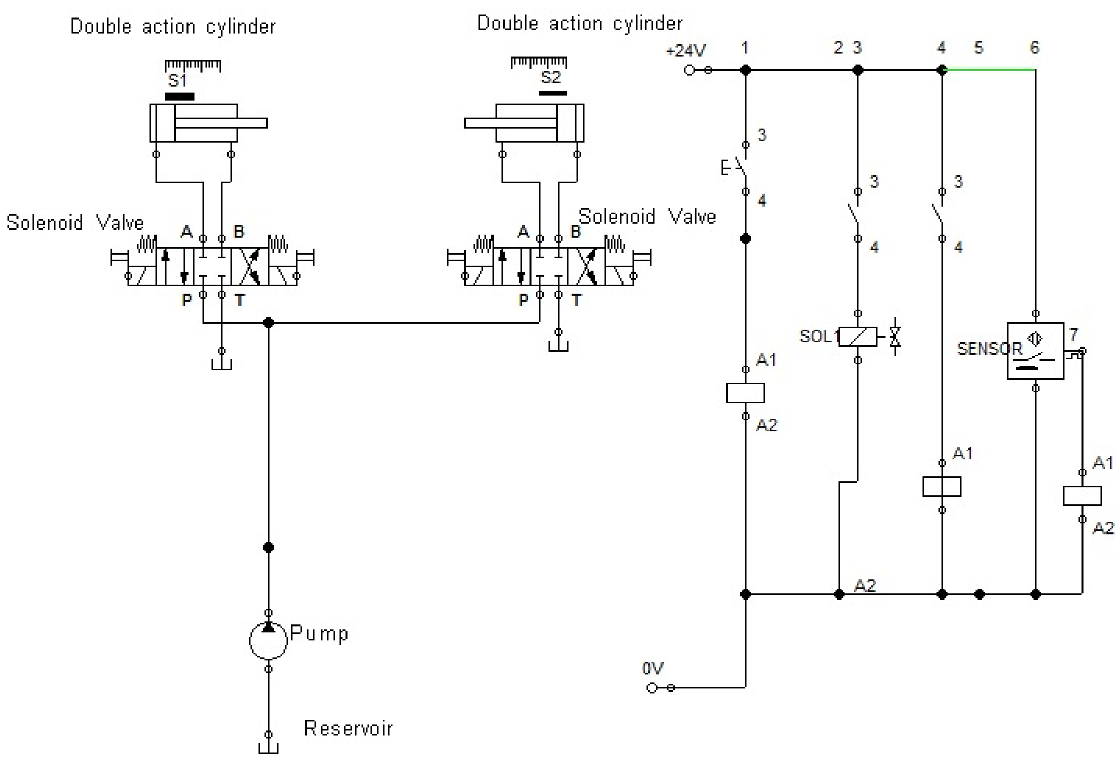


Figure 3.14: Hydraulic circuit

2. **Electrical circuit**

   The electric circuit was used to achieve automatic control of the purely hydraulic system system. The electric circuit is shown in Figure 3.15. Solid state relays were used in the circuit for activation of solenoid valves. The SSRs receive activation signals from the PLC.

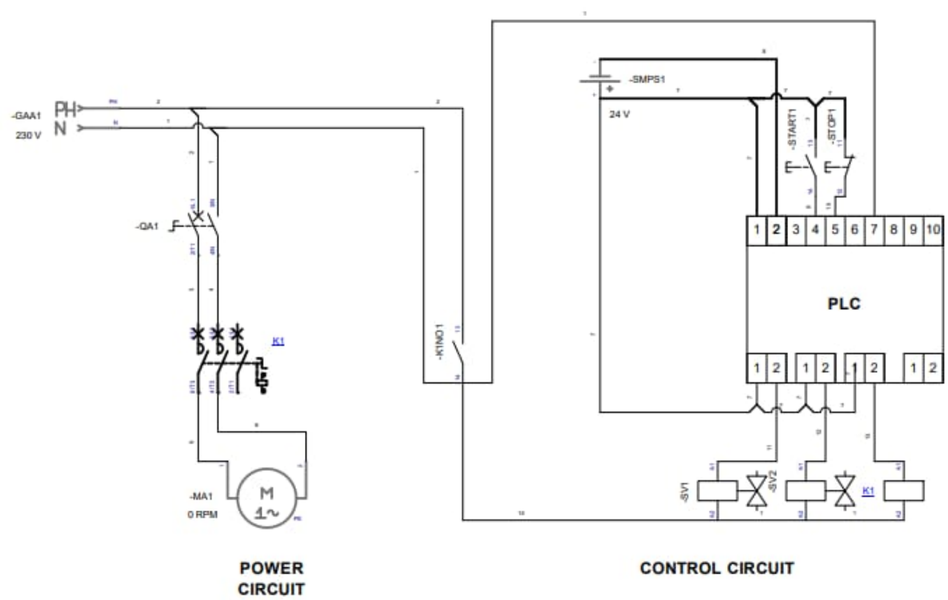


Figure 3.15: Hydraulic electric circuit

3. **Operational Logic of the Hydraulic Control System** The hydraulic control system follows a systematic operational sequence, coordinated by the PLC to ensure precision and safety.

   (a) **Initiation:**

   - The process begins when the PLC sends a signal to the SSRs, activating the solenoid valves.
   - The activated valves direct hydraulic fluid from the pump to the cylinder, initiating the desired motion.

   (b) **Actuation:**

   - Hydraulic fluid flows into the cylinder, applying pressure to the piston. This pressure generates the linear motion required for tasks such as clamping or lifting.
   - The movement of the piston is precisely controlled by the flow rate and pressure of the hydraulic fluid.

   (c) **Completion:**

   - Once the mechanical task is completed, the PLC sends a signal to reverse the solenoid valves.
   - This action redirects the hydraulic fluid back to the reservoir, allowing the cylinder to return to its original position.

Advantages of the Hydraulic Control System

- **High force output**: Hydraulic systems can generate immense force, making them ideal for heavy-duty applications.
- **Precision and control**: Accurate control over pressure and flow ensures consistent performance.
- **Durability**: Properly maintained systems have a long operational lifespan.

- **Flexibility**: Suitable for a wide range of industrial tasks, from extrusion to material handling.

3.5 Control System Integration

The individual modules were integrated into one control system after testing each separately. The electric circuit shown in the Figure 3.16 with all the components working together to achieve the control sequence illustrated in Figure 3.17 .

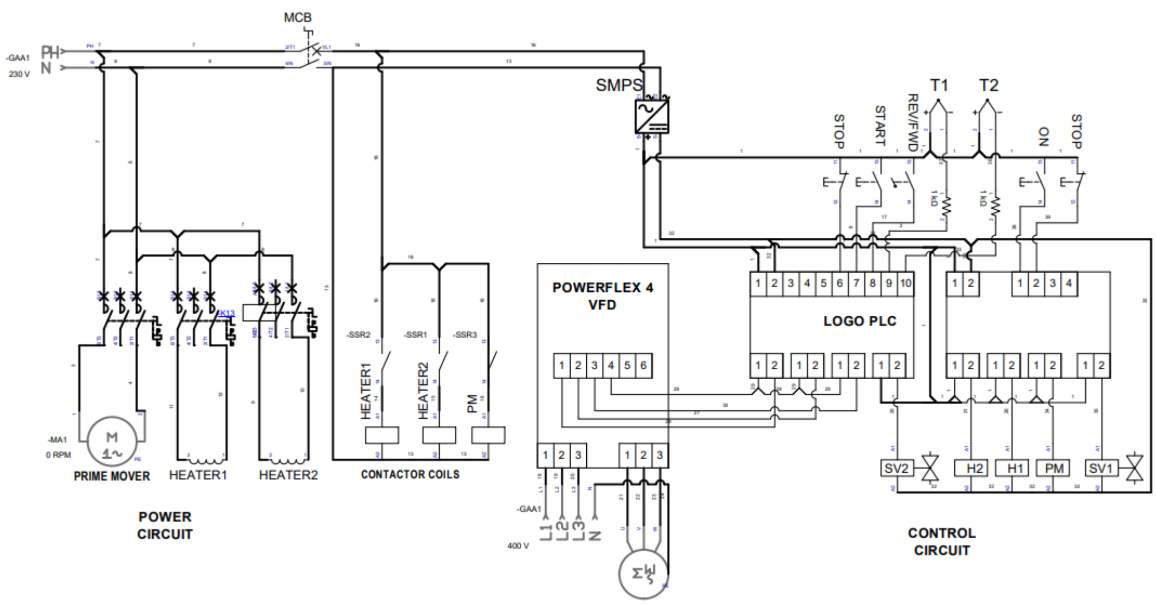


Figure 3.16: Integrated electrical circuit

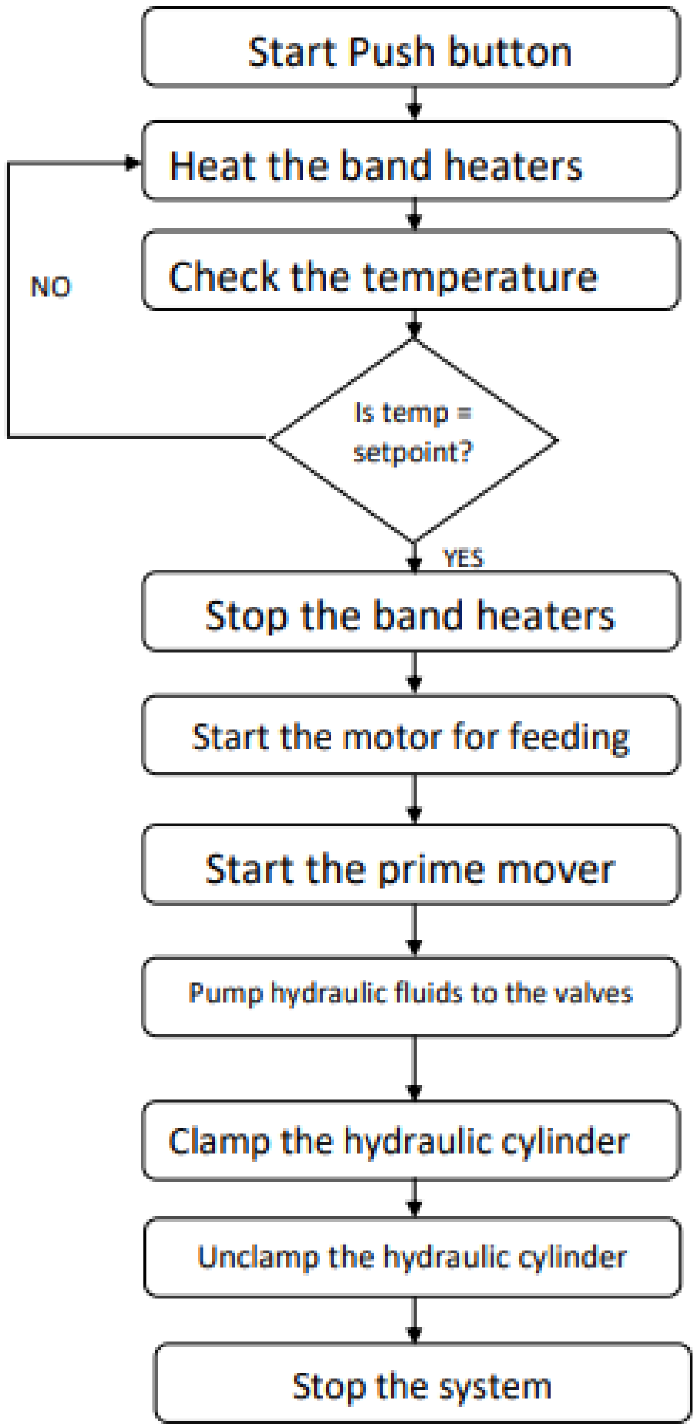


Figure 3.17: Integrated control flow chart

4 Results and Discussion

The control system's performance was evaluated based on individual subsystems operation as well as the integrated system. Each subsystem was tested for response time, accuracy, stability and energy consumption under load conditions. The integration phase assessed synchronization and system responsiveness through PLC logic and display function.

4.1 Motor Control System

The motor speed regulation was successfully implemented using a variable frequency drive (VFD) controlled through the PLC as illustrated in the setup in Figure 4.1. The following

Figure 4.1: Motor contol setup

were observed during testing:

1. Response time

   Once the motor start button was pressed the motor starts immediately and the speed would increase as the VFD potentiometer was rotated clockwise and decrease as the potentiometer was rotated counter-clockwise.

2. Current drawn

   The current would decrease with increase in speed where there was no loading.

3. Direction The motor successfully ran in forward and reverse direction. When the selector switch position was at the center the motor ran in forward direction and otherwise in reverse direction.

The immediate response highlights the effectiveness of the VFD in providing real-time control without delays or lags and smooth operation of the motor. This indicate that the material ejection rate can be operated smoothly without delays or interruptions caused by instability in running the motor. The decrease in current with increase in motor speed under no-load conditions indicates reduced torque demand at higher speeds as expected for an unloaded induction motor. This inverse relationship demonstrates the efficiency of the motor and the VFD in managing energy consumption under variable speed conditions. The motor successfully transitioned between forward and reverse operation. This reliable directional control emphasizes the precise configuration of the VFD interfacing with PLC. This indicates the advantage pf PLC control of motor through VFD in that direction is achieved through switching action rather than wiring and rewiring.

4.2 Temperature Control System

The temperature control was successfully implemented as shown in the setup in Figure 4.2 and tested for accuracy, response and stability. The following were observed:

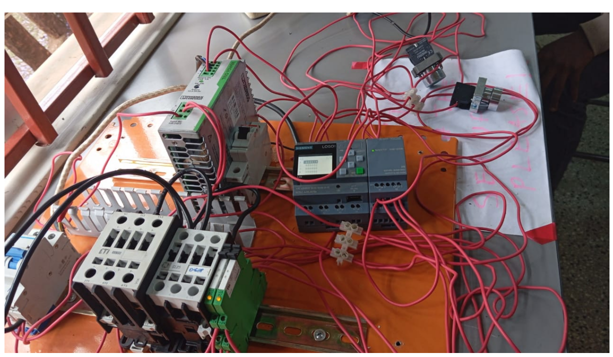


Figure 4.2: Temperature control setup

1. Accuracy

   The thermocouple reading was compared with the room temperature measured using a standard thermometer to verify the accuracy of the reading. The results were recorded and plotted in the several tests as shown in Figure 4.3. The average error

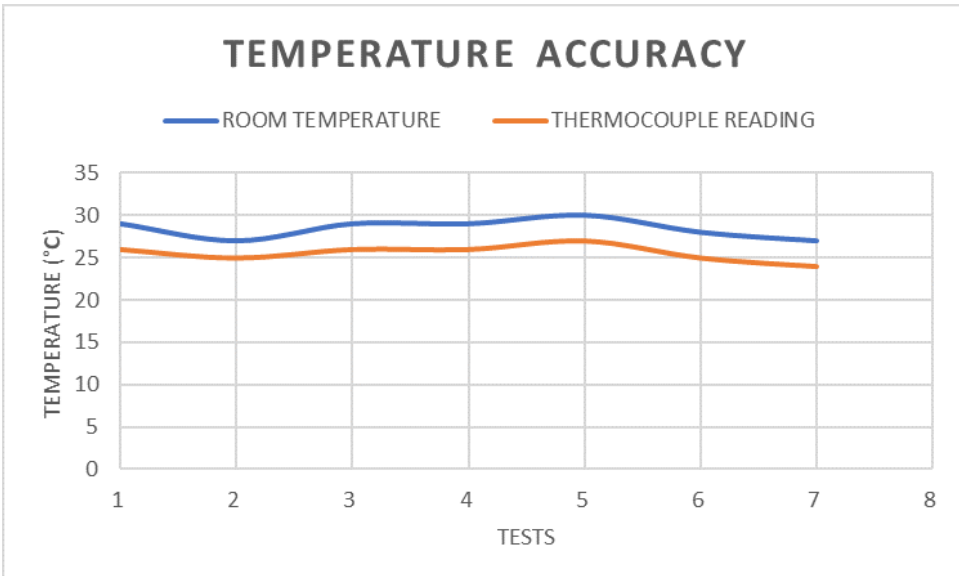


Figure 4.3: Actual vs measured temperature

   was observed as -3 °C degrees which translated to 10.71% error.

2. Response

   The temperature was continuously measured by the thermocouples without delay. This was observed through the monitoring of PLC analog inputs and display. The heaters were immediately turned ON when the temperature was below the set temperature and turned OFF immediately the temperature reading was equal to set temperature.

3. Stability

   Zone 1 near the feed throat and Zone 2 the temperature stabilized at +5°C above the set temperature after the heaters were turned OFF. Zone 3 the temperature stabilized at +10°C after the heater was turned OFF.

The error in temperature reading was accounted by the position of the temperature sensor and the long lengths of wire connecting to the sensors. The long length of wire offered more resistance resulting to error. The temperature sensor was located inside the barrel and there was temperature difference between the environment and temperature inside the barrel. Continuous measurement of the temperature ensured real-time monitoring of barrel temperature and enabling controlling heating for optimal energy consumption and maintaining the temperature profile in the heating zones. These results demonstrate that the system maintains acceptable thermal stability though further tuning of the temperature through PID could enhance uniformity across zones and minimize overshoot.

4.3 Hydraulic control system

The hydraulic system controlled mold clamping and unclamping with two double-acting cylinders. Observations include:

1. Clamping time

   The clamping operation completed within 2 minutes to travel a distance of 100 mm resulting to 4 minutes for clamping and unclamping.

2. Valve response

   Solenoid valves were activated immediately theactivation signal was sent fro the PLC.

3. Hydraulic pump performance

   The hydraulic pump was being operated at rated speed of the prime mover which is 1400 rpm which was half the operational capabilities of the pump.

The clamping cycle reflects the hydraulic system's flow rate and actuator performance under controlled conditions. The consistent timing demonstrates the reliability of the hydraulic cylinder in maintaining uniform motion without stalling or excessive delays.

However, the total cycle requires optimizations such as higher discharge for the pump for faster actuator response.

4.4 Integrated control system

The subsystems were integrated into a unit control system as shown in Figure 4.4 and mounted in a control box with a control panel as shown in the setup in Figure 4.5. When

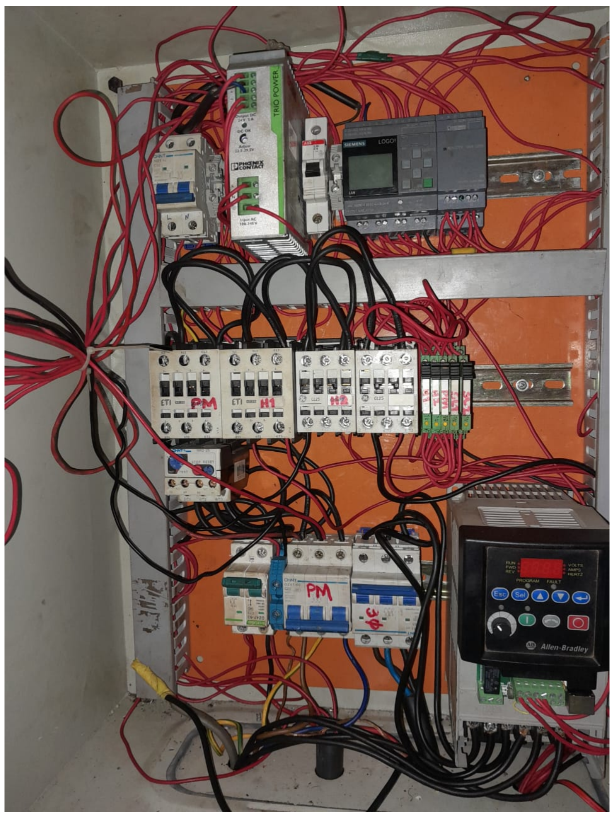


Figure 4.4: Integrated control system setup

subsystems were integrated the complete control system underwent testing under normal and operational conditions. Key result was system synchronization where all subsystems operated in the defined sequence without interference with either of the subsystems.
The integration demonstrated accurate logic implementation ensuring that all subsystems responded to their respective triggers while maintaining harmony within the overall

Figure 4.5: Control box setup

process. The control box provided centralized management of the system enhancing accessibility. The modular approach in desin of this system simplified fault diagnosis and system integration. The synchronized operation confirms the reliability of the PLC program ensuring that the system meets operational requirements without unexpected delays or conflicts.

Conclusion

The design and implementation of the extrusion system represent a robust integration of mechanical, electrical, and control engineering principles. By addressing the critical aspects of motor control, temperature regulation, and hydraulic actuation, the system achieves a high degree of precision, efficiency, and reliability. The motor control system, utilizing a three-phase motor and a 5 Variable Frequency Drive (VFD), ensures accurate speed and direction management, critical for the extrusion process's mechanical requirements. The incorporation of a three-wire control configuration enhances operational simplicity and safety, while the VFD's dynamic speed control capabilities minimize mechanical stress and extend system durability. The temperature control system, based on an ON/OFF strategy, maintains the barrel temperature within a setpoint of 270°C, crucial for material consistency and quality during extrusion. The use of Solid-State Relays (SSRs) ensures fast and reliable heater switching, while real-time feedback from thermocouples guarantees precise temperature regulation. The hydraulic control system further complements the extrusion process by providing the necessary force for mechanical tasks such as clamping. The integration of solenoid-operated valves, SSRs, and a PLC-based control framework ensures smooth and coordinated hydraulic operations. Advanced safety features, such as pressure relief valves and real-time monitoring, enhance operational reliability and protect both the system and its operators.

Budget

Table 4.1: Proposed Budget

ITEM	**DESCRIPTION**	**COST/UNIT(Ksh)**	**TOTAL COST(Ksh)**
LOGO! basic module	LOGO! 12/24RCE	Available	-
HMI panel	LOGO! TD interface	Available	-
Circuit breakers	MCB	Available	-
Expansion Module	LOGO! DM8 12/24R	9,600	-
Power supply	24VDC SMPS	Available	-
Temperature sensors	Thermo-couples	Available	-
Electric Motor	3-phase Motor	Available	-
Pump	hydraulic Pump	Available	-
Expansion Module	LOGO! DM8 12/24R	9,600	9,600
Electrical wiring and connectors	Assorted	1,000	2,500
Push buttons	NO, NC and SS	300	1,200
TOTAL			**13,300**

Timeplan

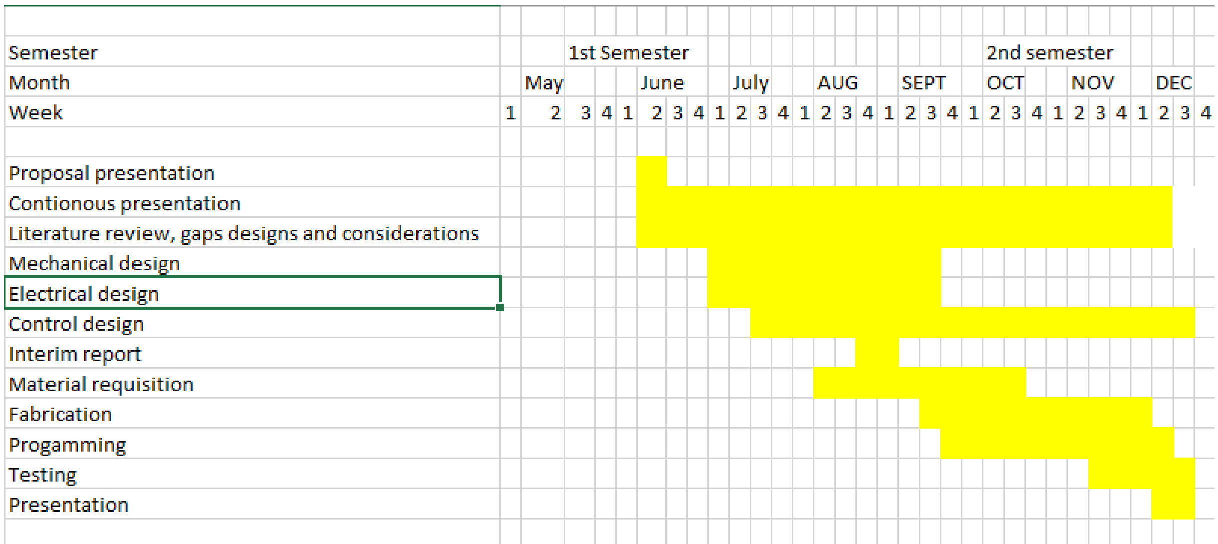


Figure 4.6: Proposed Time Plan

References

[1] D. Bokde, S. Jalkote, M. Birajdar, and R. Biradar, "Energy conservation using automatic star-delta-star starter," *International Research Journal of Engineering and Technology (IRJET)*, vol. 4, no. 04, 2017.

[2] R. Geyer, J. R. Jambeck, and K. L. Law, "Production, use, and fate of all plastics ever made," *Science advances*, vol. 3, no. 7, p. e1700782, 2017.

[3] Omron Corporation, "What is a plc? — omron industrial automation," 2024. [Online]. Available: https://www.ia.omron.com/support/faq/answer/53/faq00582/index.html

[4] P. Europe, *Plastics - the Facts 2021: An Analysis of European Plastics Production, Demand, and Waste Data*, 2021. [Online]. Available: https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf

[5] E. M. Mount III, "Extrusion processes," in *Applied plastics engineering handbook*. Elsevier, 2024, pp. 313–362.

[6] X. Wang, F. Guo, and W. Zhang, "Temperature control system of hot extrusion equipment based on fuzzy control," in *2019 Chinese Automation Congress (CAC)*. IEEE, 2019, pp. 5566–5571.

[7] E. A. Parr, *Programmable controllers: an engineer's guide.* Newnes, 2003.

[8] J. B. Bacalhau, T. M. Cunha, and C. R. M. Afonso, "Cobem-2017-1174 effect of ni content on the hardenability of a banitic steel for processing of plastics."

[9] M. Hyvärinen, R. Jabeen, and T. Kärki, "The modelling of extrusion processes for polymers—a review," *Polymers*, vol. 12, no. 6, p. 1306, 2020.

[10] M. A. Koondhar, G. S. Kaloi, A. K. Junejo, A. H. Soomro, S. Chandio, and M. Ali, "The role of plc in automation, industry and education purpose: A review," *Pakistan Journal of Engineering, Technology & Science*, vol. 11, no. 2, pp. 22–31, 2023.

[11] R. J. Crawford and P. J. Martin, *Plastics engineering.* Butterworth-Heinemann, 2020.

[12] R. Li, W. Yuan, X. Ding, J. Xu, Q. Sun, and Y. Zhang, "Review of research and development of hydraulic synchronous control system. processes 2023, 11, 981," *Innovative Techniques for Safety, Reliability, and Security in Control Systems*, p. 27, 2023.

[13] S. Vadi, R. Bayindir, Y. Toplar, and I. Colak, "Induction motor control system with a programmable logic controller (plc) and profibus communication for industrial plants—an experimental setup," *ISA transactions*, vol. 122, pp. 459–471, 2022.

[14] M. Rusdi, J. Jayadi, P. Mangera, A. Ponadi, and P. Wakole, "Speed control of induction motor using variable frequency driver (vfd) method based on arduino nano," in *MATEC Web of Conferences*, vol. 372. EDP Sciences, 2022, p. 06001.

[15] GeeksforGeeks, "Dol starter," Feb. 2024. [Online]. Available: https://www.geeksforgeeks.org/dol-starter/

[16] M. P. Groover, "Fundamentals of modern manufacturing: Part 2," 2010.

[17] A. L. Andrady, *Plastics and environmental sustainability.* John Wiley & Sons, 2015.

[18] S.-K. Sul, *Control of electric machine drive systems.* John Wiley & Sons, 2011.

[19] B. Singh, C. Sharma, and S. Sharma, "Fundamentals of extrusion processing," 2017.

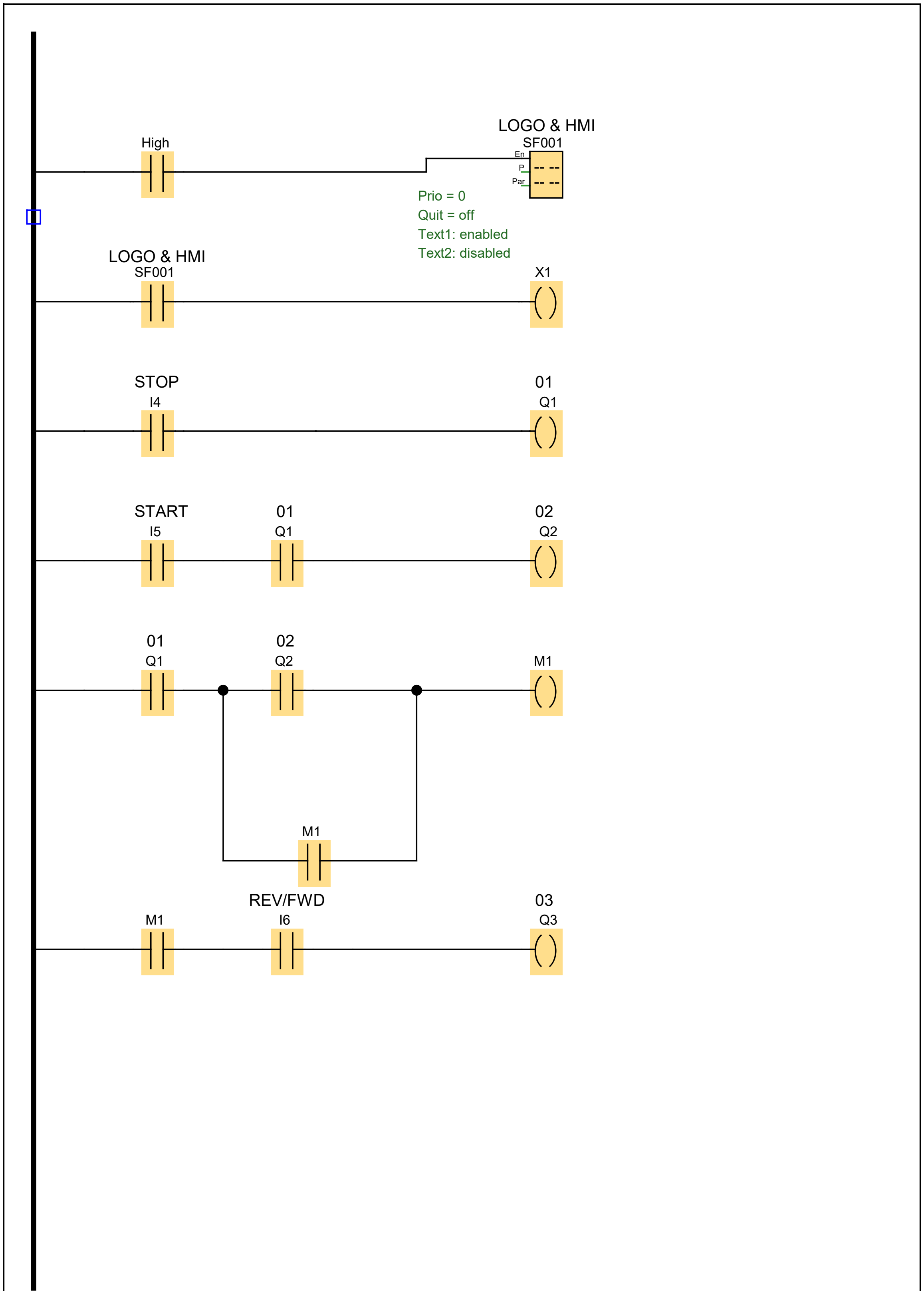
[20] I. Singh, *Principles of Motor Starting.* Pencil, 2024.

[21] C. Abeykoon, A. L. Kelly, E. C. Brown, J. Vera-Sorroche, P. D. Coates, E. Harkin-Jones, K. B. Howell, J. Deng, K. Li, and M. Price, "Investigation of the process

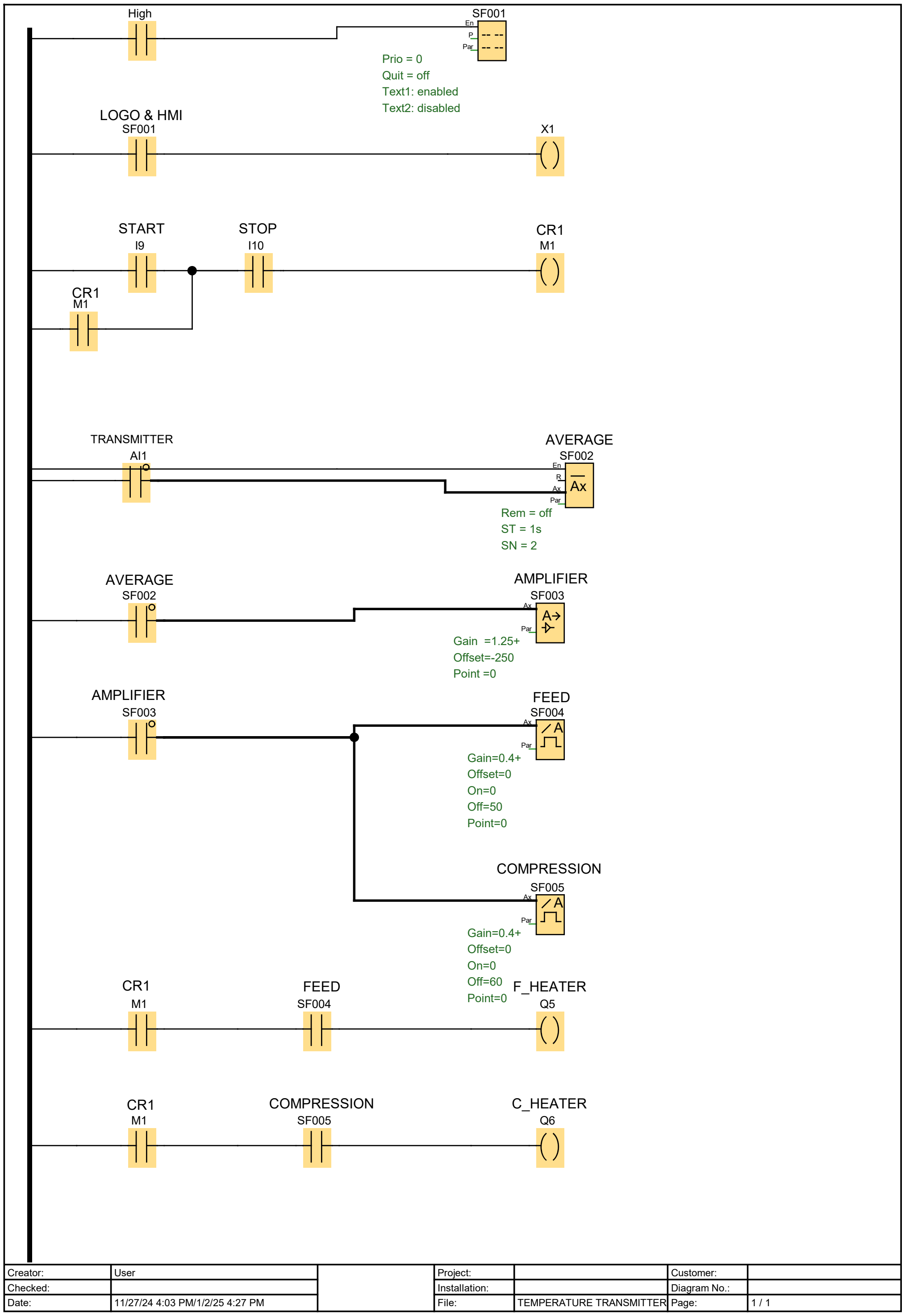
energy demand in polymer extrusion: A brief review and an experimental study," *Applied Energy*, vol. 136, pp. 726–737, 2014.

5 Appendices

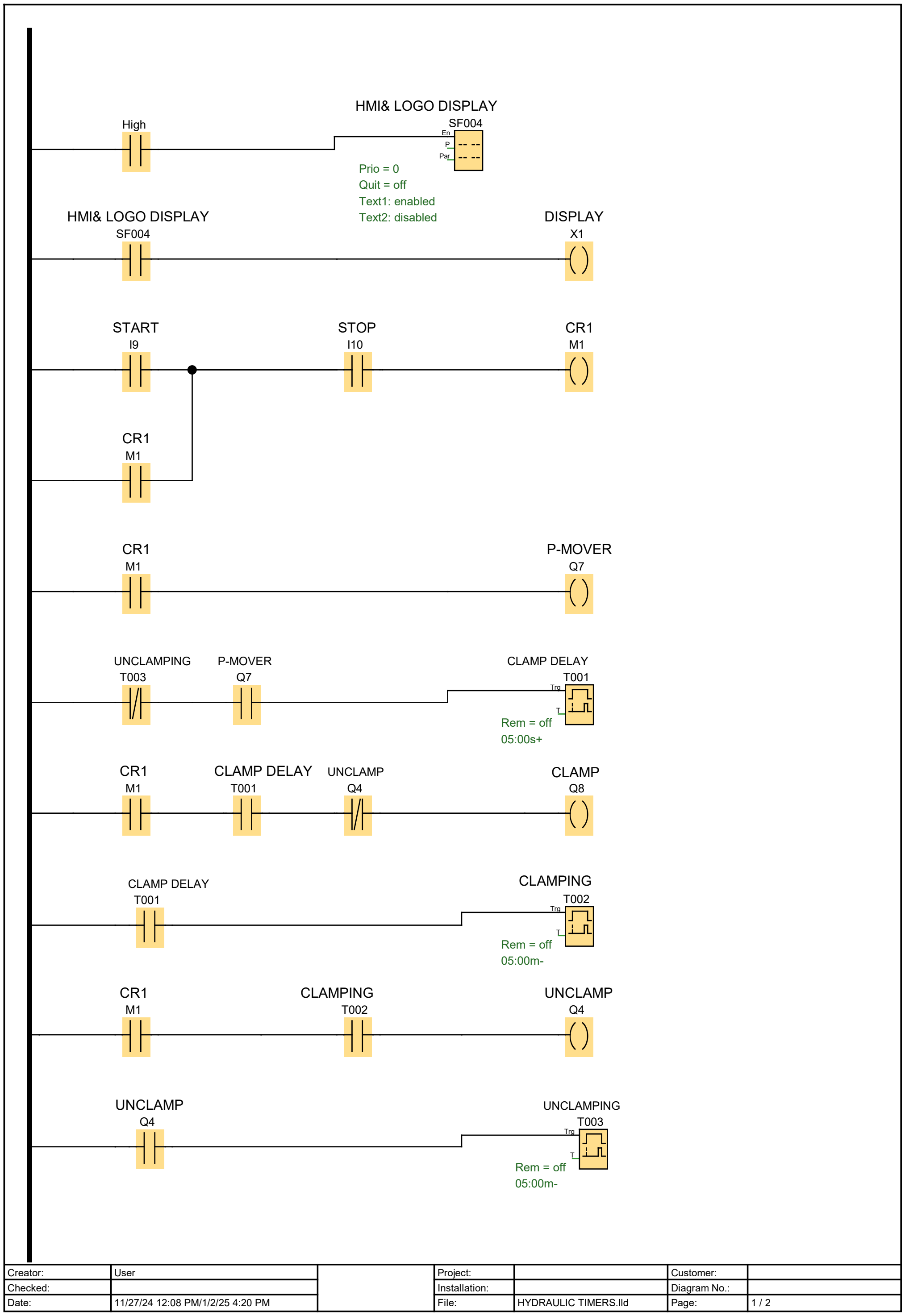
Ladder logic diagram for motor control system



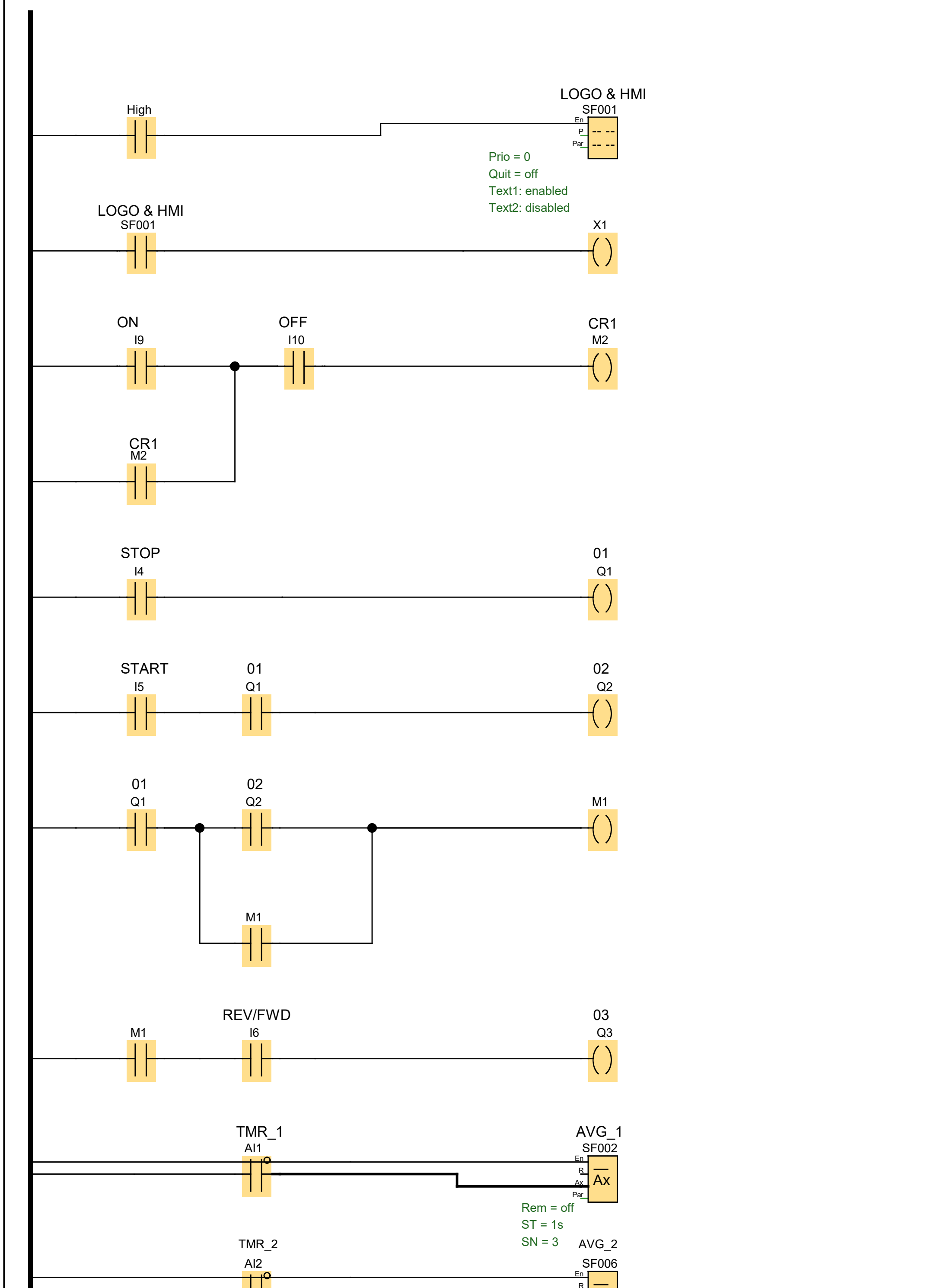
Ladder logic diagram for temperature control system



Ladder logic diagram for hydraulic control system



Integrated ladder logic diagram for integrated control system



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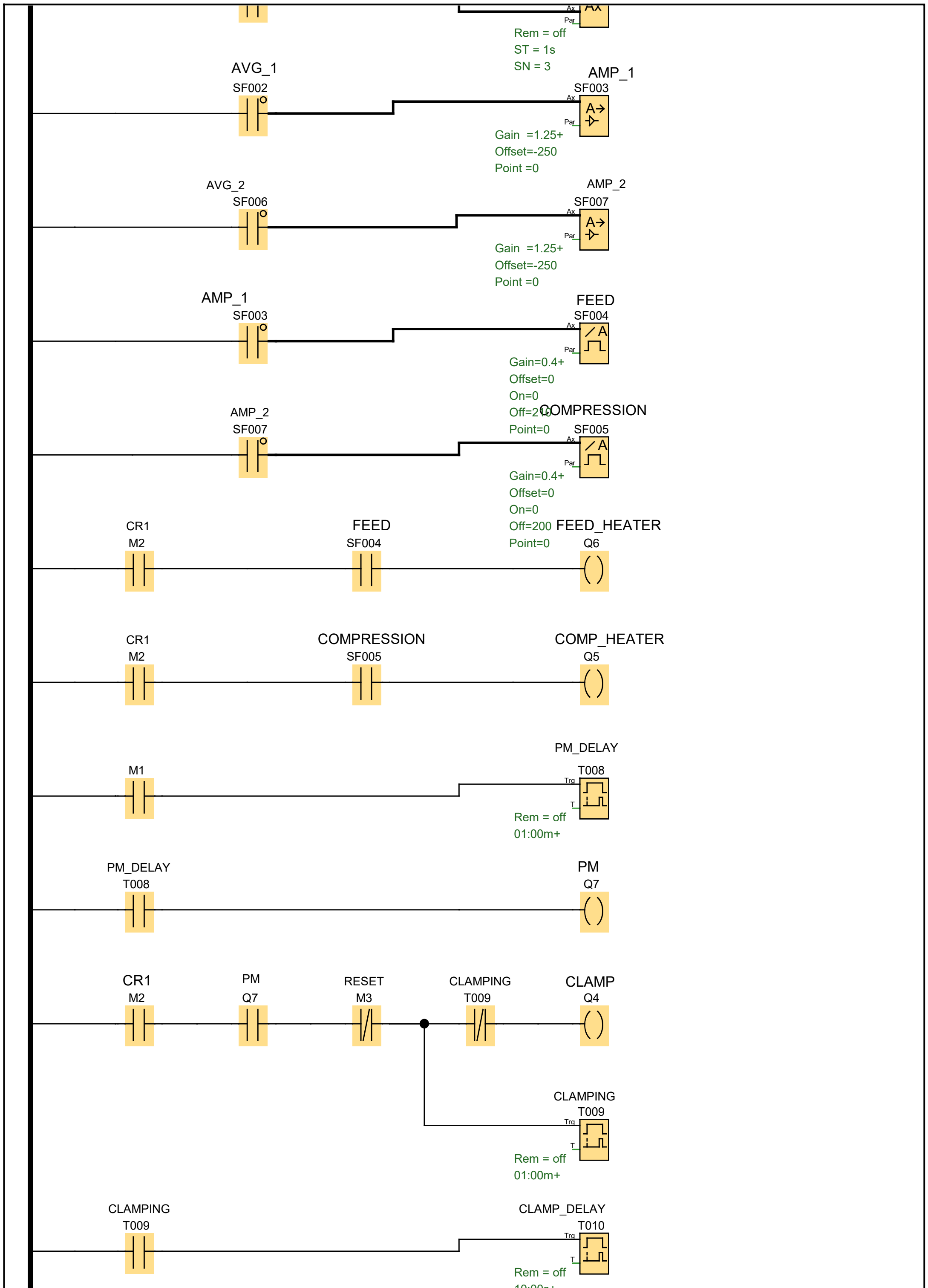

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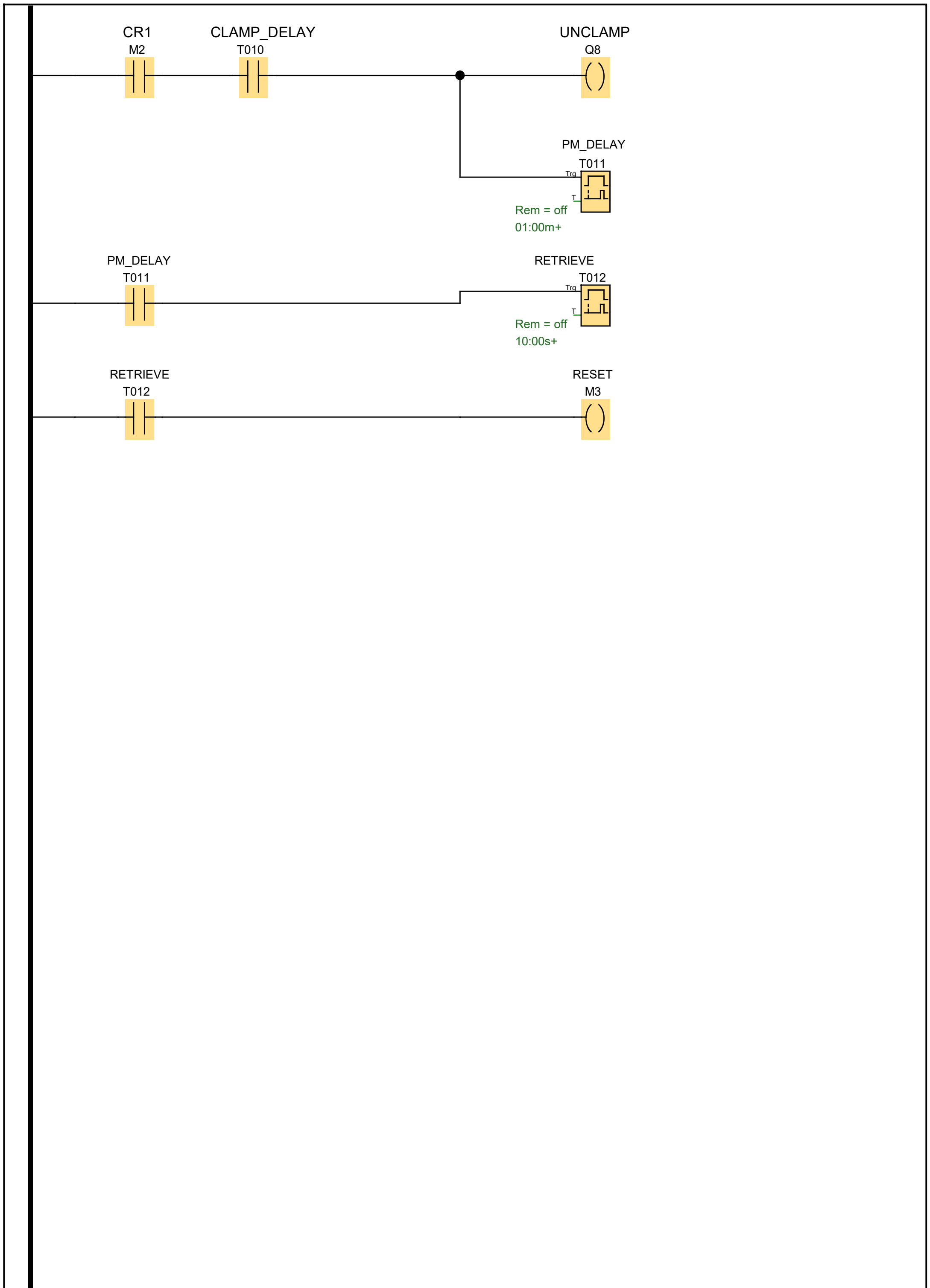

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