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# Design and Implementation of a Smart Solar Thermal Monitoring and Predictive Control System With Autonomous Fault Mitigation

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**Abstract.** Solar thermal energy systems are important in sustainable energy solutions. However, maintaining their efficiency and reliability is a challenge due to delayed fault detection and reactive maintenance practices. This study proposes a smart solar thermal monitoring and control system designed to improve system reliability through real-time monitoring, predictive control, and automated fault mitigation. The proposed system integrates sensor-based monitoring with an Arduino-based control architecture and a digital dashboard developed using Streamlit. A Proteus simulation environment was used to model the solar thermal hardware setup and monitor key parameters such as the temperature, pressure, and flow rate. The system uses autonomous fault mitigation mechanisms for abnormal conditions such as collector overheating, predictive heating control to maintain desired operating temperatures. It also includes an SMS notification system to alert maintenance personnel when critical faults occur or when automated mitigation mechanisms fail. The simulation results demonstrate that the system can successfully detect system anomalies, initiate appropriate automated responses, and provide real-time visualization of system status through the monitoring dashboard. These findings demonstrate the potential of intelligent monitoring frameworks to improve the efficiency, safety and better maintenance of solar thermal installations.

**Keywords:** Solar Thermal Monitoring, IoT, Predictive Heating, Fault Detection, Arduino Simulation, Digital Twin, Renewable Energy Monitoring.

## 1. Introduction

Solar energy systems, more especially solar thermal technologies, play an important role in sustainable energy solutions worldwide. Solar thermal systems are widely used for applications such as domestic water heating, industrial thermal processes, and electricity generation, particularly in regions with high solar irradiance [1]. Despite the advantages related to these systems, maintaining optimal performance and long-term reliability in solar thermal installations remains a significant challenge.

Traditional monitoring and maintenance approaches are often reactive, and they address system faults only after significant efficiency losses or component failures have occurred [2]. Issues such as overheating in solar collectors, unstable flow within piping systems and uncontrolled temperature changes in storage tanks can negatively affect the system. They affect its performance and eventually reduce operational lifespan [3]. Recent studies emphasize that shifting from reactive to proactive infrastructure maintenance, specifically through real-time remote sensing, is critical for managing high-risk components like leaky or unstable piping networks to ensure long-term system resilience [2]. As solar thermal installations become more widely deployed, there is an increasing need for intelligent monitoring solutions capable of detecting anomalies early and responding to them effectively.

Recent developments in intelligent monitoring and control technologies have enabled more advanced and reliable approaches to system management. By utilizing sensor data, these systems are able to continuously monitor key operational parameters such as temperature, pressure, and flow conditions in real time [4]. This capability allows operators to detect abnormal behaviour when there is time. This also allows them to implement preventative maintenance strategies rather than relying solely on reactive strategies.

The use of digital monitoring platforms and Internet of Things (IoT) technologies has further enhanced the capabilities of modern energy systems [5]. These technologies enable real-time data acquisition, remote monitoring, and automated control [6]. This provides operators with continuous access to system performance data. As a result, decision-making processes are improved. Fault detection becomes more efficient and corrective actions can be implemented more rapidly.

In this study, a smart solar thermal monitoring and predictive control system with autonomous fault mitigation is proposed. The system continuously monitors critical parameters of the solar collector, storage tank, and piping network. Autonomous fault mitigation mechanisms are implemented to address different anomalies such as collector overheating, pressure build-up and unstable pipe flow. When abnormal pipe flow is detected, maintenance alerts are automatically transmitted via SMS to the maintenance team. For other system faults, alert notifications are only issued if the autonomous mitigation mechanisms fail to restore normal operating conditions.

The proposed system is implemented using a hardware-in-the-loop simulation framework. The solar thermal system components are modelled in the Proteus simulation environment, while a digital twin monitoring interface is developed using a Streamlit-based Python dashboard. The dashboard provides real-time visualization of system states and allows for supervisory control through manual override functions.

The main contribution of this work is the development of an integrated monitoring and control system that combines real-time temperature monitoring, predictive heating algorithms, autonomous fault mitigation, and remote maintenance notification capabilities. The system demonstrates how intelligent control strategies can improve the operational reliability and safety of solar thermal installations.

# 2. Methodology

## 2.1 System Architecture

The proposed smart solar thermal monitoring and predictive control system is designed to monitor operational parameters within a solar thermal installation. The system focuses on three primary components which are the solar collector, the storage tank, and the piping network responsible for heat transfer between the collector and storage unit.

The system's architecture integrates sensor-based monitoring with an embedded control system and a remote digital monitoring interface. Temperature sensors are used to monitor the thermal behaviour of both the solar collector and the storage tank, while flow monitoring is used to detect abnormal conditions within the piping network.

The main control logic of the system is implemented using an Arduino microcontroller, which acts as the central processing unit responsible for interpreting sensor inputs and executing control decisions. The controller determines whether the system is operating under normal conditions or if mitigation actions must be initiated based on the measured parameters.

The physical system architecture and sensor integration were modelled using the Proteus simulation environment, allowing the behaviour of the solar thermal system to be evaluated under controlled simulation conditions. This is shown in Figure 1.

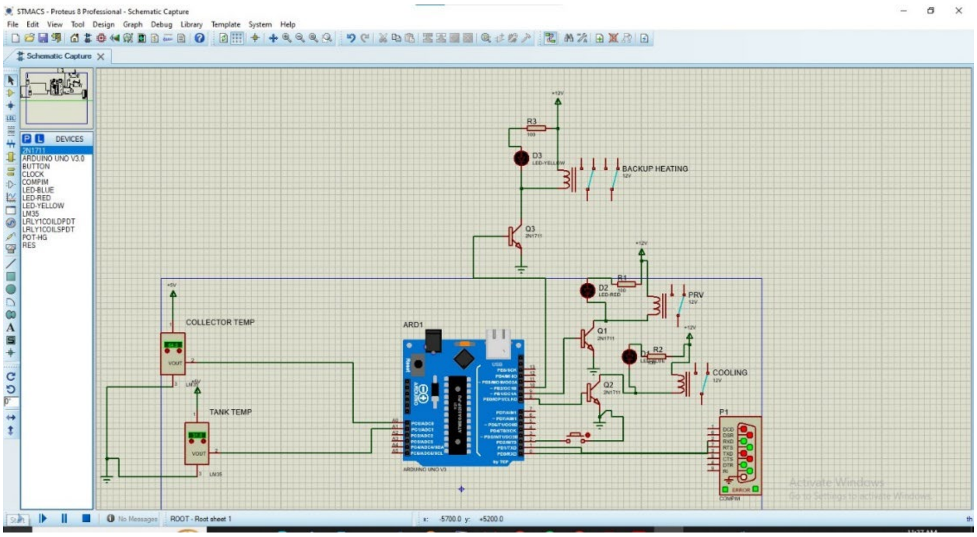


***Figure 1.*** *Proteus simulation setup of the proposed solar thermal monitoring and control system showing the Arduino controller, temperature sensing components, and system interconnections.*

The sensor readings generated within the simulation are transmitted to a remote monitoring dashboard where system performance is visualized in real time.

## 2.2 Hardware-in-the-Loop Simulation Framework

To evaluate the proposed monitoring and control strategy, a hardware-in-the-loop simulation framework was implemented. The thermal components and sensor interfaces were modelled within the Proteus simulation environment, while the system monitoring interface was implemented as a digital twin using a Python-based dashboard.

The digital monitoring platform was developed using Streamlit, which allows real-time visualization of system conditions and also provides an interactive supervisory control interface.

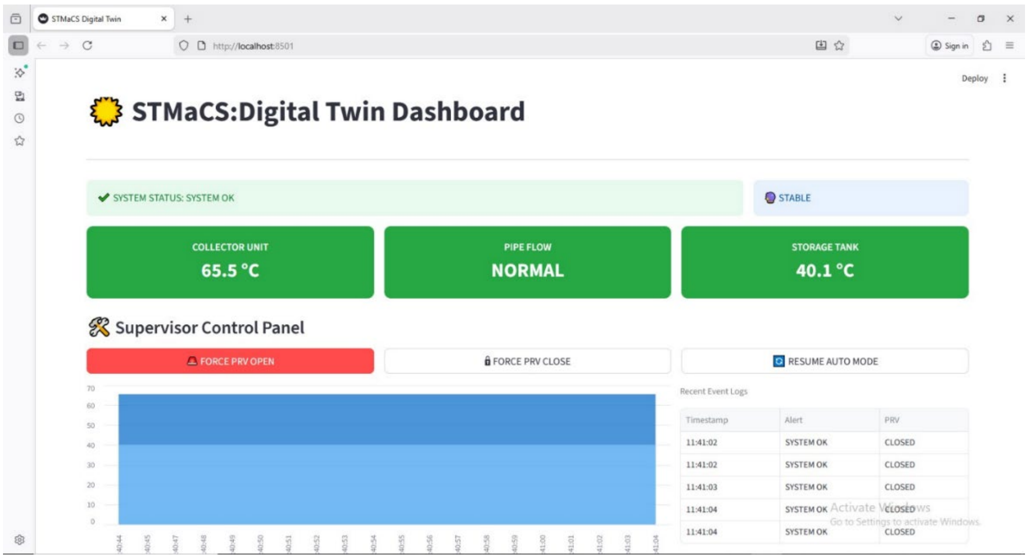
The dashboard receives sensor values from the simulation environment and represents each component of the solar thermal system using a visual digital twin model. In this representation:

The solar collector is displayed with colour transitions indicating temperature increases.

The storage tank displays its thermal state using dynamic colour gradients representing varying temperature levels.

The pipe network is represented by status indicators that signal either stable flow conditions or detected faults.

This visualization approach allows system operators to quickly identify abnormal operating conditions through intuitive graphical feedback. The dashboard is shown in Figure 2 below.



STMaCS:Digital Twin Dashboard

✓ SYSTEM STATUS: SYSTEM OK

STABLE

COLLECTOR UNIT 65.5 °C

PIPE FLOW NORMAL

STORAGE TANK 40.1 °C

Supervisor Control Panel

Recent Event Logs

| Timestamp | Alert | PRV |
|---|---|---|
| 11:41:02 | SYSTEM OK | CLOSED |
| 11:41:02 | SYSTEM OK | CLOSED |
| 11:41:03 | SYSTEM OK | CLOSED |
| 11:41:04 | SYSTEM OK | CLOSED |
| 11:41:04 | SYSTEM OK | CLOSED |

Activate Windows
Go to Settings to activate Windows.

***Figure 2.*** *Streamlit-based digital twin dashboard used for real-time monitoring and supervisory control of the solar thermal system.*

In addition to visualization, the dashboard provides a supervisory interface that allows manual control actions to be applied when required

## 2.3 Predictive heating mechanism

To improve system reliability and prevent excessive temperature drops within the storage tank, a predictive heating temperature monitoring mechanism was implemented. Rather than responding only to instantaneous temperature values, the system evaluates the rate at which the storage tank temperature is changing.

The rate of temperature change is determined using the following expression:

$$\frac{dT}{dt} = \frac{Tcurrent - Tprevious}{\Delta t} \tag{1}$$

where $Tcurrent$ represents the current measured temperature, $Tprevious$ represents the previously recorded temperature, and $\Delta t$ represents the time interval between measurements.

Using this rate of change, the system estimates the predicted future temperature as:

$$Tpredicted = Tcurrent + \left(\frac{dT}{dt} \times \Delta tp\right) \tag{2}$$

where $Tpredicted$ represents the predicted temperature at a future time horizon $\Delta tp$.

If the predicted temperature falls below a predefined minimum operating threshold, the system automatically activates an auxiliary heating element. This predictive heating mechanism prevents excessive temperature drops and improves energy efficiency by activating the backup heating system only when necessary.

## 2.4 Autonomous Fault Mitigation Mechanisms

The monitoring system also incorporates autonomous fault mitigation mechanisms designed to respond automatically to abnormal system conditions without requiring immediate human intervention.

For the solar collector, overheating conditions are detected when the collector temperature exceeds a predefined threshold. When such a condition occurs, the system activates a cooling mechanism intended to reduce the collector temperature. If the temperature continues to increase despite the cooling action, a pressure relief valve is activated to prevent excessive pressure buildup and maintain safe system operation.

Similarly, the storage tank is monitored for excessive thermal buildup. When tank temperature exceeds the safe operating range, the pressure relief valve is triggered to release excess pressure and prevent potential system damage.

When the predictive heating monitoring mechanism determines that the storage tank temperature is likely to fall below acceptable levels, the auxiliary heating element is activated to maintain stable thermal conditions.

In addition to thermal monitoring, the system continuously evaluates the operational status of the piping network. Pipe flow abnormalities are detected through flow monitoring logic, which identifies conditions such as blockages or unstable flow patterns within the circulation loop.

## 2.5 Maintenance Notification System

To help ensure fast response to system faults, the system integrates an automated maintenance notification mechanism.

When abnormal pipe flow conditions are detected, the system immediately transmits a Short Message Service (SMS) notification to the designated maintenance personnel. This ensures that faults affecting system circulation can be addressed promptly even when there is no internet connection or if the maintenance member is not technologically literate.

For other system faults, such as collector overheating or abnormal storage tank temperatures, notifications are only issued if the autonomous mitigation mechanisms fail to mitigate the situation and restore normal operating conditions. This approach prevents excessive alarm generation while still ensuring that maintenance teams are informed when manual intervention becomes necessary.

The integration of automated fault mitigation with targeted maintenance alerts enhances both the reliability and operational efficiency of the solar thermal monitoring system

# 3. Results And Discussion

## 3.1 Simulation environment

The proposed solar thermal monitoring and control system was validated using a simulation environment consisting of a hardware model implemented in Proteus and a corresponding digital twin dashboard developed using Streamlit. The simulation replicated the behaviour of the solar thermal system using virtual sensors (e.g. the LM-35 temperature sensors), actuators, and control indicators (LEDs).

To demonstrate the interaction between the physical system and the digital monitoring interface, screenshots were captured showing both the Proteus process simulation and the Streamlit dashboard simultaneously. This side-by-side configuration allows visualization of how the system state changes in the hardware model are reflected in real-time on the monitoring dashboard.

## 3.2 Autonomous Fault Mitigation

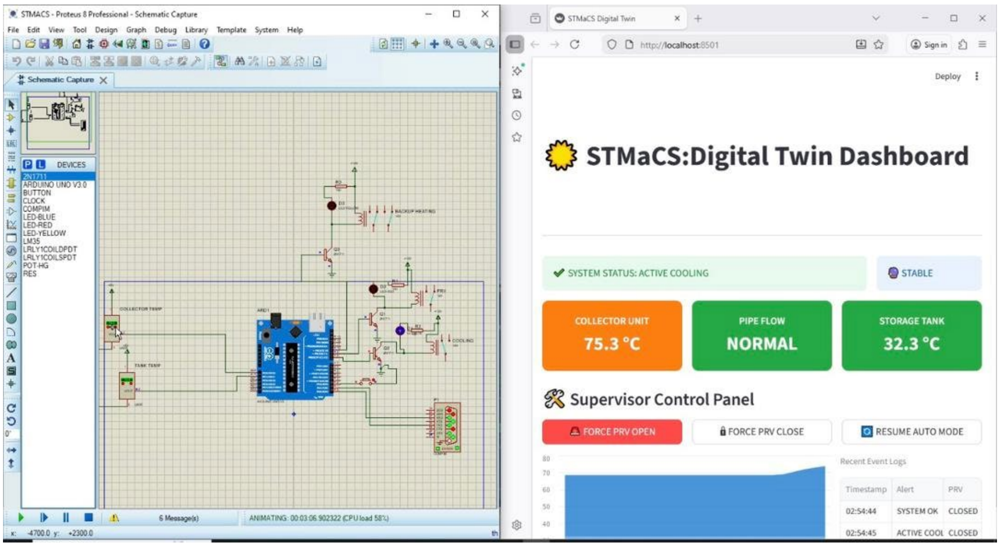
The first test scenario evaluated the system's autonomous fault mitigation capability during a solar collector overheating event.

In this scenario, the temperature of the solar collector was intentionally increased beyond the safe operating threshold. When the system detected that the collector temperature exceeded the predefined limit, the control algorithm automatically activated the cooling mechanism.

Within the digital twin visualization, the solar collector block changed colour to orange, indicating an overheating condition. Simultaneously, the dashboard status bar updated to display "Active Cooling", confirming that the control logic had initiated the mitigation response.

At the hardware level, the cooling action was represented by the activation of a blue LED, which symbolized the engagement of the cooling subsystem as shown in Figure 3.

This result demonstrates the system's ability to detect abnormal temperature conditions and respond automatically without human intervention, thereby preventing potential thermal damage to the system.



| Timestamp | Alert | PRV |
|---|---|---|
| 02:54:44 | SYSTEM OK | CLOSED |
| 02:54:45 | ACTIVE COOL | CLOSED |

***Figure 3.*** *Overheating fault simulation showing collector turning orange and cooling blue LED activation*

## 3.3 Predictive Heating Mechanism

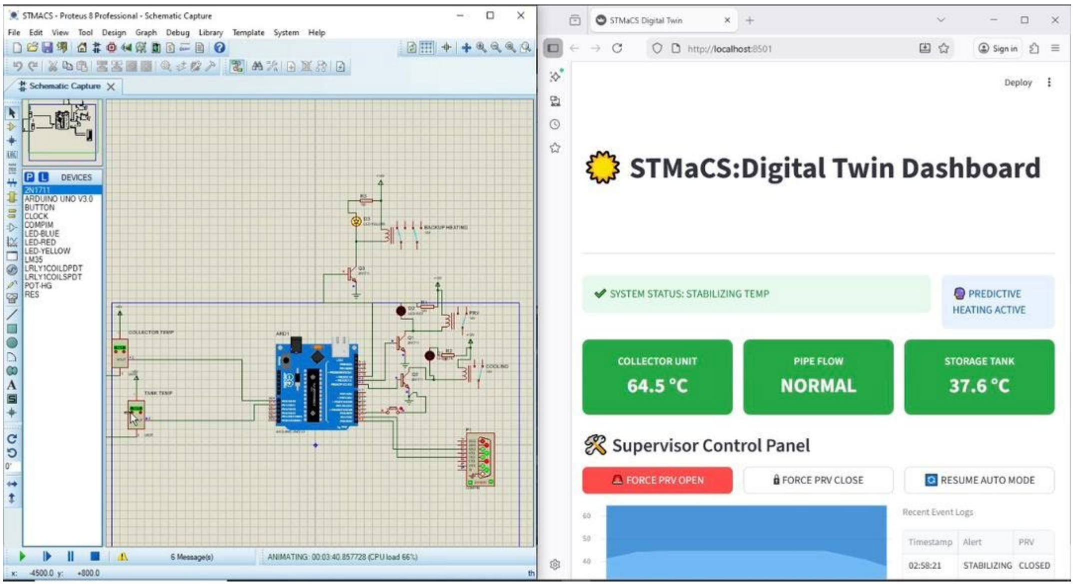
The second test evaluated the system's predictive heating functionality, which aims to maintain optimal operating temperature by responding to decreasing thermal conditions.

In this scenario, the collector temperature was gradually reduced to simulate a drop in solar energy input. As the temperature approached the lower operational threshold, the system predicted the potential loss of heating efficiency and activated the predictive heating mechanism.

The system status displayed “Predictive Heating Active” on the dashboard, indicating that the controller had initiated early thermal support to stabilize system performance as shown in Figure 4.

If the temperature continued to decrease beyond the predictive heating range, the system triggered the auxiliary heating subsystem, which acts as a backup heat source as shown in Figure 5.

In the Proteus simulation, this response was represented by the activation of a yellow LED, signifying the activation of predictive heating mechanism.



STMaCS:Digital Twin Dashboard

SYSTEM STATUS: STABILIZING TEMP

PREDICTIVE HEATING ACTIVE

COLLECTOR UNIT 64.5 °C

PIPE FLOW NORMAL

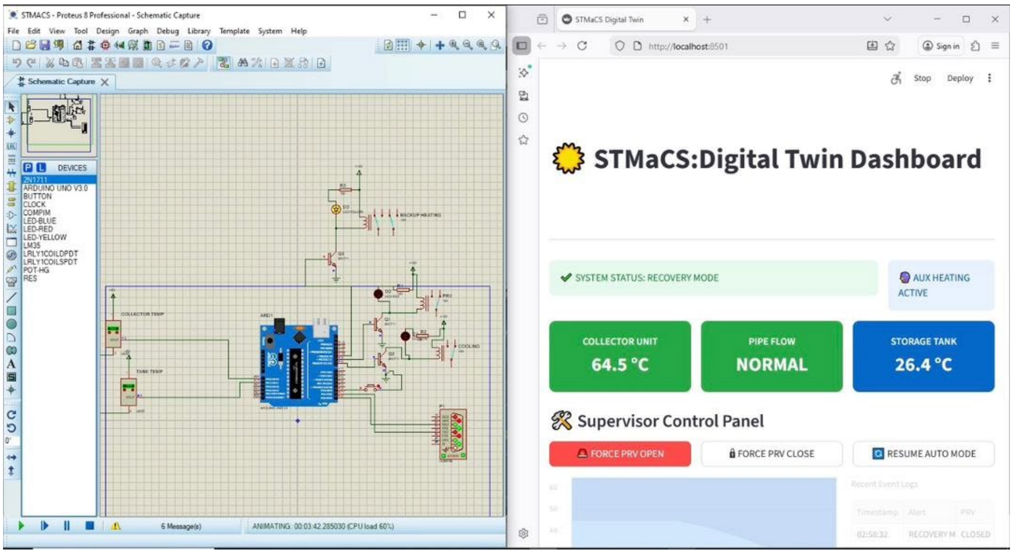
STORAGE TANK 37.6 °C

Supervisor Control Panel

Recent Event Logs

| Timestamp | Alert | PRV |
|---|---|---|
| 02:58:21 | STABILIZING | CLOSED |

**Figure 4.** *Predictive heating activation shown on dashboard with yellow LED on proteus simulation.*



STMaCS:Digital Twin Dashboard

SYSTEM STATUS: RECOVERY MODE

AUX HEATING ACTIVE

COLLECTOR UNIT 64.5 °C

PIPE FLOW NORMAL

STORAGE TANK 26.4 °C

Supervisor Control Panel

Recent Event Logs

| Timestamp | Alert | PRV |
|---|---|---|
| 02:58:32 | RECOVERY M | CLOSED |

**Figure 5.** *Auxiliary heating activation shown*

As the predictive heating process involves gradual temperature transitions, the dynamic behaviour of this mechanism is more effectively demonstrated through a video recording of the simulation. A QR code linking to this demonstration video can be provided for further observation of the system's real-time behaviour.

## 3.4 Pipe Fault Detection and Maintenance Notification

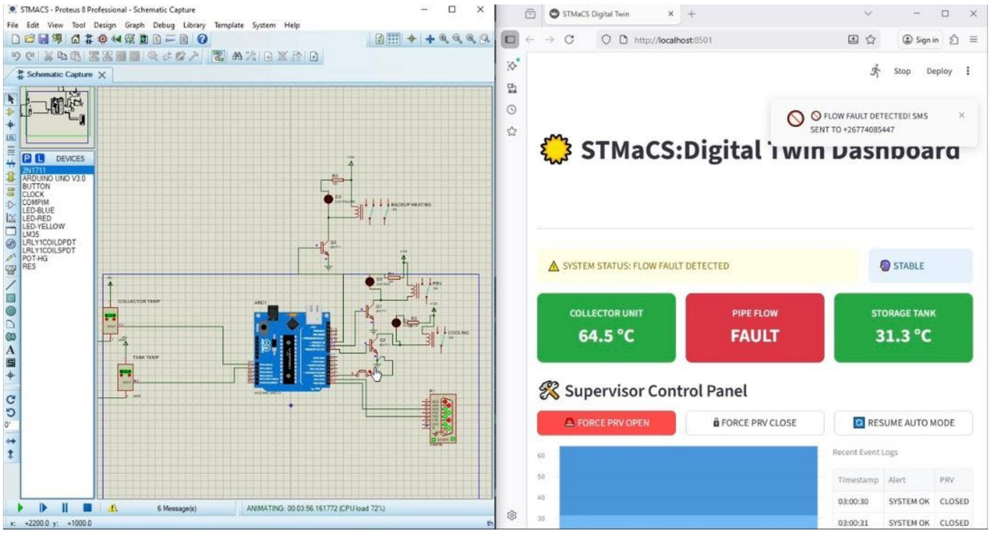
Another test scenario evaluated the system's response to pipe flow faults, which may occur due to blockages or leaks within the solar thermal circulation loop.

In this simulation, a push-button input was used to represent the occurrence of a pipe fault condition. When the fault was triggered, the digital twin interface immediately reflected the issue.

The pipeline component within the digital twin visualization changed to red, indicating a detected failure in the circulation system. At the same time, the dashboard generated a pop-up alert indicating that an SMS notification had been sent to the system maintenance team as shown in Figure 6.

This SMS alert mechanism ensures that critical faults are immediately communicated to maintenance personnel, enabling rapid intervention and reducing system downtime.

Unlike other faults where autonomous mitigation is attempted first, pipe flow faults trigger direct maintenance notification, as they typically require physical inspection or repair.



STMACS - Proteus 8 Professional - Schematic Capture

ANIMATING: 00:03:56.161772 (CPU load 72%)

6 Message(s)

STMaCS Digital Twin

http://localhost:8501

⦸ FLOW FAULT DETECTED! SMS SENT TO +26774085447

STMaCS:Digital Twin Dashboard

⚠ SYSTEM STATUS: FLOW FAULT DETECTED

STABLE

COLLECTOR UNIT 64.5 °C

PIPE FLOW FAULT

STORAGE TANK 31.3 °C

Supervisor Control Panel

Recent Event Logs

| Timestamp | Alert | PRV |
|---|---|---|
| 03:00:30 | SYSTEM OK | CLOSED |
| 03:00:31 | SYSTEM OK | CLOSED |

***Figure 6.*** *Pipe fault simulation with red digital twin indicator and SMS notification alert*

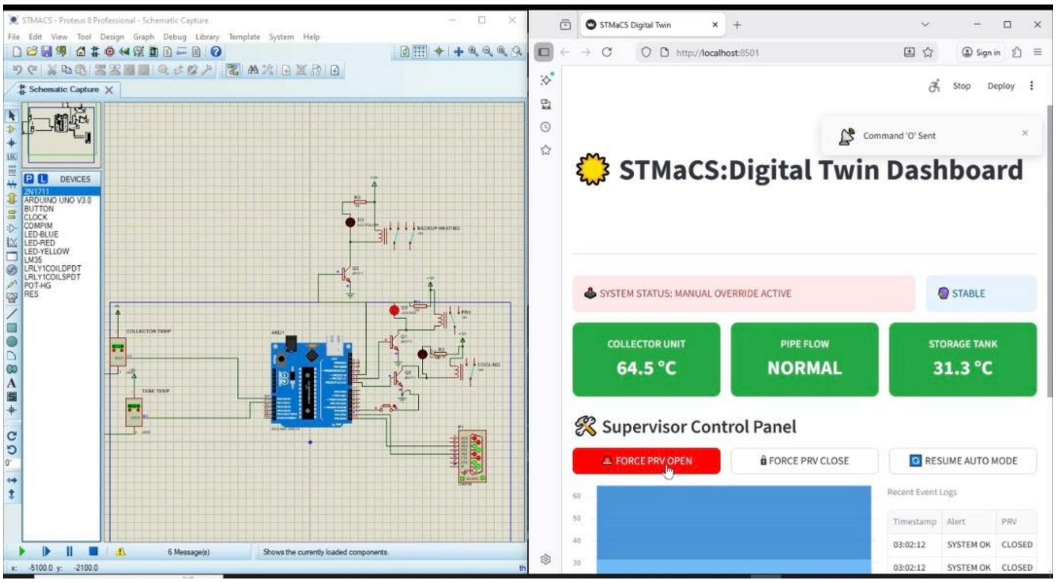
## 3.5 Remote Manual Override Control

The final test scenario demonstrated the manual override capability of the system through the digital dashboard interface.

Using the Streamlit dashboard, the operator can remotely control specific components of the solar thermal system. During the test, the Pressure Relief Valve (PRV) was manually activated through the dashboard control interface.

Once the command was issued, the Proteus simulation immediately responded by activating a red LED, indicating that the valve had been successfully opened.

This result confirms that the system supports remote intervention, allowing operators to manually control critical components when necessary. Such functionality is particularly useful in cases where automated responses may not fully resolve system issues. Figure 7 shows this feature.



Command 'O' Sent

SYSTEM STATUS: MANUAL OVERRIDE ACTIVE

| Timestamp | Alert | PRV |
|---|---|---|
| 03:02:12 | SYSTEM OK | CLOSED |
| 03:02:12 | SYSTEM OK | CLOSED |

***Figure 7.*** *Manual override command on dashboard with corresponding red LED activation in simulation*

## 3.6 Discussion

The simulation results demonstrate that the proposed system successfully integrates real-time monitoring, predictive control, automated fault mitigation, and remote system management within a unified digital twin framework.

The side-by-side visualization of the Proteus simulation and the dashboard confirms that system states are accurately reflected in the monitoring interface, validating the effectiveness of the communication architecture.

Autonomous responses such as cooling activation during overheating and predictive heating during temperature drops illustrate how the system can maintain stable operating conditions without continuous human supervision.

Additionally, the SMS-based fault notification mechanism ensures that maintenance teams are alerted when faults cannot be resolved automatically or when physical intervention is required.

Overall, the results highlight the potential of combining IoT-based monitoring, control algorithms, and digital twin visualization to improve the reliability, efficiency, and maintainability of solar thermal installations.

# 4. Conclusions And Recommendations

A comprehensive study was conducted on the design and simulation of a smart solar thermal monitoring and control system. The system aimed at improving the reliability and operational efficiency of solar thermal installations. The study began with an overview of solar thermal technologies and the challenges associated with maintaining optimal system performance using traditional monitoring strategies. A literature review highlighted the importance of intelligent monitoring systems, predictive control mechanisms, and IoT-based data acquisition for improving system efficiency and enabling proactive maintenance strategies.

The methodology presented a systematic approach to the development of the proposed system. A sensor-based monitoring architecture was designed to monitor key operational parameters including temperature, pressure, and flow rate. The system was implemented using an Arduino-based control platform and simulated in Proteus to model the physical process components. A digital monitoring interface was developed using Streamlit to provide real-time visualization of system parameters and control actions. The system architecture incorporated several intelligent control mechanisms including autonomous fault mitigation, predictive heating control, and a notification system for maintenance teams through SMS alerts. The integration of the simulation environment and the monitoring dashboard enabled the creation of a digital representation of the physical process, allowing the operational behaviour of the system to be observed in real time.

The simulation results demonstrated the successful operation of the proposed monitoring and control framework. The system was able to detect abnormal conditions such as collector overheating and automatically activate cooling mechanisms to mitigate the fault. Predictive heating functionality was also demonstrated, where the system anticipated decreasing temperature levels and activated heating mechanisms before critical thresholds were reached. Additionally, pipe flow faults were successfully detected and triggered SMS alerts to maintenance personnel, ensuring that critical failures requiring manual intervention could be addressed promptly. The real-time dashboard effectively reflected system status and allowed manual override control of certain components, confirming the successful integration between the process simulation and the monitoring interface.

The results indicate that the proposed system can effectively improve monitoring, fault detection, and operational control of solar thermal installations. By combining real-time sensing, automated control responses, and remote monitoring capabilities, the system demonstrates the potential to enhance the reliability and promote easier maintenance of solar thermal energy systems.

However, it should be noted that the system was evaluated within a simulated environment, and certain real-world factors such as environmental variations, sensor inaccuracies, and hardware limitations were not fully represented. Additionally, long-term operational data was not analysed since the system behaviour was demonstrated through controlled simulation scenarios.

Future research could focus on implementing the system on a physical solar thermal installation to validate its performance under real operating conditions. Further improvements may include the integration of advanced predictive algorithms such as machine learning models for improved fault forecasting and system optimization. Additional sensors such as solar irradiance sensors and more precise flow measurement devices could also be incorporated to enhance system monitoring capabilities. Furthermore, expanding the communication infrastructure to include cloud-based monitoring platforms could allow large-scale deployment and centralized monitoring of multiple solar thermal systems.

Overall, the proposed intelligent monitoring and control system demonstrates a promising approach for improving the efficiency, reliability, and operational management of solar thermal installations.

## Data availability statement

The data used in this study were generated through simulation of the proposed solar thermal monitoring and control system. The simulation data supporting the findings of this study are available from the corresponding author upon reasonable request. No external or third-party datasets were used in this research.

## Author contributions

**Gorata Matsapa**: Conceptualization, Investigation, Methodology, Software, Formal analysis, Visualization, Writing–original draft.

**Prof O. S. Motsamai**: Supervision and review of manuscript.

**Prof. K. N. Nwaigwe**: Supervision, Validation, Writing – review & editing.

## Competing interests

The authors declare that they have no competing interests.

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