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Research article

Automatic Switching System for Submersible Motor Pump: Case Study of a Cocoa Processing Company in Ghana

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Abstract: Cocoa processing companies are pivotal to Ghana's economy and the sustainability of its cocoa industry. Cocoa processing companies transform raw cocoa beans into a paste-like form known as cocoa liquor, which serves as the foundation for various cocoa-based products. These operations require using pumps to supply water for different stages of production. Most of these companies are particularly concerned about potential pump failures and the associated costs of replacements. To mitigate this risk, they have developed a technique to protect the pumps from burnout. Currently, the existing pump protection system is manually operated and suffers from inaccuracies in switching times. Additionally, fluctuations in weather conditions pose further threats to the pumps' integrity. This research focuses on automating the pump protection system to address these issues effectively. In this project, a Programmable Logic Controller (PLC) was utilized to design an automated protection system. The control program was simulated using RSLogix Micro Starter Lite to verify its functionality. Simulation results demonstrated that the system provides effective automatic protection for the pumps, thereby enhancing their operational efficiency and equipment longevity.

Keywords: Programmable Logic Controller, RSLogix Micro Starter Lite, automatic pump protection, control systems

1. Introduction

Cocoa processing is a cornerstone of Ghana's economy, playing a pivotal role in its agricultural and industrial sectors. As the world's second-largest producer of cocoa, Ghana's reliance on this commodity is profound, with cocoa bean exports contributing $1.48 billion, an increase of 2.0% year-on-year in 2020 [1]. The cocoa industry is not only a major revenue generator but also a vital source of employment. It directly supports the livelihoods of over 800,000 farmers and indirectly benefits millions more through related industries such as transportation, marketing, and processing. The revenues from cocoa exports enable the government to invest in essential sectors like education, healthcare, and infrastructure, thereby fostering national development. Despite its critical importance, Ghana's cocoa processing sector faces significant challenges that threaten its sustainability and profitability [2], [3]. Recent reports indicate that cocoa processing units have been forced to shut down intermittently due to a shortage of beans. Major processors, including Cargill Inc., Cocoa Processing Co. Ltd., and Niche Cocoa Ghana Ltd., have experienced operational disruptions, highlighting vulnerabilities within the supply chain.

The decline in cocoa production can be attributed to several factors, including adverse weather conditions, the prevalence of diseases such as the cacao swollen-shoot virus, and economic challenges faced by farmers [2], [4], [5]. Notably, despite record cocoa prices in 2024, many farmers have resorted to uprooting their cocoa plants in favor of more lucrative crops like oil palm. This shift is driven by inadequate government support, fixed farmgate prices that limit farmers' earnings, and the high costs associated with maintaining cocoa farms. In the face of these challenges as well as sporadic energy supply, cocoa processing companies need to enhance their operational efficiency and resilience [6]. One critical aspect of this endeavor involves the maintenance and protection of essential equipment, such as motor pumps, which are integral to various stages of cocoa processing. Motor pumps are extensively utilized across industries in Ghana, including cocoa processing, to facilitate essential services such as water supply [7], [8]. However, the continuous operation of these pumps without appropriate safeguards can lead to overheating and eventual burnout, especially when water levels are insufficient to provide the necessary cooling.

Several cocoa processing companies rely on submersible motor pumps to extract water from underground sources into reservoirs, supporting various processing activities. During periods of low underground water levels, the pumps may operate without adequate water flow, leading to overheating. This overheating occurs because the water serves as a coolant for the motor; without it, the motor becomes exposed to heat accumulation, increasing the risk of damage. Research indicates that operating pumps without sufficient water flow can result in bearing failures, as the bearings are typically water-lubricated [9], [10]. Additionally, prolonged operation can cause sand entrapment within the pump, leading to clogs and subsequent overheating [11], [12]. To mitigate these risks, most of these companies have implemented a manual intervention strategy, assigning technicians to switch the pumps on or off every three hours. While this approach aims to preserve pump integrity and reduce costs, it is labor-intensive and susceptible to human error, particularly concerning the accuracy of switching times [13]. Moreover, external factors such as fluctuating weather conditions can worsen the challenges associated with manual pump operation.

Variations in rainfall and temperature can unpredictably affect underground water levels, making it difficult for technicians to determine optimal pump operating schedules [14]. This unpredictability, which is common in sub-Saharan Africa, increases the likelihood of either overworking the pumps during low water periods or underutilizing them when water is abundant, both scenarios leading to inefficiencies and potential equipment damage [15]. To address these issues, there is a compelling need to transition from manual to automated pump control systems. Much research has been done on the control and automation of pumps in the food industry. In [16], the authors focus on the development of an automated dispatch control system for pump units at water pumping stations. The study emphasizes the importance of unified hardware and software tools, incorporating PLCs, frequency converters (FCs), and Supervisory Control and Data Acquisition (SCADA) systems. The proposed system aims to enhance the efficiency and reliability of water supply operations by implementing effective algorithms and application software based on contemporary information technologies. While the research provides a comprehensive framework for water pumping stations, it does not specifically address applications in other industries, such as cocoa processing.

The authors in [17] presented a practical example of submersible pump control using a combination of PLCs and Variable Frequency Drives (VFDs). The integration of these devices, along with field measuring instruments, forms a cohesive system capable of control, supply, protection, and monitoring of processes driven by induction motors. The study provides detailed insights into the description of electrical devices, signal processing, and operational principles. However, the focus is primarily on the technical implementation, with limited discussion on the broader implications for industrial applications or specific sectors. In [18], the author explored the design and implementation of an automated water pump system aimed at regulating water distribution based on real-time data and conditions. The system utilizes sensors and control algorithms to reduce energy consumption and water wastage while ensuring efficient distribution. The research highlights the advantages of automated systems over traditional manual operations, including increased efficiency and resource conservation. Nonetheless, the study lacks a focus on specific industrial applications, such as the cocoa processing industry, where water usage and pump protection are critical.

A control system designed to prevent dry running in pumps by monitoring water levels and controlling pump operations accordingly was the focus of the authors [19]. The system employs sensors to detect water levels in overhead and underground tanks, ensuring that the pump operates only when necessary. The implementation aims to conserve electrical energy, protect the pump from damage due to dry running, and prevent water wastage. While the study offers valuable insights into pump protection mechanisms, it primarily addresses domestic or small-scale applications rather than large-scale industrial contexts. The research in [20] describes a PLC-based control system designed for managing pressure in multi-pump applications. The study presents a mathematical model of the pumping process, focusing on variables such as flow rate, head, and brake power on the pump shaft. The implementation aims to optimize the efficiency of multi-pump systems through precise control mechanisms. While the research offers valuable insights into pressure control and pump efficiency, it does not specifically address pump protection strategies or applications within the cocoa processing industry.

The reviewed literature provides a deep insight into automated pump control and protection systems across various industrial applications. However, there is a lack of research focusing on the implementation of automated pump protection systems within specific food industries, such as cocoa processing, especially in Sub-Saharan Africa. Industry-specific studies address unique challenges and operational requirements that are peculiar to that sector. The adoption of automated systems aligns with the broader objective of enhancing the resilience and efficiency of Ghana's cocoa processing industry. By safeguarding critical equipment through technological advancements, companies can maintain continuous operations, even amidst external challenges such as raw material shortages or environmental fluctuations. This operational stability is essential for meeting both domestic and international demand for processed cocoa products, thereby sustaining the industry's contribution to Ghana's economy. The research objectives of this paper will be:

- To design an automated pump protection system using a Programmable Logic Controller (PLC) to enhance system accuracy and responsiveness.
- To develop a control program for the automated protection system and simulate its functionality using RSLogix Micro Starter Lite.

The proposed automated pump protection system builds upon existing manual protection methods by eliminating inaccuracies in switching times, reducing human intervention, and improving response efficiency. Traditional pump protection in cocoa processing companies relies on manual monitoring and operation, which introduces delays and potential errors that can lead to premature pump failures, higher maintenance costs, and increased downtime [7], [21], [22]. These systems are also ineffective in adapting to environmental fluctuations, such as temperature and humidity variations, which can impact pump performance [23], [24]. Unlike existing methods, the proposed system leverages a Programmable Logic Controller (PLC) to automate pump control, ensuring real-time adjustments and precise activation and deactivation of pumps based on predefined operational parameters. By integrating RSLogix Micro Starter Lite for simulation, the system is validated before deployment, reducing implementation risks. Additionally, the automated approach enhances energy efficiency by optimizing pump operation, minimizing unnecessary power consumption, and extending equipment lifespan. A key differentiator is the system's adaptability to changing weather conditions, which existing manual systems fail to address effectively. Through programmed logic, the PLC can adjust pumping schedules and flow rates dynamically, preventing overheating, cavitation, and wear due to fluctuating environmental factors. Moreover, by reducing labor dependency and operational delays, the system improves overall productivity, ensuring uninterrupted cocoa processing.

2. Methods

In the current operational framework, technicians are required to oversee and regulate the submersible pump every three hours manually. However, field observations indicate that the underground water level does not consistently decline to critical levels within this interval, leading to unnecessary interventions. Additionally, seasonal variations, such as rainfall and dry periods, render this fixed monitoring schedule inadequate for ensuring the pump's optimal performance and longevity. To address these challenges, an automated system was designed to manage the submersible pump's operations with minimal manual oversight. This system employs a level sensor to continuously monitor the underground water level, transmitting real-time data to a central control unit. Based on predefined thresholds, the control unit activates or deactivates the pump, initiating operation when water levels rise and ceasing function when levels fall below safe operating conditions.

2.1. Components for the Proposed Design

The integration of this automated solution not only enhances the efficiency of water resource management but also safeguards the pump against potential damage due to dry running or overuse. By adapting to actual water level fluctuations rather than relying on rigid time-based schedules, the system ensures a more responsive and protective approach to pump operation. The accompanying block diagram in Figure 1 illustrates the architecture of the proposed system, detailing the interaction between the level sensor, control unit, and submersible pump.

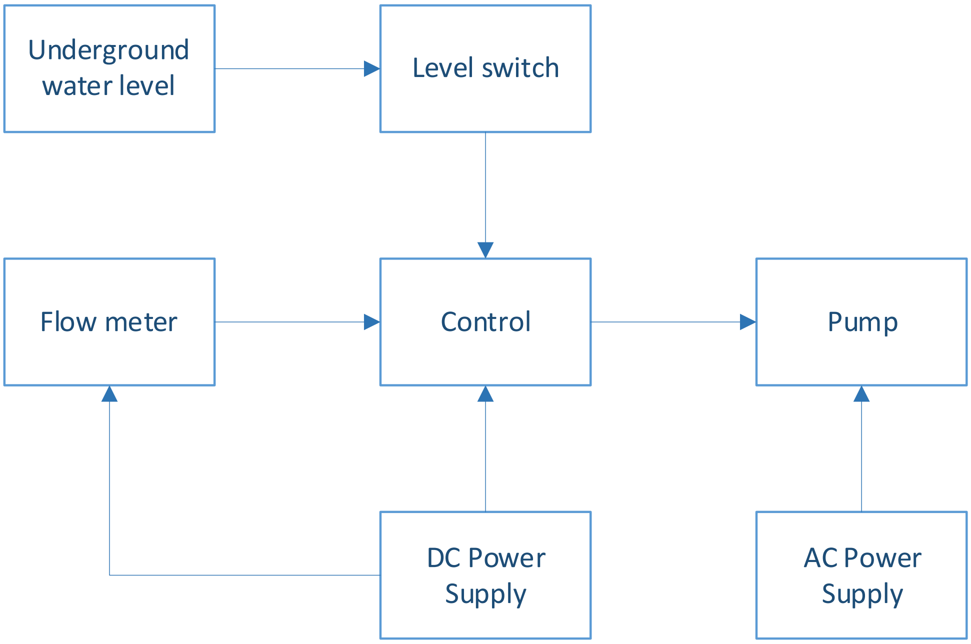


Figure 1. System's block diagram.

2.1.1. Pump

When selecting a pump for a specific application, it is essential to consider both the required flow rate and the pressure head. The total dynamic head determines the operational flow rate of each pump. For applications necessitating higher flow rates, typically between 25 and 100 cubic meters per hour, at a head of approximately 10 to 30 meters, a centrifugal submersible pump is appropriate [25], [26]. These pumps are commercially valued for their capability to move substantial volumes of water efficiently, making them suitable for such requirements.

In the current system, a 2-inch 2SR Submersible Centrifugal Pump is utilized. Based on data collected from the company's field technicians, the specifications of this existing pump are outlined in Table 1. The Total Dynamic Head (TDH) of the submersible pump is calculated using Equation 1, and the schematic diagram is shown in Figure 2.

$$TDH = P_l + H_v + F_p + F_v \tag{1}$$

This is the difference between the suction pressure and the discharge pressure while the pump is in operation. In simple terms, it is the amount of pressure difference created by a pump as it operates. It is an important parameter to determine the amount of work to be done by the pump to move water from the source to a discharge point.

Table 1. Existing pump specifications.

Item	Specification
Discharge port	2-inch (5.08 cm)
Pumping depth	15 m
Rated flow rate	40±20% l/min
Pumping liquid	Water
Operating speed	90 rpm
Liquid temperature	Up to 35°C
Rated operating voltage (3-phase)	400 V / 50 Hz
Maximum sand content	20 g/m^3

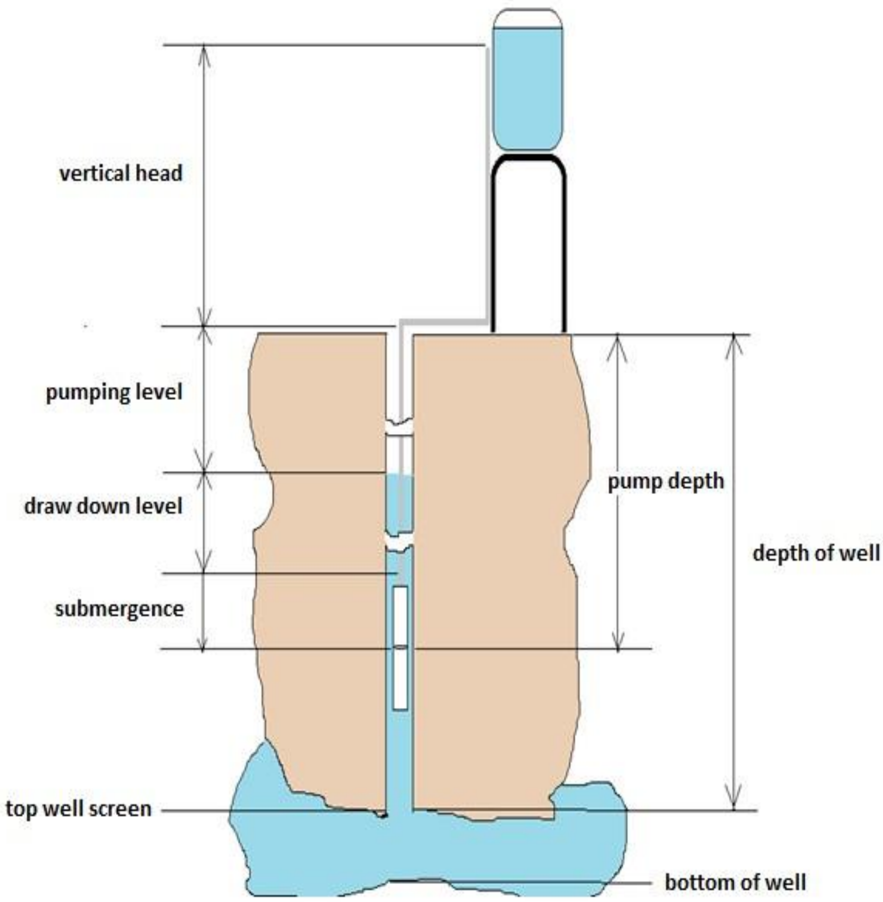


Figure 2. Schematic diagram of the total dynamic head of a submersible pump.

2.1.2. Relay

A 12 V DC coil power relay, single pole double throw (SPDT) relay, is considered for the design as shown in Figures 3 and 4. It has simple constructional properties and a simple operating principle, and it is less expensive than the others. Its operating principle is by electromagnetic attraction. The relay forms the control circuit and it controls the load circuit [27]. When the control switch is turned ON, current starts to flow through the coil, which produces a magnetic field to attract the armature, hence activating the load circuit. From Figure 3, when the relay switch is closed, the coil gets magnetized to pull the armature, which will then close the load circuit to turn on the bulb. The same principle applies to Figure 4, but in this case, the bulb goes off.

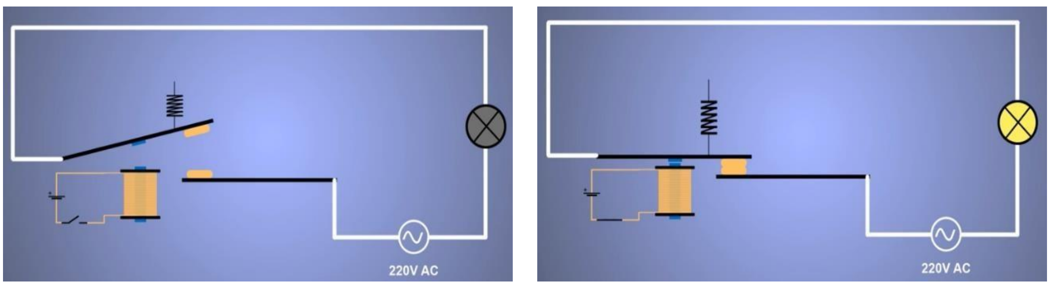


Figure 3. Operating principle of electromagnetic - attraction type relay: Normally Opened.

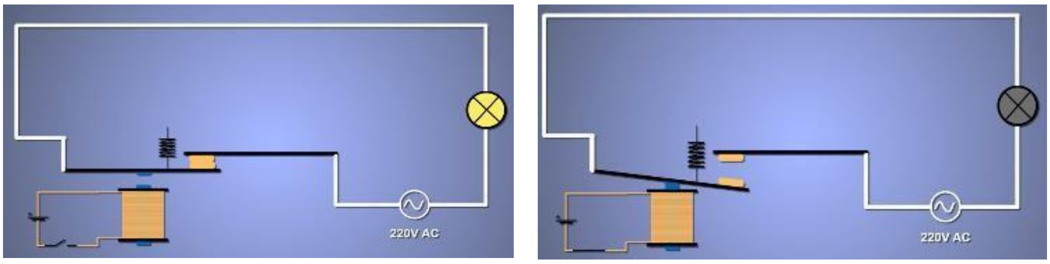


Figure 4. Operating principle of electromagnetic - attraction type relay: Normally Closed.

2.1.3. Flow Meter

Figure 5 shows an image of a YF-S201 Hall Effect water flow sensor, which is considered for the design. It has a digital display, making reading of values simpler. Compared with the other flow meters, it is very reliable for determining the flow rate [28], [29]. This flow meter type has an embedded flow sensor/switch that allows a predetermined flow rate value to be set in order to match that of the pump. Below this predetermined set value, a tripping signal will be sent to the control circuit to shut down the pump.

Figure 5. YF-S201 Hall effect water flow sensor with digital LCD controller.

In selecting a pipe for this design, Chlorinated Polyvinyl Chloride (CPVC) was chosen due to its superior properties compared to other materials such as Polyvinyl Chloride (PVC), Unplasticized Polyvinyl Chloride (UPVC), Cross-Linked Polyethylene (PEX), brass, cast iron, and galvanized pipes. An EL series conductivity level sensor (switch) is selected for the design. Its principle of operation is by conduction. According to [30], its electrodes are stainless steel, which makes it resistant to corrosion. It has a withstand temperature of -10 °C to 120 °C and is suitable for underground applications. It also has a waterproof circuitry housing protecting the conductors from making contact with water. An AC 220 V 16 A digital programmable time counter switch is considered for the design. It is a normally closed switch that opens after the set counting time is up. The proposed design is to keep the submerged pump running at the initial stage when the start button is engaged for the set time (60 seconds). After the pump has taken up its maximum speed in 60 seconds, the time counter switch opens. The flow meter (sensor/switch) and relay switch need a direct current (DC) supply for their respective operations. Hence, the UPG UB1250 Sealed Lead Acid (SLA) Battery Combo + Charger, as seen, is selected for the design. It is a 12V DC lead-acid battery, inexpensive and portable, and its rechargeability makes it suitable for the design [31].

2.2. Design Setup

Figure 6 shows the schematic diagram of the proposed design. Regarding Figure 5, the pump depth (position of the motor in the pump) is the sum of the pumping level, draw-down level, and submergence and is given by Equation 2.

$$P_d = L_p + L_d + S \tag{2}$$

where P_d represents the pump depth, L_p is pumping level, L_d is draw down level and S is the submergence.

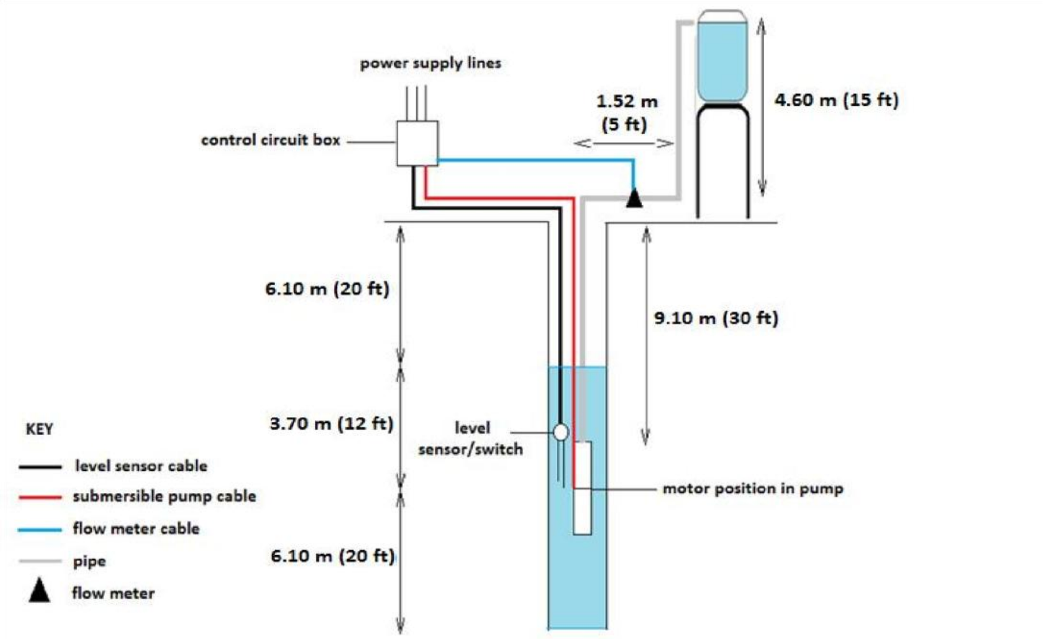


Figure 6. Diagram of the proposed design.

From Figure 7, the level sensor/switch is positioned at the pump depth (the actual position of the motor) to open the circuit when the motor is exposed. Hence, the predetermined level for the pump switching is 9.8 m below ground level.

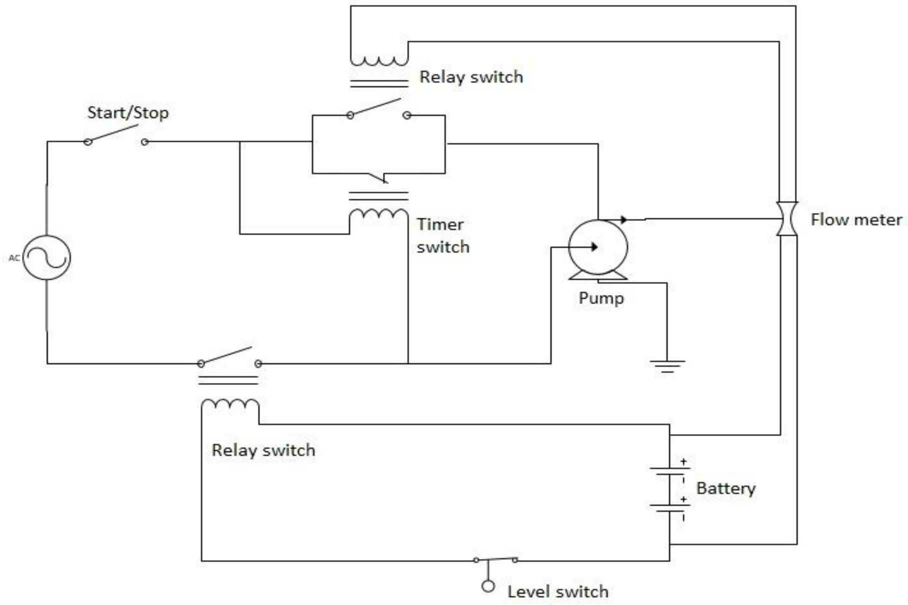


Figure 7. Circuit representation for the proposed design.

2.3. System Flow Chart and Ladder Logic

Figure 8 shows the flow chart, which is developed to create a representation of the sequence of operations that are carried out to define the logic basis for the programming. After the system is initialized, the level sensor/switch checks the water level and whether it is at the predetermined level. If it is false, the system ends the process. If it is true, then the pump is started. The flow rate is measured afterward by the flow meter to see whether it is within the set range. If the information is false, the pump is stopped and the process ends. But if it is otherwise, the system keeps running and the process ends. To test the validity of the program and its response to water level conditions, a simulation of the PLC program was carried out. The PLC ladder logic for the proposed protective system was developed using RSLogix Micro Starter Lite. It is a programmable package compatible with Rockwell Software. Figure 9 illustrates the user interface of RSlogix Micro Starter Lite, while Figure 10 shows the ladder logic of pre-automation process in running mode.

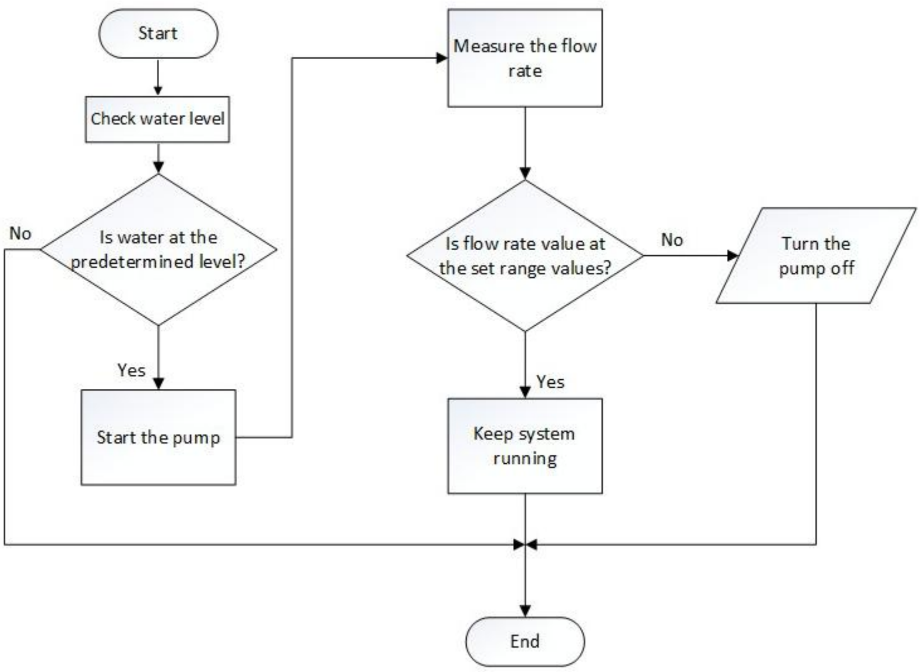


Figure 8. Flowchart of the proposed design.

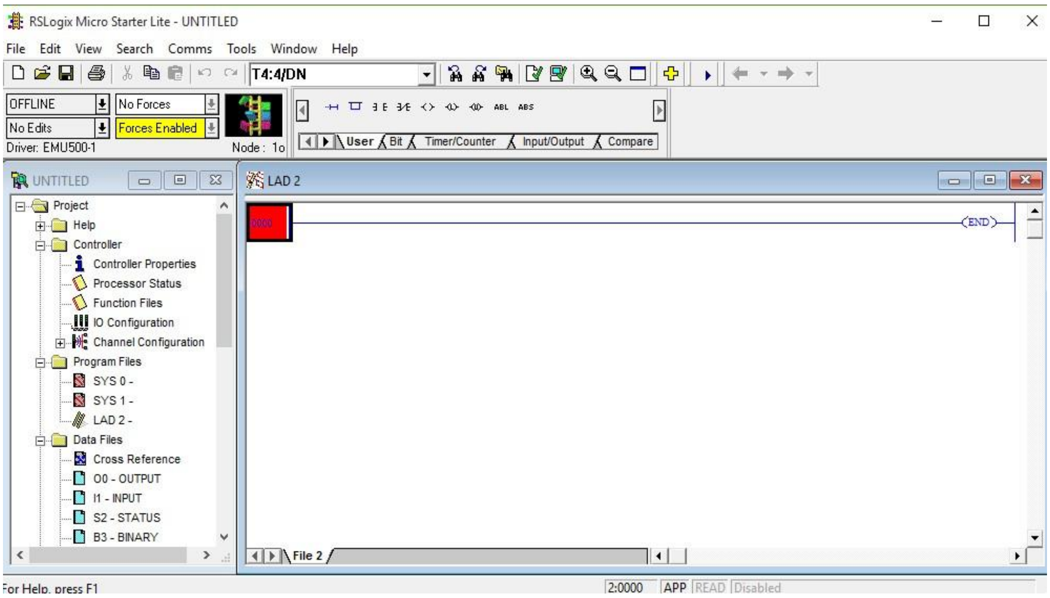


Figure 9. RSLogix Micro Starter Lite user interface.

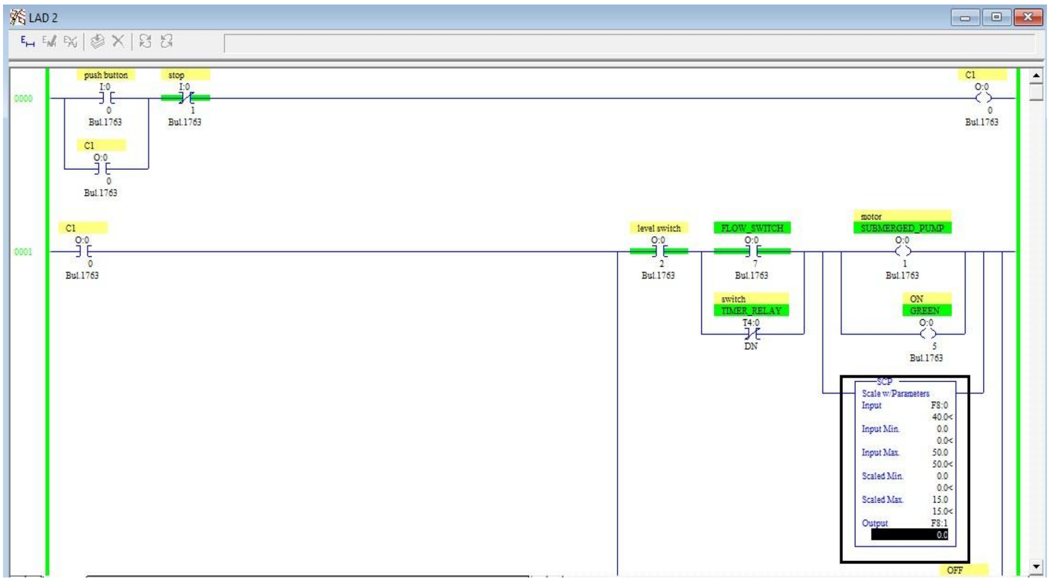


Figure 10. Ladder logic of pre-automation process in running mode.

3. Results and Discussion

Before the system starts, the pushbutton must be engaged. This causes the contactor C1 to energize and close any contact C1, as shown in Figure 11. At the initial stage, the level switch electrodes make contact with the well water at the predetermined level, which activates the level switch, as shown in Figure 12. The contact C1, the level switch contact, the timer switch contact, and the submerged pump form a complete closed circuit. This causes the pump to start running, as seen in Figure 13.

Figure 11. Submerged pump in running mode after pushbutton is engaged.

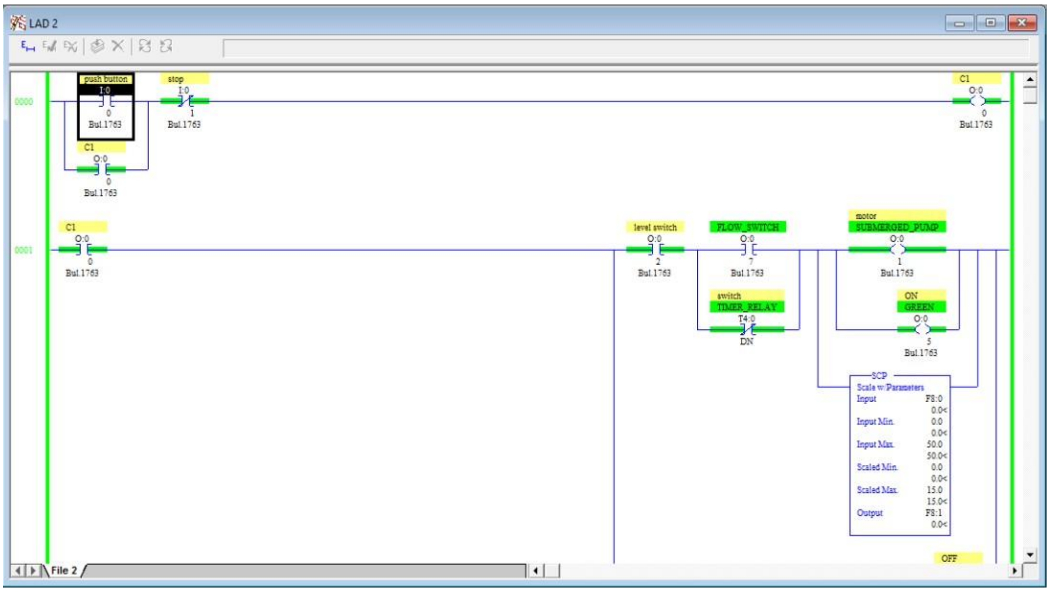


Figure 12. High water level detection by level switch electrodes.

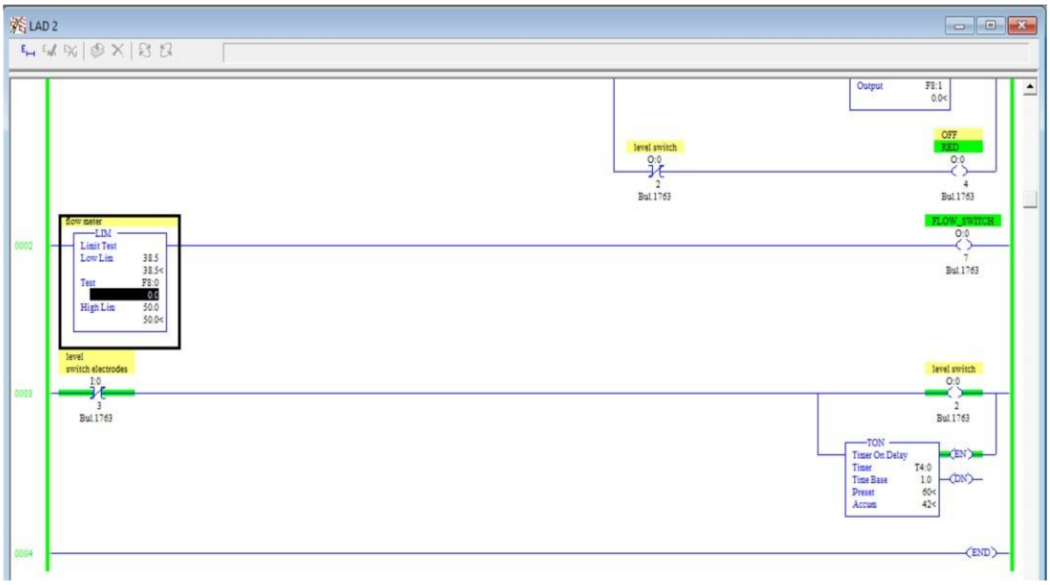
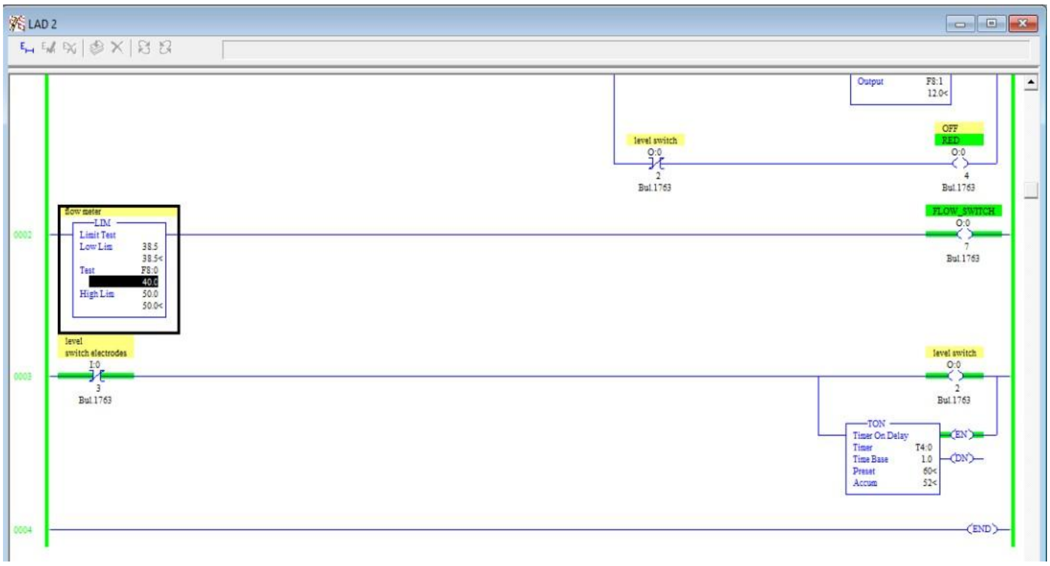


Figure 13. Activated flow switch.



The timer on delay (TON) holds the timer relay switch in closed mode for 1 minute (60 seconds) for the pump to pick up speed. In Figure 13, the initial flow rate value recorded by the flow meter is zero (0), and it increases gradually as the pump speeds up. In Figure 14, the flow meter is reading a flow rate value of 40±20% liters/min, which is the actual flow rate value to activate the flow switch as the pump runs to its maximum speed. The pump now forms a close circuit with contact C1, the level switch contact, the flow switch contact, and the submerged pump as illustrated in Figure 14. Hence, the pump continues to remain in the running mode.

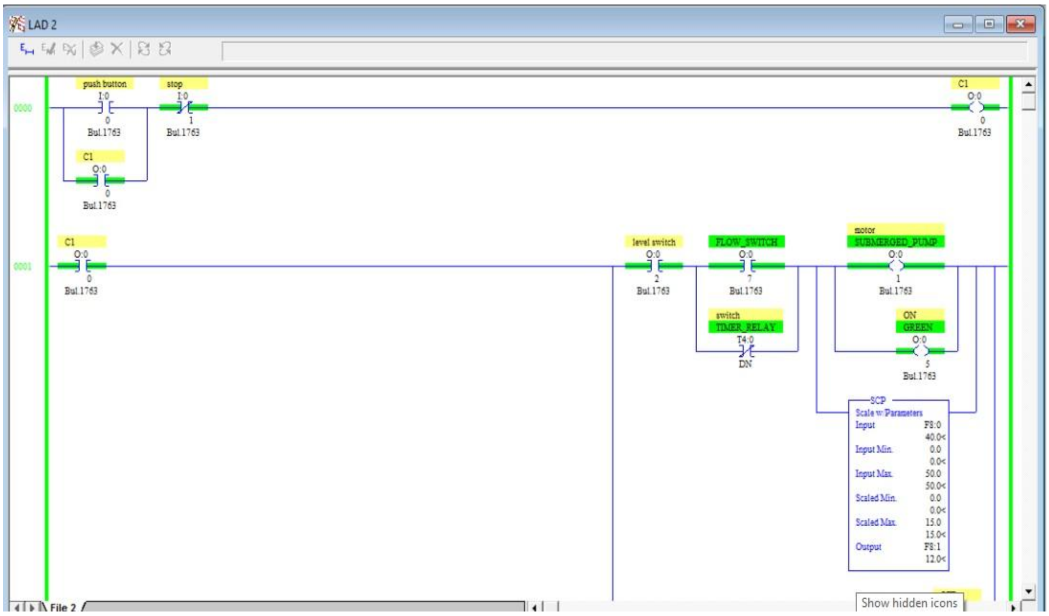


Figure 14. Pump still in running mode with flow switch contact energized.

In a situation where the well water gets low, the level switch electrodes become open-circuited and de-energize the level switch, as illustrated in Figure 15. The de-energized level switch contactor opens the level switch contact in the pump circuit to stop the pump from running, as seen in Figure 16. Moreover, the flow switch is opened as the pump comes to a stop. The process cycle begins when the well water comes up to the predetermined level.

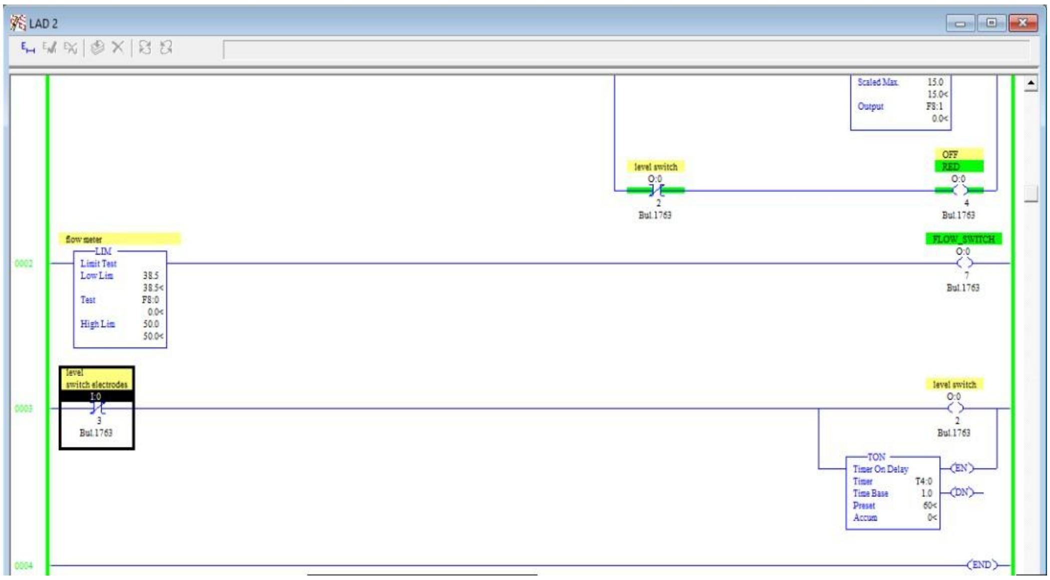


Figure 15. Low water level (level switch electrodes are opened).

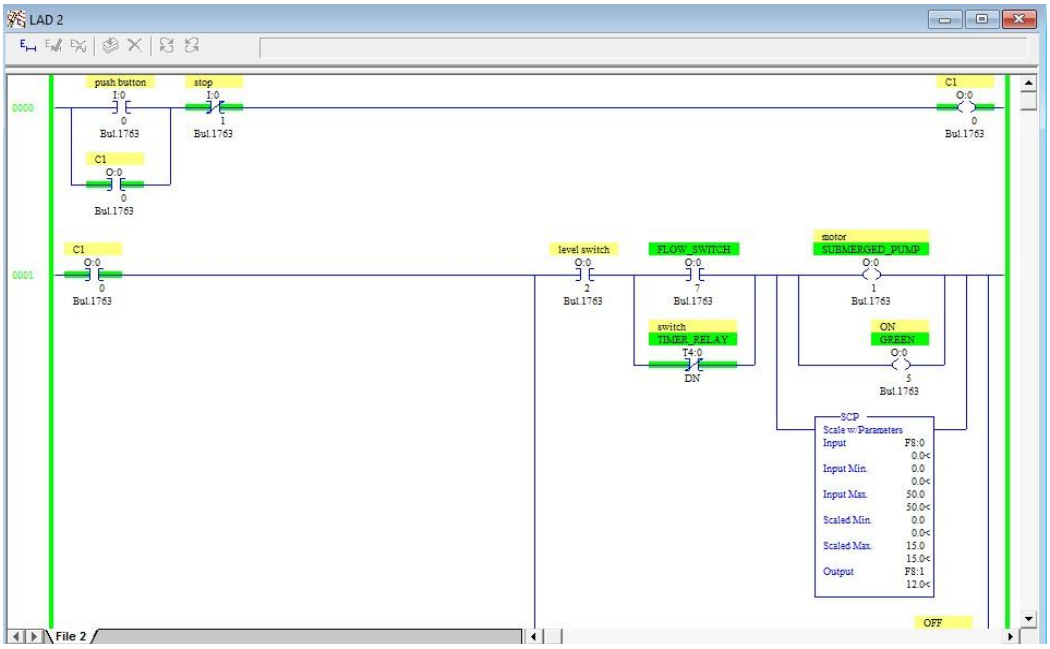


Figure 16. Pump shut down when well water level is low (level and flow switches are opened).

4. Conclusion

The implementation of an automatic switching system for submersible motor pumps in cocoa processing companies represents a significant step toward enhancing operational efficiency and equipment longevity. This study, conducted in the context of a cocoa processing company in Ghana, addresses the critical challenges of manual pump operation, such as inaccuracies in switching times, susceptibility to human error, and vulnerability to fluctuating environmental conditions. By leveraging a Programmable Logic Controller (PLC) and integrating components like level sensors, flow meters, and relays, the proposed system automates pump operations, ensuring optimal performance and protection against dry running and overheating. The simulation results using RSLogix Micro Starter Lite demonstrate the system's effectiveness in monitoring water levels, controlling pump activation, and preventing damage due to insufficient water flow. The automated system not only reduces the reliance on manual intervention but also adapts to real-time conditions, making it a robust solution for the cocoa processing industry.

By safeguarding essential equipment and improving operational efficiency, the proposed system contributes to the sustainability and resilience of Ghana's cocoa industry. Automating the pump protection system in cocoa processing companies presents significant economic benefits, including a 20-40% reduction in pump replacement and maintenance costs by preventing failures and extending equipment lifespan. It minimizes downtime, ensuring continuous cocoa processing and higher productivity while optimizing pump operation to cut energy consumption by 15-30%, leading to lower electricity costs. The system also reduces labor expenses by minimizing manual intervention and lowers water wastage by 5-15% through precise supply regulation. Additionally, it enhances equipment longevity by mitigating weather-related damage, reducing frequent repairs, and enabling predictive maintenance. The study's findings can be generalized and adapted to various industries that rely on pump systems for fluid management, including food processing, chemical manufacturing, water treatment, and oil refining. The automated pump protection system, with its PLC-based control, IoT integration, and predictive maintenance capabilities, can be tailored to optimize pump efficiency, reduce failures, and lower operational costs across these sectors. By adjusting system parameters to suit industry-specific fluid dynamics and environmental conditions, businesses beyond cocoa processing can enhance equipment longevity, improve energy efficiency, and ensure uninterrupted operations, making the technology scalable and widely applicable.

The simulation approach, while effective for validating the automated pump protection system, has limitations and underlying assumptions that may impact real-world implementation. One key limitation is the idealized conditions used in the simulation environment. In RSLogix Micro Starter Lite, factors such as sensor inaccuracies, electrical noise, and mechanical wear and tear are not fully represented, meaning the actual performance of the system in a physical setting may differ. Additionally, the model assumes a consistent power supply and stable network connectivity, which may not always be the case in real-world industrial environments where power fluctuations and communication delays can affect system responsiveness. Future work could focus on the practical implementation of advanced technologies, such as IoT-based monitoring, predictive maintenance, and AI-driven optimization, to further enhance the system's performance and scalability. IoT sensors can be strategically installed on pumps to continuously collect real-time data on temperature, pressure, vibration, and flow rate, transmitting it to a centralized cloud-based platform for remote monitoring and control. To make this implementation practical, companies could leverage existing industrial PLCs with IoT capabilities and integrate wireless connectivity for easy communication between multiple pumps across different processing stages. Additionally, AI-driven control algorithms could be embedded into the PLC to self-optimize pump operations in response to changing environmental conditions, ensuring maximum efficiency.

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