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DESIGN AND IMPLEMENTATION OF A LOCALIZED MONITORING FOR GEL-TYPE BATTERY WITH FAULT DETECTION AND IDENTIFICATION

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ABSTRACT

The reliable operation of solar photovoltaic (PV) systems is critically dependent on the performance and stability of their battery storage components, which remain among the most failure-prone and technically challenging elements to manage. Effective battery monitoring is essential, yet traditional manual inspection methods are impractical due to the heterogeneous electrical characteristics of individual batteries, the variability of operating conditions, and the large number of units within a typical installation. These limitations often lead to inefficiencies in maintenance practices, unexpected system downtime, and a shortened overall battery lifespan. This study addresses these challenges through the design and implementation of a localized, real-time monitoring system specifically developed for Gel-type batteries in solar PV applications. In addition to monitoring, the system incorporates advanced fault detection and identification algorithms, enabling predictive maintenance by issuing timely notifications of emerging faults. Such functionality enhances diagnostic accuracy, supports informed decision-making, and allows for rapid mitigation strategies. The results of this work demonstrate that integrating real-time monitoring with automated fault diagnostics significantly reduces operational and maintenance costs while simultaneously enhancing system efficiency and reliability. Furthermore, the proactive management enabled by this approach extends battery service life and contributes to improved safety and resilience of solar PV infrastructure.

I. INTRODUCTION

Storage and controller systems are the backbone of today's renewable energy configurations. Innovations on these systems have developed the overall environment of sustainable energy generation requirement into enhanced functionality and increased safety operation of the whole set-up. With most of the recent applications, devices and systems being dependent on battery energy storage support, there is an urgent need to explore more ways to enhance and improve the current technological implementation where energy sustainability dependence is crucial. The need to improve the implementation and operation of real-time monitoring systems is crucial to mitigate possible problems. As technology advances in real-time monitoring systems applications, and with the integration of fault detection and notification systems, photovoltaic systems and installations have seen an overwhelming progress on systems' efficiency, operational safety and improved reliability with an optimized management and processes.

Fault and error detection and identification systems with notifications have shown to improve data interpretation and analysis, streamline administration, optimize troubleshooting strategies and decrease intervention and manual monitoring processes [1]. As these systems are integrated, they play a very important role in system optimization through enhanced predictive troubleshooting and maintenance strategies and fault and anomaly mitigation. Lead-acid batteries are the preferred storage solutions for renewable energy because of their low cost, high stability, less explosive in nature and mature regeneration technology [2]. Among the available lead-acid batteries, GEL-type has been identified to be the best suited for storing energy from renewable systems because of its physical characteristics of having the highest number of life cycles [3]. Battery health monitoring systems have been implemented to improve the performance and efficiency of battery storage systems which is vital and critical to ensure the long and healthy life of battery storage.

I.2 LITERATURE REVIEW

According to Ansari et al. [4], due to various factors and environmental conditions having significant impact on the operation and functionality of solar photovoltaic systems, employing an efficient monitoring system can improve its accuracy and performance. Real-time monitoring of battery status using various tools and devices such as power sensors and temperature sensors to detect the battery needs to be addressed so as to extend the life of the battery through advanced error detection and improved battery maintenance. Secondary battery protection has become a new focus on improving the reliability and safety of battery systems as more commercial products and large-scale energy management systems have relied on rechargeable batteries [5]. Multiple methods of monitoring had been developed in improving the management and control of a system. Real-time monitoring has been integrated into several applications and systems such as health [6],[7], agriculture [8], [9], weather [10],[11] among others.

A study by Rani et al. in [12] proposed a monitoring and control system for green house implementation. In the study, micro-climactic parameters are effectively monitored to achieve optimal plant growth in diverse conditions. For the monitoring functionality, multiple node sensors are deployed that collect real-time information on these parameters for a comprehensive and accurate data collection. In optimizing the plant growth potential, collected data are analyze so that the system can regulate and maintain favorable growing conditions for the plants. Through real-time monitoring and system management, energy systems' efficiency and reliability are maximized. According to the study of Sumarmad et al. in [13], a monitoring and energy management system was developed for microgrids to smart homes using fuzzy logic. In their proposal, using real-time data analysis, an improved load management and performance and monitoring system was developed for interconnected distributed generators in the microgrid system. A method of energy management was implemented by equally distributing available electricity to the individual user through balanced demand and consumption.

In a similar study by Mutlag et al. in [14] for microgrids systems, the proponents developed a maximum power tracking algorithm that monitors energy for power management and voltage regulation in a solar photovoltaic system. Through the monitoring functionality of real-time data such as temperature and solar radiation, battery charging and discharging processes are controlled. Likewise, through the monitoring of the battery's state of charge, the bidirectional boost converter connected to photovoltaic panels is controlled. As one of the most important and efficient ways of supporting the needs for sustainable energy, energy storage batteries are considered to be the forefront component to complement said technologies. The study of Rakhimov et al. in [15] differentiated the most common type of battery solutions that are commonly used as energy storage devices. These are the a) lithium-ion batteries, 2) lead-acid batteries, 3) flow batteries and 4) sodium-ion batteries. The first two types of batteries are favored for renewable energy storage because of their electrical and physical characteristics.

Lithium-ion batteries have high density and which gives them the advantage to be used on portable and mobile systems while in comparison, the lead-acid type batteries offer robust and cost-effective solutions. Lead-acid batteries had been the preferred option as energy storage systems particularly in solar power systems, especially in homes and small businesses, due to their availability, low-cost installation and maintenance and improving research development in manufacturing this type of batteries [16]. Batteries have gained significant importance in storage systems with a projected expansion of 14.1% in the global battery market between 2020 and 2027. Lead-acid batteries have the maximum share of 29% of the total battery market volume primarily because of its low operational and maintenance cost and high energy capacity [17]. A study by Olarte et al. in [18] designed a battery management system with electrochemical impedance spectroscopy in monitoring lead-acid battery performance. It was designed to monitor temperature, voltage and impedance spectra of a battery using an improved algorithm that can monitor state of health and state of charge of lead-acid battery.

A similar study by Olarte et al. in [19] performed an experimental analysis that provided an important battery health diagnostic tools for predictive maintenance operation. According to this study, monitoring the health status of a battery storage system can significantly reduce the number of service failures while maximizing its life expectancy. With the study of Tao et al. in [20], it presented a different parameter in measuring the efficiency of a battery system. It identified the irreversible sulfation as a major problem that restricts the safe and efficient operation of a battery system. The study introduced a proactive maintenance strategy based on the capacitive nature of sulfation that helped determine the resonant frequency of sulfation on the battery. According to Wen et al. in [21], battery ageing is accelerated when the battery storage system experiences harsh conditions such as high temperature, high rate of charging and discharging and high overcharge time. These conditions can exponentially degrade the battery performance. Another study by Aprillia et al. in [22] presented a passive voltage balancer for rechargeable lead-acid batteries.

In their design, battery voltage balance level is managed such that energy storage is improved and rechargeable batteries are fully utilized. Through the battery voltage detection and power dissipation circuits, battery electrical parameters were displayed for monitoring. A separate study by Syafii et al. in [23] designed a battery state of charge monitoring and control system that accurately predicts the state of charge of the battery to extend the lifespan of the battery. Based on coulomb counting method, the algorithm calculates the incoming and outgoing current thus providing a reliable estimation of state of charge of the battery. With the addition of fault and error detection and identification functionality, an improved and optimized renewable energy system can be achieved. Because of this added functionality, predictive maintenance results in enhanced management and proactive troubleshooting strategies which eliminates system downtime occurrences. Mellit et al. [24] have identified three methods in identifying and detecting faults and errors in the system.

These methods include the manual process, semi-automatic method and the automatic method. The third method was identified to be more efficient as this method uses node sensors as data loggers which collects information through its monitoring systems and has the capability of fault detection and identification that automatically checks its system performance. As fault and anomaly detection and identification are integrated into the system, it has shown to have reduced operational and maintenance costs [25]. With a more optimized system, it has greatly reduced process and system downtime, avoided unidentified and unknown system issues and greatly minimized operational hazards and risks. For an improved and optimized maintenance and troubleshooting strategies and techniques, collection of up-to-date and current data on the situation of systems being monitored is very crucial in determining its system performance and reliability. With systems and applications that are prone to critical and dangerous situations, an early and accurate fault detection and identification system is very crucial. Examples of such systems are the battery backup storage systems. As batteries' chemical composition is very unpredictable, it is prone to failure which can quickly turn into a dangerous situation and worst a potential disaster if not immediately corrected. The safety of the system and its users are of utmost importance, thus a precise detection and identification of faults and errors have a great effect on the system's continuous and safe operation [26]. Analyzation of real-time battery parameters is essential in order to have an early warning capability that can isolate battery failures at an instant. Most of the available fault detection and identification functionality are integrated into battery monitoring systems for electric vehicles lithium-ion batteries. On the study of Kosuru et al. in [27], a deep learning based sensor fault detection was designed for a smart battery management system for electric vehicles. In the proposal, based on incipient bat-optimized deep residual network (IB-DRN) was developed for a false battery data detection and classification system.

With this method, it was shown that the safety and reliability of the battery management system was improved. A similar study on electric vehicle lithium-ion batteries was proposed by Cong et al. in [28]. In the study, a signal-based fault diagnosis method was developed in determining faults based on voltage signals inside the individual battery cells. This method was validated to be capable of early detection of anomaly, reduction of false alarms and identification of anomalous performance of the battery. Another study was proposed through internal short-circuit fault detection for lithium-ion batteries of electric vehicles. As presented by Zhang et al. in [29], thermal runaway has been a major problem with lithium-ion batteries and internal short-circuit was identified to be one of the major causes of it. For the safety enhancement of the electric vehicle through the reduction of thermal runway incidents, an early short-circuit fault detection method was introduced using a temporal convolutional network. The proposal demonstrated a detection of a maximum of 25 hours earlier detection of possible fault occurrence. With these monitoring and diagnostic capabilities for battery management, it ensures an accurate report on battery health conditions that increases life-expectancy of these batteries. This study is intended to design and implement a localized monitoring for gel-type batteries implemented into a contemporary stand-alone off-grid solar charge controller system. Fault detection and identification is integrated into the functionality.

II. THEORETICAL REFERENCE

The research is to design and implement a localized monitoring system for the health status of Gel-type batteries used in a contemporary solar charge controller system. Fault detection and identification functionalities are included in the scope of the study. The overall system is designed to operate continuously while logging all pertinent data and operation locally into a writable storage. Node sensors collect all battery electrical parameters and microcontroller processes this information then stores into a local storage device.

II.1 FRAMEWORK

Input-process-output is the model used as the framework of this study as presented in the figure below at Figure 1. The inputs are represented by the battery electrical parameters collected by the node sensors and output are represented by information displayed on the LCD and stored in the SD card. Algorithms performed by the microcontroller as a monitoring process include the fault detection and alarm notification processes. Real time status and analysis of data received from sensors determines the information displayed on the output for proactive maintenance strategy and troubleshooting techniques.

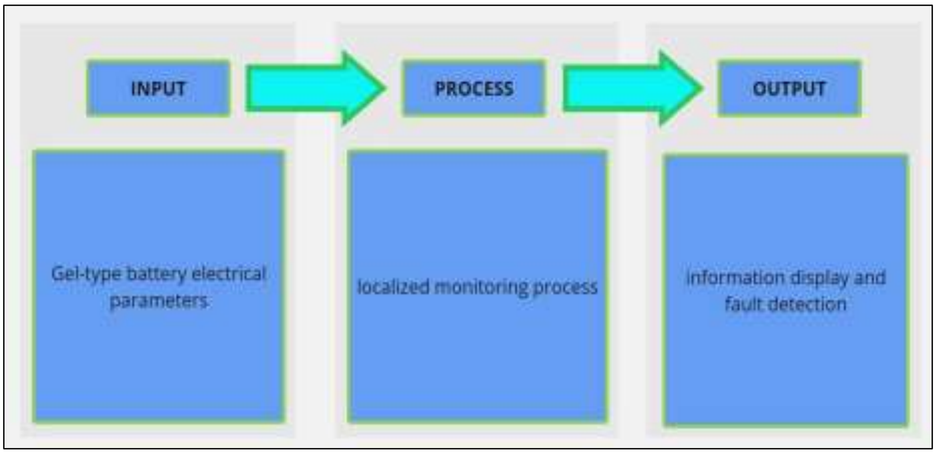

Figure 1: Framework.
Source: Authors, (2025)

II.2 DIAGRAM

The block diagram, shown in Figure 2 below, illustrates the overall structure as a monitoring system for the real-time status of a GEL battery on a solar photovoltaic energy system. Each component serves a specific function in enabling efficient operation, ensuring accurate data interpretation for enhanced monitoring capabilities.

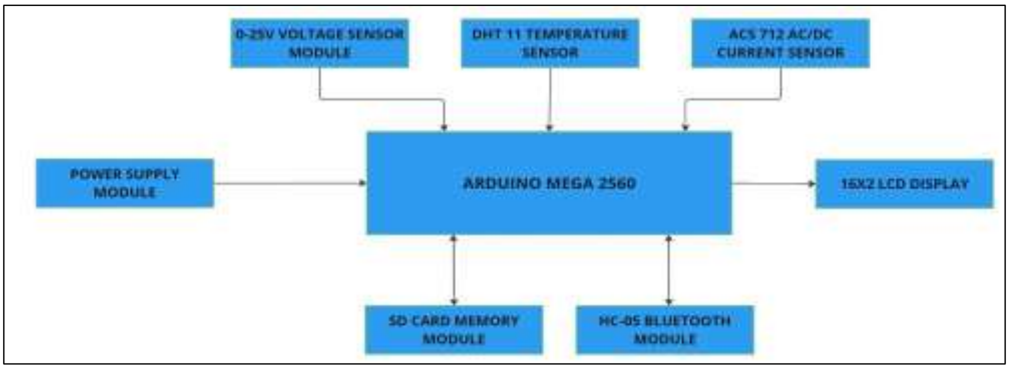

Figure 2: Block Diagram.
Source: Authors, (2025).

A set of node sensors are used in collecting battery electrical parameters such as voltage, current and temperature. The Arduino Mega serves as the brain of the system and the one responsible for analyzing and interpreting data received from node sensors. SD card module serves as data storage for received and analyzed data while Bluetooth module is used for data extraction from the SD card module into a PC laptop for a more enhanced data processing and analysis. Sensor data readings from battery voltage, battery temperature and battery charging and discharging currents are continuously recorded and sent to the microcontroller every minute for data processing and interpretation.

III. MATERIALS AND METHODS

III.1 CONTEMPORARY SOLAR CHARGE CONTROLLER SYSTEM

Composing the solar photovoltaic solar charge controller system are 2 parallel connected 100W 18V solar panels connected to a 40A MPPT solar charge controller with a combination of parallel connected 12V 150Ah Gel-type battery as energy storage. Figure 3 below shows the actual set up of the solar photovoltaic system. The actual installation location of the system is presented in the Figure 4 below showing the generated average daily Direct Normal Irradiation (DNI) of 3.973 kWh/m2/day and an average of annual DNI of 1450.2 kWh/m2 using Global Solar Atlas information [30].

Figure 3: Contemporary Solar Charge Controller System.
Source: Authors, (2025)

Figure 4: Global Solar Atlas Information.
Source: Authors, (2025)

III.2 DC LOAD COMPOSITION

To simulate an actual DC load, a 12V wireless antenna (10W) and CCTV (18W) are connected on the load side which will operate 24 hours a day and 7 days a week continuously.

Figure 5: DC Load consisting of Wireless Antenna and CCTV.
Source: Authors, (2025)

III.3 LOCALIZED MONITORING SYSTEM

The localized monitoring system is designed to determine the estimated remaining usable life of a Gel-type battery and locally monitor the health status of the battery through its real-time data displayed into an LCD display. Over the course of time, with the inconsistent decrease of battery state of health happening, future battery degradation is not always like with previous recorded pattern of the battery. It can be said that battery degradation over time is a non-linear pattern. Accurate determination of remaining useful life is important to better understand the approximate time that the battery will reach its end of life to help in proactive maintenance activities. Voltage, current and temperature are the common parameters that are measured to determine the approximate remaining useful life of the battery through its charging and discharging rate, depth of discharge and state of charge.

The monitoring system is composed of the following materials and components:

Arduino Mega 2560 acts as the brain of the system. All algorithms and codes are embedded in their internal memory. It is a microcontroller board based on the Atmel 8-bit low-power CMOS chip on AVR enhanced RISC architecture. A combination of analog and digital I/O ports can be used as an interface to different types of sensors and modules. This microcontroller is selected for its capability to have 4 hardware serial ports (UARTS). 0-25V Voltage Sensor measures voltage across terminals. It is the preferred voltage sensor because of its ability to use the analog input of a microcontroller to monitor voltages much higher than the microcontroller is capable of sensing. For current measurements, the ACS712 AC/DC Current Sensor is utilized. This current sensor uses an internal hall effect sensor that measures the electromagnetic field strength and direction of current flowing inside the internal conductor. This current flow generates a voltage proportional to the current passing through the sensor.

The DHT11 Temperature Sensor module can measure temperature from 0C to 50C with a +-2.0C accuracy. With its sampling rate of 1Hz it can read and provide new reading every 1 second. This module has the DHT11 temperature sensor composed of NTC thermistor and humidity sensing components. The resistance in the NTC thermistor will change with a change of temperature. The NTC refers to Negative Temperature Coefficient which gives a decrease of resistance as temperature rises. The Bluetooth module facilitates wireless communication between the wireless microcontroller stored data on the SD card and a PC laptop for data extraction. Bluetooth communication is a short-range data transmission capable of exchanging data between devices for a maximum distance of 10 meters without obstruction. The Bluetooth module is incorporated with Bluetooth transceiver that enables both data transmission and reception.

For displaying real-time sensor readings, a 16x2 LCD module is used. Alphanumeric characters can be displayed in 2 lines representing the information to be displayed regarding the status of the battery and the operation of the system. Alphanumeric characters and custom characters can be created by activating corresponding pixels. The SD card module is used as data storage for continuous data logging. With this, data can be written or read from a FAT32 formatted SD card. Using the SPI communication interface protocol, data transfer from the microcontroller to the SD card is straightforward.

III.4 FAULT DETECTION AND IDENTIFICATION

With the capability of fault detection, the system can identify the occurrence of fault on the battery storage system which will influence the operation of the load. Information about batteries will be displayed on the LCD screen to notify for an occurrence of a fault. Information on the source of such a fault will also be identified and displayed. For a continuous and safe system operation, fault detection and fault identification play a very important role which optimizes the management and control of a renewable energy system. With the capability of identifying system faults and errors, proactive maintenance is realized through the real-time management decision during occurrences of serious system situations and circumstances, resulting in improved troubleshooting and maintenance strategies. Alert system through fault detection and identification of the localized monitoring system serves as its primary function and an important part of its operation. Four alert levels are presented for proper identification of faults encountered by the system.

These are Critical Level, Error Level, Warning Level and Normal Level. Critical Level alert is identified once lifespan of battery is analyzed to be declining through the calculation of its remaining useful life, Error Level alert is displayed if no data from sensors are received or received value is 0 on any of the sensors, Warning Level alert represents sensors receiving data that are outside of its acceptable range, and Normal Level alert shows that the system is performing at normal operation and displays sensor values only. According to the general specification of GEL battery [31], the ideal operating temperature ranges from 10C and 27C with 25C as the recommended center point. As temperature deviates from its center point, such as high temperatures, there is a significant effect on the service life of the battery. The specific float charging voltage is given as 13.5 to 13.8 volts and absorption charging voltage is 14.1 to 14.4 volts. Based on the specified load of approximately $12V_{DC}$ 30W, the calculated discharge current is between 1A and 3A. Charging current are in the range of 8-11A based on the solar panels provided.

III.5 BATTERY REMAINING USEFUL LIFE

With the calculation of the available battery capacity [32], Columb Counting method is utilized. Estimating the State of Charge (SoC) and State of Health (SoH) of the battery, the remaining battery capacity is achieved. Actual battery capacity is calculated as battery real time State of Health (SoH) multiplied with battery rated capacity (3). Real time SoH (2) is based on the ratio of real-time battery capacity (1) and previously calculated battery capacity. State of Charge calculation is shown in (4).

Real-time Battery Capacity

BatteryCapacityRT = BatteryCapacityPR + I(Charging – Discahrging) (1)

where:

BatteryCapacityRT = real-time battery capacity (Ah)
BatteryCapacityPR = previously calculated battery capacity (Ah)
I(Charging – Discahrging) = difference of the average charging and discharging current for the past hour (Ah)

Real-time Battery State of Health

StateofHealthRT = BatteryCapacityRT / BatteryCapacityPR (2)

Actual Battery Capacity

BatteryCapacityAC = StateofHealthRT * BatteryCapacityR (3)

where:

BatteryCapacityAC = actual battery capacity (Ah)
StateofHealthRT = real-time battery State of Health
BatteryCapacityR = rated battery capacity (Ah)

Real-time State of Charge

StateofChargeRT = BatteryCapacityRT / BatteryCapacityR (4)

As SoC and SoH declines with time, so as the battery capacity will also decline together with Soc and SoH. Once the algorithm detects that battery capacity has a downward trend within specified time, a Critical Alert is activated.

IV. RESULTS AND DISCUSSIONS

The localized monitoring system was able to continuously monitor GEL type battery electrical parameters through its node sensors. The periodic collection of these parameters was performed by the Arduino microcontroller, where this information is further analyzed and interpreted for decisions regarding the status of the battery's useful life. Processed and interpreted data are then stored into locally available storage for backup and further analyzation and interpretation processing. The code for the Arduino programming was created using the Arduino IDE, shown in Figure 6 below. The syntax for the code follows the algorithm of collecting node sensor values and saving it to SD card. This process is done every minute and the processing of identification of alert level type is determined for displaying on the LCD screen.

Figure 6: Arduino IDE Code Syntax.
Source: Authors, (2025).

As soon as the codes were checked for syntax errors and compilation issues, it was simulated in the proteus simulation environment. The figure below, Figure 7, displays the circuit used in the simulation software. All modules and components were integrated to simulate the output with respect to the input parameters given to node sensors. This simulation process is an integral part in the design as codes are tested before deploying actual devices and components. As the need to update the syntax algorithm, it has made the design process easier and faster.

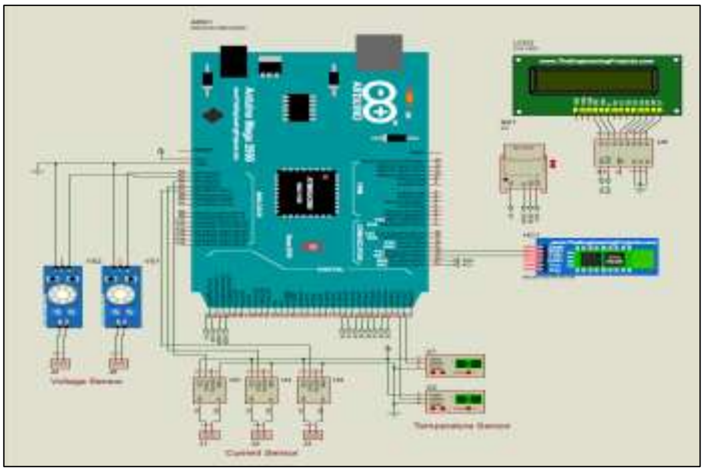

Figure 7: Circuit Simulation.
Source: Authors, (2025)

Once the running codes were verified to work as designed, the assembly of actual parts and components for the hardware system followed. The analog input pins A0-A3 serve as data receiver from node voltage, current and temperature sensors. Digital input pin 17 (Rx) as input to Bluetooth module and digital pin 16 (Tx) as output to Bluetooth module. Figure 8 below shows the actual interconnection of the different parts and components of the system.

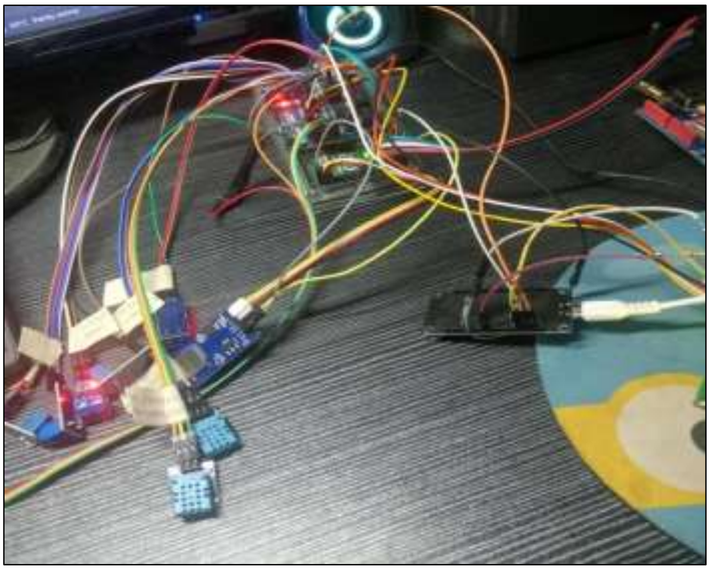

Figure 8: Hardware System.
Source: Authors, (2025)

Output of the logic process of the microcontroller based on the received data from node sensors are displayed into the LCD display. Displayed are the alert status level of the monitoring system based on the result of data analyzation and processing. As discussed, alert status level can be either Critical Level, Error Level, Warning Level or Normal Level, as displayed in the Figures below.

Figure 9.a: LCD Normal Display Output.
Source: Authors, (2025).

Figure 9.b: LCD Error Display Output.
Source: Authors, (2025).

Data collected by the microcontroller is saved on the SD card module for storage as a backup in case there is a need for further processing and analyzation. If more complex understanding of the recorded data is required, it can be extracted into a PC or laptop device through the Bluetooth module. Figure 10 below shows the entries of data that are saved into the *data.csv* file into the SD card.

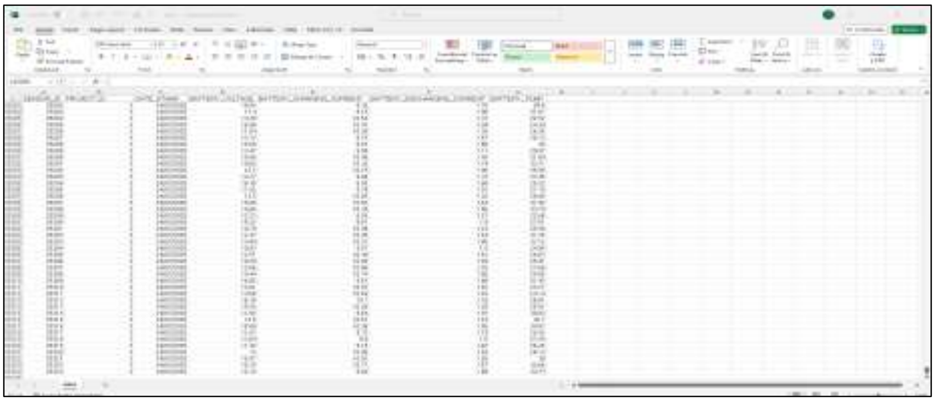

Figure 10: SD Card Stored Data.
Source: Authors, (2025).

Real time analysis and interpretation of data is crucial in the management and monitoring of a battery backup system. With added capability of fault detection and identification, maintenance and troubleshooting techniques are enhanced and made more efficient through proactive management decisions. System optimization is likewise improved through systems' continuous and safe operation resulting in lesser downtime of the system and reduced operational costs. Integrating these functionalities into a battery energy backup system ensures the enhanced management strategies as well as the improvement of system reliability. Although the existing system enables real-time monitoring of battery status, the implementation of an online monitoring infrastructure is needed for achieving a more sophisticated and optimized monitoring strategy. The capacity for localized data analysis and interpretation is naturally constrained by the limited computational resources of the microcontroller. However, the integration of cloud- and web-based platforms allows for advanced data analytics and robust processing capabilities, and as such enhances the precision, reliability, and interpretability of the acquired data. The integration of a mobile application as a visualization interface would significantly augment the system's functionality. Such an interface would not only provide an enhanced understanding of real-time data representation for the user but also enable more intuitive interaction, thereby improving the comprehensibility and accessibility of the solar photovoltaic system. Finally, in light of recent advancements in sensor technologies and data communication protocols, the deployment of a fully remote, online monitoring framework offers considerable potential to strengthen the management and operation of the system. This would improve troubleshooting efficiency and predictive maintenance practices. In the same vein, the incorporation of advanced fault detection and diagnostic algorithms within the monitoring architecture would enable proactive maintenance, thereby improving system reliability and the overall performance of the solar photovoltaic system.

V. CONCLUSIONS

A localized monitoring system with fault detection and identification is essential in the monitoring of a battery-based energy source system. For a solar photovoltaic system to operate continuously without disruption, the need to understand the common cause of problems with the system is very crucial. A common problem with this type of renewable energy system is the monitoring of the battery storage component of the system. Because of the unique individual electrical characteristics of each battery, it is very complex and complicated to manually check the status of every battery used. With a real-time monitoring system that automatically records periodic and timely battery parameter values, the management and operation of the solar photovoltaic system will be optimized and enhanced, ensuring a continuous operation without interruption. Leveraging the fault detection and identification functionality into a monitoring system enhances its troubleshooting and maintenance capability as faults are identified accurately and can be diagnosed and fixed efficiently.

With this process, system downtime during faults and errors are minimized ensuring the continuous operation of the monitored system. Together with its enhanced diagnosis and mitigation processes, system resiliency against emerging challenges and issues is strengthened resulting in an optimized system. System performance can be evaluated effectively through the availability of stored battery parameters that are used for further processing and analysis. The need to interpret the available stored data would also enhance system performance through design improvements and system operation. As sensor node values depend on the environmental conditions that surround the monitored system, data and information collected needs to be an accurate representation of the values recorded. Ensuring the security and availability of data is crucial for the management of the monitored system.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Chito A. Petilla
Methodology: Chito A. Petilla and Edward M. Querikiol.
Investigation: Chito A. Petilla.
Discussion of results: Chito A. Petilla.
Writing – Original Draft: Chito A. Petilla.
Writing – Review and Editing: Edward M. Querikiol.
Supervision: Edward M. Querikiol.
Approval of the final text: Edward M. Querikiol.

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