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Design of a Remote Monitoring System for Solar Thermal Energy: A Case Study in an Educational Institution

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A B S T R A C T

This paper explores the development of a remote monitoring system for solar thermal units, focusing on a case study in an educational institution. It addresses the challenge of real-time monitoring in decentralized renewable energy systems using the Pahl and Beitz process for task clarification and the Functional Analysis System Technique (FAST) for system decomposition. The system encompasses data reading, processing, transmission, storage, and broadcasting for remote access. Data collection is achieved through heat meters with integrated flow meters and temperature sensors, processed into a readable format, and transmitted to a Modbus with a local IP address. An Arduino module with an ESP8266 chip converts the data for uploading to a server, enabling remote monitoring via a custom dashboard. The architecture includes a switch interfacing with an Arduino for processing and an ESP8266 Wi-Fi module for wireless transmission to a cloud database. This setup facilitates real-time monitoring and analysis of solar thermal units' performance, demonstrating the system's effectiveness in providing detailed insights into energy, volume, flow rate, and power, and establishing its potential as a comprehensive tool for performance assessment in solar thermal systems.

Keywords: Renewable Energy, Solar Thermal Units, Remote Monitoring, Data Processing, System Design.

1. Introduction

Solar energy, with its vast potential as a renewable and sustainable power source, is increasingly recognized as a key solution to the energy challenges in regions rich in sunlight. Sub-Saharan Africa is embracing this clean energy source to address its electricity supply issues. Zimbabwe, within this context, has embarked on an ambitious journey to integrate solar energy into its national energy framework. This paper delves into a specific aspect of this transition: the development of a remote monitoring system for solar thermal units, focusing on a case study within a local educational institution.

The Southern African Solar Thermal Training and Demonstration Initiative (SOLTRAIN) plays a crucial role in promoting solar thermal technologies in Zimbabwe and its neighboring countries. Central to this initiative is the National Solar Water Heating Program (NSWHP) in Zimbabwe, which aims to retrofit existing electrical geysers with solar water heating systems in up to 300,000 households. This initiative is not just a significant move towards energy sustainability but also a practical approach to reducing the heavy reliance on electric geysers, known for their substantial energy consumption.

2. Background

The implementation of solar water heating (SWH) systems across various sectors – including residential, public, commercial, and industrial – marks a significant development in Zimbabwe's approach to energy management. To date, approximately 600 SWH systems have been installed under the NSWHP, demonstrating the program's initial success, (Mhlanga et al, 2019). These systems are utilized for both heating and cooling in buildings, as well as in industrial processes. However, a notable gap in the operational framework of these systems is the lack of a comprehensive performance monitoring mechanism, particularly during peak consumption periods.

Currently, the performance assessment of these SWH units largely relies on manual data collection, a process that is both time-consuming and inefficient. This method does not provide real-time insights into the systems' performance, which is crucial for effective decision-making and optimization. Consequently, there is a clear need for a sophisticated, real-time remote monitoring system. Such a system would streamline data collection and analysis processes, enhancing the management and efficiency of solar thermal operations, (Sarema, 2023).

The proposed remote monitoring system aims to bridge these gaps by offering a centralized platform for real-time data acquisition and analysis. This system is poised to transform the monitoring and management of solar thermal units, leading to enhanced efficiency, reduced operational costs, and better alignment with energy consumption patterns. The case study of a local educational institution will provide a practical context for the development and implementation of this remote monitoring system, offering valuable insights and a replicable model for other similar settings.

3. Design and Development

The project focused on developing a Remote Monitoring System for Solar Thermal Units. Various routes were explored and evaluated to achieve the desired results, with each component and module developed individually before integration in the final phase. The Functional Analysis System Technique (FAST) Model, illustrated in Fig. 1, was employed to graphically represent the system's functions, ensuring the solution met the project's needs.

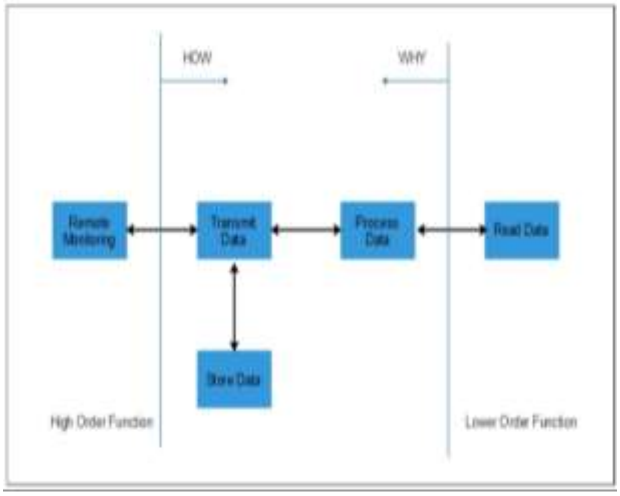

Fig. 1: FAST Model

Concept generation utilized morphological charts, as shown in Table 1, to explore various problem-solving methods, covering aspects like temperature and flow measurement, data processing, data transmission methods, and database management systems.

Table 1: Morphological Chart

Function/Feature	Function description	Alternative 1	Alternative 2	Alternative 3
Temperature and Flow Measurement	Measures real time temperature and flow rate of the water in the system.	Zelsius Heat Meter	Techem Ultra S3 Heat Meter	Kampstrup Multical 302
Data Processing	Transforms raw data into meaningful output that is information.	Arduino Mega 2560 Microcontroller	ATmega328 Microcontroller	PIC 18F4550 Microcontroller
Data Transmission Method	Communicates information to central database.	Text Messaging (GSM technology)	Bluetooth Technology	Wired Ethernet
DBMS	Database Management System.	MongoDB Atlas	MySQL	

The selection of components for the development of the remote monitoring system for solar thermal units was a critical decision, guided by the specific functionalities required, as outlined in the FAST model diagram (Fig. 1). For the function of reading data, the Zelsius C5 Heat Meter was selected. This choice was influenced by its high precision, ease of use, and the ability to operate with a long-life battery, making it ideal for consistent and accurate temperature and flow measurements in various environmental conditions. The data processing component was designated to the Arduino Uno/Mega. This selection was based on the versatility and robustness of these microcontrollers. Their compatibility with a wide range of sensors and modules, along with their user-friendly programming environment, makes them suitable for processing the raw data collected by the Zelsius C5 Heat Meter into meaningful information. For data transmission, TCP/IP (http) was chosen. This protocol is widely used and reliable for sending data over the internet, ensuring that the data collected and processed can be transmitted efficiently and securely to a central database. MongoDB Atlas was selected for data storage. Its scalability, flexibility in handling large volumes of data, and robust security features make it an excellent choice for managing the data transmitted from the solar thermal units. Lastly, a web interface was chosen for remote monitoring. This allows for easy access to the system's data from any location, providing a user-friendly and interactive platform for stakeholders to monitor and analyze the performance of the solar thermal units.

The current setup of the data acquisition and transmission system for the solar thermal units, as depicted in Fig. 2, involves a configuration where temperature and flow sensors are integrated with a transmitter, typically a heat meter. This setup is designed to process raw data into meaningful information, which can be viewed on the heat meter's LED display. Additionally, the system incorporates a GSM module, which facilitates the sending of SMS notifications. This module is connected to the heat meter through a combination of M-Bus and Mod-Bus TCP Ethernet protocols, accessible via a network switch. This arrangement provides a functional solution for real-time data monitoring and communication.

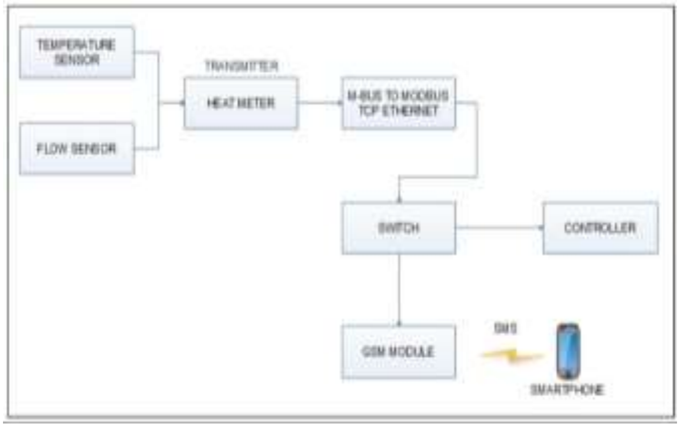

Fig. 2: Current Set-Up Architecture

However, in the context of the SOLTRAIN initiative, the current control setup is proprietary, necessitating a tailored approach for any modifications or enhancements. Therefore, the proposed system, illustrated in Fig. 3, aims to introduce minimal changes to the existing infrastructure while enhancing its capabilities. The proposed enhancements involve tapping information from Port 4 of the existing switch. This data will then be interfaced with an Arduino microcontroller using an RS485 module and an Ethernet shield. The Arduino microcontroller serves as a pivotal component in processing and preparing the data for transmission.

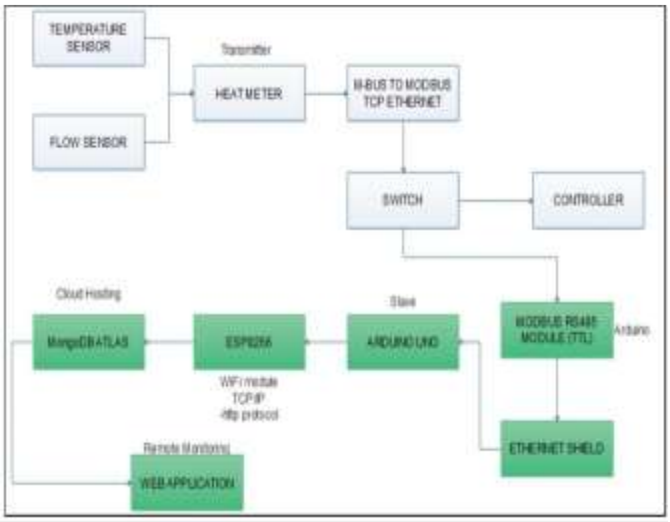

Fig. 3: Proposed Set-Up Architecture

For the transmission of processed data, the proposed system employs an ESP8266 Wi-Fi module. This module is instrumental in wirelessly sending the processed data to a cloud-based database. The use of a cloud database not only ensures secure and scalable data storage but also facilitates easy access and retrieval of data from virtually any location. Finally, the processed and stored data in the cloud database can be broadcast and monitored remotely through a web interface. This aspect of the proposed system significantly enhances the accessibility and usability of the data, allowing for real-time monitoring and analysis of the solar thermal units' performance from remote locations. The web interface is designed to be user-friendly, ensuring that users can easily interact with and interpret the data, which is crucial for effective monitoring and decision-making.

4. System Architecture

In the detailed interfacing process where data acquired by heat meters is transformed into meaningful information, the switch plays a crucial role. The information processed by the switch is then transmitted from the MBUS-GEM to an Arduino for further processing. The processed data is next sent over an ESP8266 WiFi module using the HTTP protocol, facilitating the transmission of data to MongoDB Atlas for data management and to a web application for remote monitoring. The M-Bus (Meter-Bus) interface, renowned for its ease of installation and robustness, is ideal for industrial environments. It is defined in the standard EN 13757 and includes both a physical layer and a protocol. In automation contexts, MBUS-GEM functions as gateways, enabling direct transmission of meter data to control systems.

The interfaces and connectors of the MBUS-GEM, as detailed in Table 2, are positioned on different sides of the device. This table outlines connectors for the power supply (24VDC, GND), MBUS (+, -), and the Ethernet interface. The power supply connectors are designed for positive and negative power, while the MBUS connectors handle the positive and negative bus lines. The Ethernet interface is crucial for network connections. Network configuration of the MBUS-GEM is accessible via its Ethernet network interface.

Table 2: Connectors and Interfaces

Connector Type	Marking	Pinning Description
Power Supply	24VDC GND	24VDC: Positive power supply GND: Negative power supply
MBUS Connectors	MBUS + MBUS -	MBUS +: Positive bus line (2x) MBUS -: Negative bus line (2x)
Ethernet Interface	Ethernet	1: TX+ 2: TX- 3: 4: 6: 7: 8:

Fig. 4 shows the CHIPtool from Beck IPC GmbH, which is used when direct connection using pre-configured settings is not successful. This tool is efficient in identifying all accessible devices in the local network. The MBUS-GEM can be configured through its internal website or manually using configuration files, allowing for changes in device parameters, meter configuration, and services.

Fig. 4: Overview of the CHIPtool Displaying All Detected MBUS-GEM Devices in the Local Network

Fig. 5 demonstrates the meter tab on the MBUS-GEM's internal website, showing the management and configuration of connected meters. For reading M-Bus data registers, code written in C++ within the Arduino Integrated Development Environment (IDE) is used. The MBUS-GEM employs a fixed address structure of Modbus registers.

Fig. 1: Tab Meter

The next step involved the initialization and incorporation of essential libraries, as shown in Fig. 6a. This step was crucial for setting up the Arduino environment to read data from the M-Bus registers. The ESP8266WiFi.h library enabled the ESP8266 module to connect to WiFi, essential for data transmission, while the ModbusIP_ESP8266 library facilitated communication via the Modbus protocol. The next phase, illustrated in Fig. 6b involved connecting the Arduino to the WiFi network. This step was critical to ensure continuous data transmission; in case of connection failure, the system was programmed to retry after a 5-second delay.

```
#ifdef ESP8266
 #include <ESP8266WiFi.h>
#else
 #include <WiFi.h>
#endif
#include <ModbusIP_ESP8266.h>

IPAddress remote(192, 168, 1, 36);  // Address of Modbus Slave device
const int LOOP_COUNT = 10;

String apiKey = "BPMKQLRTGAL6BS2T";
const char* server = "api.thingspeak.com";

WiFiClient client;
ModbusIP mb;  //ModbusIP object
```

a

```
  WiFi.begin("MASH", "incorr3ct");

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  Serial.println("");
  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());

  mb.master();
}
```

b

Fig. 2: Arduino Code for a) Initialization and Libraries b) Connecting to the WiFi

As shown in Fig. 7a, the system extracted data values from the first four Modbus registers. These values, initially in decimal form, were converted to hexadecimal for concatenation and then back to decimal to obtain the final data values. The system then posts to the server, as outlined in Fig. 7b. Here, a unique API key was used to grant Arduino access to post the acquired data to the Thingspeak.com server, ensuring secure and reliable data transmission. Finally, the data was displayed on a dashboard, a crucial step for remote monitoring.

a

```
void loop() {
  postData();
}

long getData(int addr){
  String packetsV = "";
  for(int g=0;g<4;g++){
    if (mb.isConnected(remote)) {   // Check if connection to Modbus Slave is established
    mb.readHreg(remote, addr+g, &res);  // Initiate Read Coil from Modbus Slave
    } else {
     mb.connect(remote);           // Try to connect if no connection
    }
    mb.task();
    delay(100);

    packetsV.concat(String(res,HEX));
    }
    long A = strtol(packetsV.c_str(),NULL,16);
    return A;
```

String api Key = "BPMKQLRTGAL6BS2T”.

const char* server = "api.thingspeak.com”.

b

Fig. 3: Arduino Code a) Getting the Data Values b) Posting to the Server

Fig. 8, illustrates the code segment responsible for posting critical values such as energy usage, cumulative volume, and flow rates to the web dashboard. This allowed for real-time monitoring and analysis of the solar thermal units' performance.

```
void postData(){
 if (client.connect(server,80)){
      String postStr = apiKey;
      postStr +="&field1=";
      postStr += String(getData(40) - getData(38));
      postStr +="&field2=";
      postStr += String(getData(70));
      postStr +="&field3=";
      postStr += String(getData(120));
      postStr +="&field4=";
      postStr += String(getData(110));
      postStr += "\r\n\r\n";
      client.print("POST /update HTTP/1.1\n");
      client.print("Host: api.thingspeak.com\n");
      client.print("Connection: close\n");
      client.print("X-THINGSPEAKAPIKEY: "+apiKey+"\n");
      client.print("Content-Type: application/x-www-form-urlencoded\n");
      client.print("Content-Length: ");
      client.print(postStr.length());
      client.print("\n\n");
      client.print(postStr);
      Serial.print("done posting : ");
      Serial.println(postStr);
   }else{
    Serial.print("failed to post : ");
   }
   client.stop();
   delay(15000);
}
```

Fig. 4: Arduino Code for Posting Data to the Dashboard

The final functional setup, as depicted in Fig. 9, illustrates the successful integration of the WiFi router into the system, enabling efficient data communication and retrieval. This setup is a testament to the adaptability and problem-solving approach taken during the project.

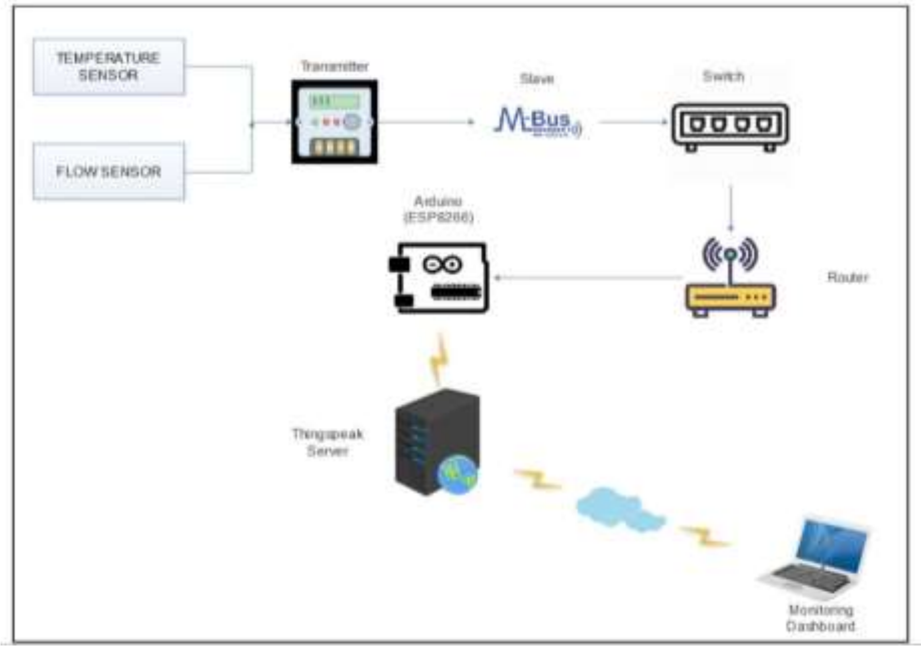

Fig. 5: Final Functional Set-up

Moreover, the hardware components of this setup, comprising the M-Bus, the switch, and the Arduino, are detailed in Fig. 10. This figure provides a visual representation of the physical arrangement and connections of the hardware components, offering a clear understanding of the system's architecture.

Fig. 6: Set-up Hardware

4. Results

The development of a remote monitoring system for solar thermal units yielded significant insights into the system's performance, leveraging a web application for effective data manipulation and assessment. This system's adaptability and utility were highlighted through various key parameters. In terms of energy analysis, the system's proficiency in monitoring energy usage was a success. Data obtained from Heat Meter 691 was crucial in this regard. The energy values illustrated in Fig. 11, were derived by deducting previously stored energy readings from the current cumulative values extracted from the Modbus registers. This approach enabled a dynamic and continuous assessment of energy consumption, which is vital for gauging the system's efficiency over time.

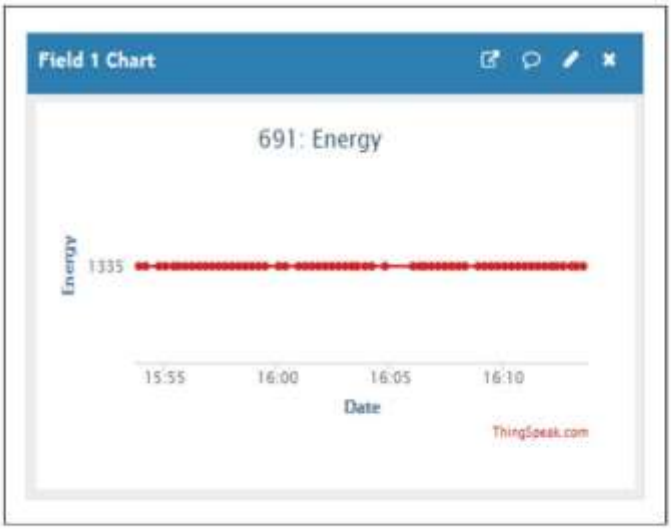

Fig. 7: Heat Meter Energy Values

The cumulative volume assessment, as depicted in Fig. 12, provided a comprehensive view of the total volume of fluid that had flowed through the system since the meter's installation. However, the direct extraction of monthly data from the Modbus was not feasible, necessitating manual tracking of cumulative volume at regular intervals. Despite its manual nature, this method offered valuable insights into the long-term consumption patterns and throughput of the system.

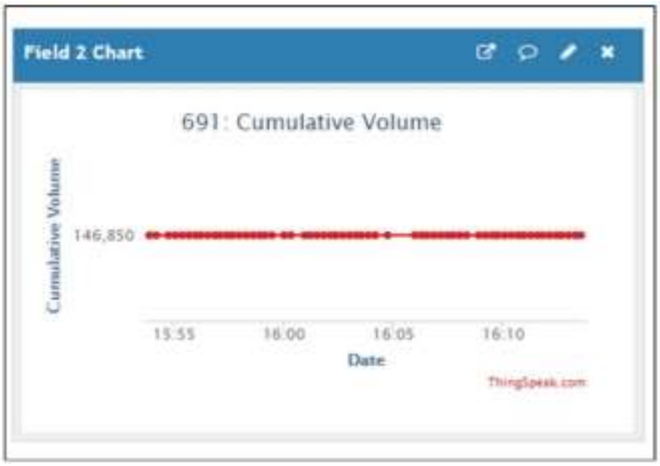

Fig. 8: Cumulative Volume Values

Flow rate monitoring was another critical aspect, with the system offering near real-time monitoring capabilities, as shown in Fig. 13. This feature allowed for the identification of minimum and maximum flow rates by analyzing the troughs and crests in the data, which was instrumental in detecting any operational anomalies and ensuring the system functioned within its expected parameters.

Fig. 9: Flow Rate Values

Similarly, power consumption tracking was effectively executed. The power graph, presented in Fig. 14, provided instantaneous readings of power consumption with minimal delay. This real-time tracking was key in identifying fluctuations in power usage, thereby aiding in the optimization of the system's energy efficiency.

Fig. 10: Power Values

The dashboard's functionality was central to the system's effectiveness. It not only facilitated the display of data in an easily accessible format but also enabled the manipulation of first loop values to derive more meaningful second loop values. This capability was essential for customizing the data presentation to meet the specific monitoring requirements of the solar thermal units. In summary, the results from the developed remote monitoring system highlighted its capability in delivering detailed and real-time insights into the performance of solar thermal units. Its ability to track and analyze energy, volume, flow rate, and power provided a thorough understanding of the unit's operational efficiency, establishing it as an invaluable asset for continuous performance assessment and optimization.

5. Conclusion

In concluding this project, which focused on the development of a Remote Monitoring System for Solar Thermal Units, significant progress has been made in the field of solar energy management and monitoring. The project successfully achieved its design goals, creating a system that meets market needs and demonstrates practicality and market readiness. The primary accomplishment of this project is its capability to enable remote monitoring of solar thermal units. By effectively posting data to a web dashboard, the system provides a comprehensive tool for analyzing the performance of these units over time. This is particularly important for understanding and improving the efficiency and operation of solar thermal systems.

However, there are areas for future improvements. Recommendations such as regular maintenance, the installation of a dedicated router, upgrading the dashboard license, and adding a sunlight intensity reader, are all steps that can further enhance and refine the system. These improvements would not only boost the system's reliability and data precision but also broaden its functionality to provide deeper insights into the performance of solar thermal units under different environmental conditions. Overall, this project has established a solid foundation for advanced monitoring of solar thermal systems.

It has filled an important gap in remote monitoring technology, offering a scalable and efficient solution for optimizing the use of solar thermal energy. The success of this project serves as a promising example for similar implementations in other institutions and settings, leading the way for more sustainable and efficient energy management practices in solar thermal technology.

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