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Battery Management System for Solar Power Plants in Uganda: An IoT-Driven Approach

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Abstract: In Uganda, the efficiency and reliability of solar power plants are often compromised due to inadequate battery management, leading to reduced battery lifespan and suboptimal performance. To address this challenge, this project develops and prototypes a smart Battery Management System (BMS) tailored for solar power plants. The system continuously monitors key battery parameters, including voltage, load current, and temperature, while leveraging Internet of Things (IoT) technology for real-time data transmission and remote monitoring. Intelligent algorithms autonomously regulate charging and discharging cycles to prevent overcharging and deep discharge, optimizing battery performance. Testing demonstrated that the BMS significantly improved battery lifespan and energy efficiency by disconnecting charging at 100% and isolating the load at 10% discharge to prevent battery degradation. Additionally, the system disconnects power when battery temperature exceeds 30℃ (ambient temperature: 25℃) and detects abnormal current levels above 0.16A to mitigate faults such as short circuits. These automated protections enhance battery reliability and longevity. By implementing proactive battery management strategies, the developed BMS contributes to more efficient and resilient energy storage systems, promoting sustainable energy development in Uganda.

Index Terms: Battery Management System, Solar Power Plants, IoT, State of Charge, Depth of Discharge

1. Introduction

Battery Management Systems (BMS) play a crucial role in monitoring and regulating battery packs, which consist of multiple battery cells arranged in a matrix configuration to deliver a specified voltage and current over a given period. These systems are essential in energy storage applications such as solar power plants and electric vehicles, ensuring efficient energy utilization and battery longevity. Among commonly used battery technologies, lithium-ion batteries (LiBs) stand out due to their high power density, low self-discharge rate, and cost-effectiveness. However, maintaining uniform performance at the battery pack level is challenging, as individual cells within a pack may experience uneven charge/discharge rates, varying temperatures, and aging effects, leading to inefficiencies and potential safety hazards. To address these challenges, an efficient BMS is required to track, manage, and optimize battery performance at both the cell and pack levels, ensuring operational safety and longevity.

Uganda, like many developing nations, faces significant energy access challenges. While solar power presents a viable alternative, its adoption is hindered by inefficient energy storage solutions and high initial costs associated with conventional BMS technologies. In Uganda, electricity access is 57.2% in urban areas but only 10% in rural regions [1], highlighting the need for affordable and reliable energy storage solutions. Similar challenges have been reported in other countries, such as Bangladesh, where solar energy adoption is constrained by BMS limitations [2]. Despite the critical role of batteries in solar power plants, existing BMS solutions often lack real-time monitoring capabilities, proactive fault detection, and optimized charge-discharge management, making them less effective in ensuring long-term energy storage reliability. There is a clear demand for an advanced yet cost-effective BMS that integrates intelligent monitoring and control mechanisms to improve solar energy utilization. Such a system would enhance energy access, reduce carbon emissions, and stimulate economic growth. Moreover, monitoring these systems is crucial [3, 4] to ensure their proper functioning and efficiency.

To address these limitations, this study proposes an IoT-enabled BMS designed to enhance solar energy storage efficiency, offering real-time remote monitoring of battery voltage, charge/discharge current, and temperature. The system estimates State of Charge (SoC) and State of Health (SoH) based on real-time data, enabling proactive maintenance and performance optimization. Additionally, it incorporates automated charge-discharge regulation, where the battery is disconnected at full charge (100%) and isolated from the load when reaching a predefined low voltage threshold, preventing overcharging and deep discharge. To further improve reliability, the system includes fault detection mechanisms, continuously monitoring for abnormal temperature variations and excessive current levels to detect potential failures such as short circuits or overheating. Unlike conventional BMS solutions that rely solely on threshold-based cut-offs, this system leverages intelligent algorithms to dynamically optimize charge-discharge cycles based on real-time battery conditions. Furthermore, IoT integration enables global remote monitoring via a cloud-based interface, providing users with instant alerts and historical performance data features often missing in traditional systems.

By integrating real-time monitoring, intelligent control algorithms, and IoT-based accessibility, the proposed system offers a robust, cost-effective, and scalable solution for managing solar power storage. Its successful implementation contributes to Uganda’s sustainable energy initiatives, supporting greater solar power adoption and long-term energy security in underserved regions.

This paper is organized as follows: Section 2 reviews related works, highlighting existing battery management solutions and their limitations. This section also compared the key features of the proposed BMS with the traditional ones. Section 3 presents the design and implementation of the proposed IoT-based BMS, including the selection of components, system architecture, intelligent monitoring algorithms and implementation of the system architecture. Section 4 analyzes the results of the proposed system, and discusses the limitations and potential biases. Finally, Section 6 concludes the paper by summarizing the findings and suggesting future research directions to further enhance battery management efficiency and reliability in solar power applications.

2. Related Works

The field of BMS for solar power plants has seen significant developments. The important works and pertinent literature that influenced the research done for this project are highlighted in this section. Tejero-Gomez and Bayod-Rujula emphasise photovoltaic generation as an essential renewable energy technology, but they point out that because solar radiation is sporadic, it is difficult to integrate into the current electrical system. Additionally, they suggest that anticipated price drops for battery storage systems may improve their compatibility with utility-scale solar farms [5]. In addition, Chaitrashree, Kashyap, and Sidharthan stress that battery storage has emerged as the go-to option for solar photovoltaic (SPV) infrastructure. Solar panels are recognized for their safety and are among the most frequently used renewable energy sources today [3]. The important importance of lithium-ion batteries (LiBs) and their SoC estimation techniques is highlighted in their review, which examines a variety of energy storage technologies and Battery Energy Storage Systems (BESS). For energy storage systems to operate effectively and dependably, the authors emphasise the necessity of combining BMS with solar PV and BESS [6].

The function of secondary batteries in storing energy generated by solar panels was examined by AR Afif, B.S. Aspillia, and W. Priharti. They noted that incorrect management can result in damage from overcharging and overdischarging. The goal of their study was to create a BMS for a valve-regulated lead-acid (VRLA) battery by estimating the SoC using the Coulomb Counting (CC) approach. When the SoC reached the charging limit of 100% and the discharging limit of 20%, their results showed that the BMS was successfully developed and executed, automatically cutting the current [7]. Md. Alamgir Hossain, Carlos Macana Moreno, and Hemanshu Roy Pota also underlined the need of energy storage systems as essential parts of renewable energy production. They pointed out that these technologies save operating costs in addition to easing the difficulties related to intermittent power generation. The authors suggested adding a dynamic penalty function to the cost function's charging length in order to maximise battery energy management and further reduce expenses. This method uses solar power generation data and real-time residential electricity prices (RRTP) to effectively regulate the battery's charging and discharging times [8]. Anurag K. Srivastava, Parviz Famouri, Paramarshi Banerjee, and Solmaz Nazaralizadeh emphasise that Battery Management Systems (BMSs) are made to prolong battery life and guarantee safe operation, which lowers early degradation. Certain BMSs offer precise state estimations, which are essential for risk mitigation and safe battery operation. These systems' efficacy depends on accurate assessments of battery health that are obtained by examining a number of factors [9]. For safe battery charging and discharging while supplying loads, Filippo Spertino, Alessandro Ciocia, Paolo Di Leo, Gabriele Malgaroli, and Angela Russo point out that a basic BMS is necessary. Through the prohibition of quick charge and discharge cycles and the maintenance of SoC restrictions, this technique shields batteries from rapid degradation. When combined with photovoltaic (PV) generators, more sophisticated BMSs can reduce peak demand and further protect storage systems [10]. According to Reference [11], the BMS is a basic battery monitor that continuously measures variables including temperature, voltage, and current when the battery is being charged and discharged.

Traditional BMS for solar power primarily focus on basic charge regulation and protection from overcharging and deep discharge, relying on threshold-based cut-offs [7, 10]. These systems often lack real-time monitoring and cannot detect faults, such as short circuits or abnormal temperatures. While some systems incorporate local microcontrollers, they generally lack remote accessibility. In contrast, the proposed BMS integrates IoT technology for real-time remote monitoring and automated fault detection based on current and temperature variations, providing proactive protection. Unlike conventional systems, it dynamically optimizes charge/discharge cycles to improve battery lifespan and energy efficiency. This combination of features makes the proposed BMS more reliable and efficient than existing solutions. To highlight these improvements, Table 1 compares the key features of the proposed BMS with those of conventional battery management systems.

Table 1. Comparison of key features of the proposed BMS

Feature	**Existing BMS Solutions**	**Proposed BMS**
Battery Type	Various (Lead-acid, Li-ion)	Tailored for solar power plants (Li-ion)
SoC Estimation	Coulomb Counting, SoC estimation	Dynamic regulation, automated control
Overcharge/Over-discharge Protection	Basic threshold cutoffs	Intelligent charge/discharge regulation based on real-time conditions
Temperature Monitoring & Protection	Limited in some systems	Automatic disconnect at 30 ℃ to prevent overheating
Fault Detection (e.g., short circuits)	Not included	Detects abnormal current levels and triggers automatic protection
Remote Monitoring & Control	Some advanced BMS systems include local monitoring	Fully integrated with IoT for real-time remote monitoring and alerts
Optimized Charging/Discharging	Static thresholds	Adaptive control based on real-time battery health and external factors (e.g., solar generation, temperature)

The table clearly illustrates how the proposed BMS enhances traditional solutions by incorporating smart automation, real-time monitoring, and proactive fault protection, making it a more efficient and reliable solution for solar power applications.

3. Methodology

This section describes the systematic approach used to create the suggested system. It lists and explains the different tools and applications that were utilised, along with the steps that were followed to create the prototype.

3.1 Conceptual Frame Work

This section presents the various equipment and components used to develop the project structure, as illustrated in the block diagram of Fig. 1.

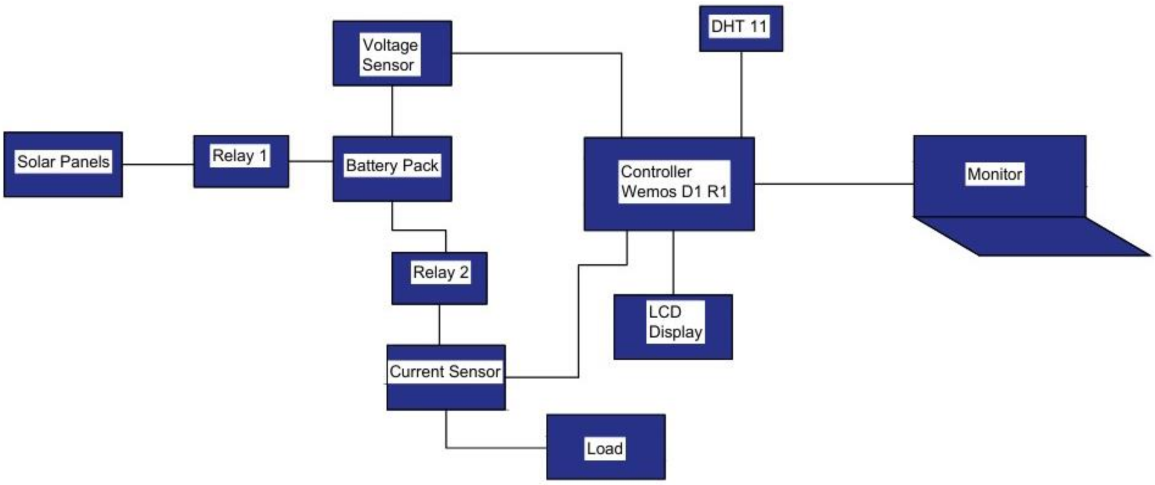

Fig. 1. System Block Diagram

3.2 System Components

The project involves implementing various components, sensors, and control equipment, such as solar panels, voltage sensors, current sensors, cell balancers, batteries, a DHT11 temperature and humidity sensor, a liquid crystal display (LCD), a NodeMCU ESP8266, relays, and a monitor (laptop or phone), among others.

3.2.1 Photovoltaic Panels

These are also known as photovoltaic panels. They capture solar energy and convert it into electrical energy, generating direct current (DC) electricity from sunlight exposure. In this project, the solar panels serve as the primary energy source, charging the battery bank and powering the load directly during the day (if connected). Note: Monocrystalline solar panels were used in this project as shown in Fig. 2.

Fig. 2. Monocrystalline Solar panel used in the project

3.2.2 Batteries

Rechargeable batteries, such as lead-acid or lithium-ion batteries, are commonly used. In solar power plants, multiple battery cells are connected in series or parallel to form a battery pack. These batteries store excess energy generated by the solar panels and provide power to the load during nighttime or periods of low sunlight. A visit was made to the battery room at the Kololo Solar Power Plant to observe the setup and arrangement of the battery pack. Fig. 3 shows the battery room during the visit.

Fig. 3. Battery room at Kololo solar power plant

Note: In this project, lithium-ion batteries were used. These batteries were connected together to form a simple battery pack, as shown in Fig. 4.

Fig. 4. Lithium ion batteries used in the project

The solar panel was connected to the battery pack through a relay and a manual switch, providing both autonomous and manual control over the charging process. The relay enables automatic switching based on predefined conditions, such as battery voltage levels, while the manual switch allows for user intervention when needed, ensuring flexibility in managing the charging of the battery pack.

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3.2.3 Voltage Sensor

The voltage sensor is essentially a voltage divider consisting of two resistors with resistances of 30KΩ and 7.5KΩ, forming a 5:1 voltage divider. It was connected across the battery pack terminals to measure the pack's voltage. The sensor was then linked to the controller (Wemos D1 R1) through a multiplexer for data acquisition. The voltage sensor used in the project is shown in Fig. 5.

Fig. 5. Voltage sensor used in the project

3.2.4 Current Sensor

The ACS712 current sensor module was employed to measure the current drawn from the batteries by the connected loads. This sensor was properly calibrated and connected in series with the load, enabling accurate current measurement. It was then linked to the controller (Wemos D1 R1) through a multiplexer for effective data processing and monitoring. The current sensor used in the project is shown in Fig. 6.

Fig. 6. Current Sensor used in the project

3.2.5 Controller (Wemos D1 R1)

Wemos D1 R1 is used in the project as depicted in Fig. 7 and this controller was used to manage the various components in the system, ensuring that each one performs its intended functionality. The Wemos D1 R1 features an ESP8266 chip, which enables IoT capabilities for monitoring the battery pack parameters remotely. All components involved in measuring the system parameters and controlling operations are connected to this controller.

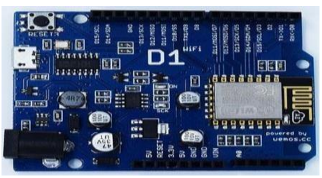

Fig. 7. Wemos D1 R1 used in the project

3.2.6 Multiplexer

Given that the Wemos D1 R1 board has only one analog pin (A0) but requires reading data from two sensors (voltage and current sensors), a multiplexer was implemented to facilitate data collection from both sensors using the single analog pin. This approach allows for efficient switching between the sensors, enabling the controller to alternate readings and accurately monitor both voltage and current in real time. By employing the multiplexer, we can maximize the functionality of the Wemos D1 R1 while ensuring that critical battery parameters are continuously monitored. The Multiplexer connected to ESP8277 is shown in Fig. 8.

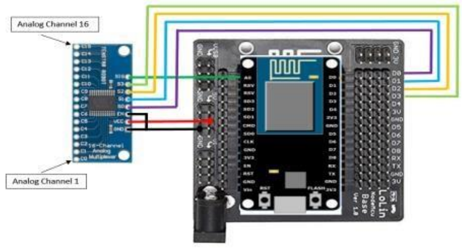

Fig. 8. Multiplexer connected to ESP8277

3.2.7 DHT 11

A DHT 11 is used in the project as depicted in Fig. 9 and this sensor was employed to measure the temperature of the battery pack. It was connected to a digital pin on the controller, allowing for accurate temperature readings to be processed and monitored in real time. This functionality is crucial for ensuring the safe operation of the battery pack, as temperature fluctuations can significantly impact battery performance and lifespan.

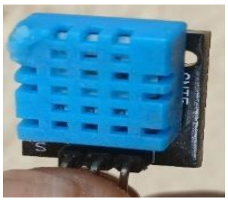

Fig. 9. DHT 11 used in the project

3.2.8 Relays

Relays are electronically controlled switches that connect or disconnect loads, solar panels, or battery packs based on decisions made by the BMS. This functionality helps protect the system from faults and ensures safe operation under various conditions. The relays were connected to the digital pins of the controller, allowing for precise control over the connections and enabling automated management of power flow in the system. The relay used in this project is shown in Fig. 10.

Fig. 10. Relay used in the project

3.2.9 Liquid Crystal Display

This component is used to display essential battery parameters, including voltage, battery percentage, load current, and battery pack temperature. By providing a clear visual representation of these metrics, it enables on-site personnel to easily monitor the status of the battery pack. In this project, an LCD with I2C interface was utilized for its simplicity and efficiency in communication. The connection between the Wemos D1 board and the LCD is outlined is shown in Fig. 11.

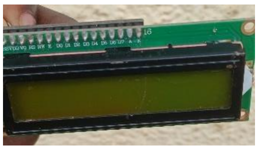

Fig. 11. LCD used in the project

3.2.10 Monitor (Laptop or phone)

This component facilitates the remote display of real-time data, receives alerts, and enables configuration and control of the BMS through a user-friendly interface. This capability allows users to monitor system performance, make configuration adjustments, and troubleshoot issues from any location with internet access. By providing such remote accessibility, it enhances operational efficiency and responsiveness, ensuring that any potential problems can be addressed promptly, ultimately contributing to the reliability and longevity of the battery management system.

3.3 Algorithm of the Project

This project aims to protect the solar power plant's battery pack from critical issues such as overcharging, over-discharging, and thermal runaway, which can occur when operating outside the normal temperature range. Additionally, the system is designed to balance the voltage of individual cells, thereby extending the lifespan of the battery pack and enhancing the overall efficiency of the solar power plant. To achieve these objectives, the system follows the algorithm outlined below:

- The system continuously measures key parameters, including battery pack voltage, load current, and battery pack temperature. This is accomplished using voltage sensors, current sensors, and a temperature sensor (DHT11).
- These parameters are utilized to calculate the battery pack's SoC and depth of discharge (DoD), providing critical insights into the battery's health and performance.
- Based on the calculated state of charge, the system determines whether to initiate charging of the battery or disconnect the solar charging system. Additionally, it assesses whether to continue supplying power to the load or disconnect the load from the battery pack to prevent potential damage.
- The battery pack parameters are displayed on a LCD and uploaded to the internet, allowing for real-time monitoring of the battery's status from anywhere in the world.

3.4 Flow Diagram for Project Implementation

The flowchart shown in Fig. 12 illustrates the overall project flow, outlining the various steps taken to execute the intended functions. It indicates when and under what conditions different tasks are performed, ensuring the system operates effectively.

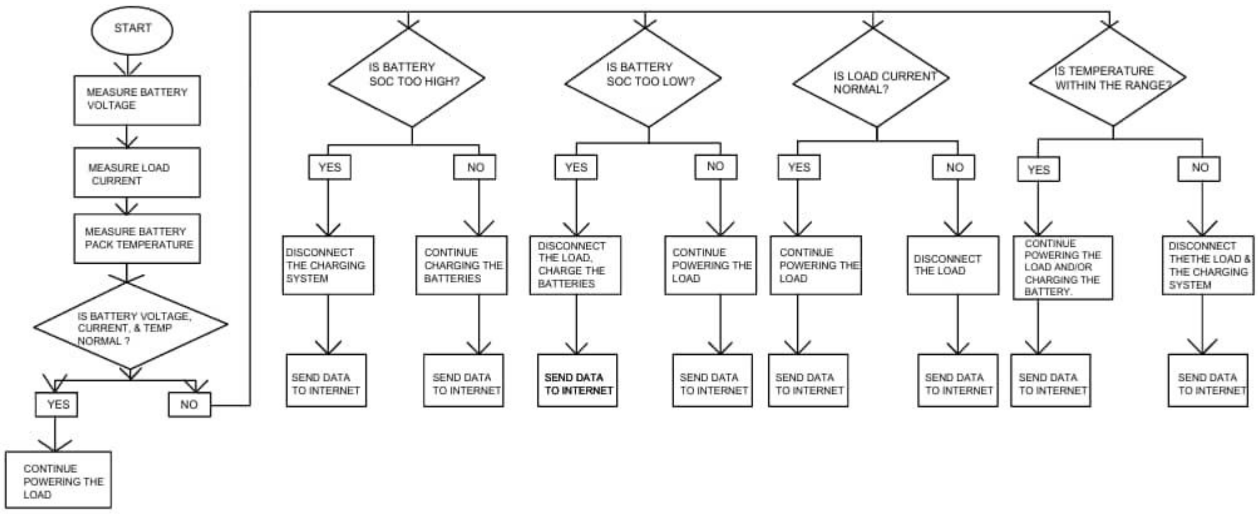

Fig. 12. Flowchart of the project processes

3.5 Software Development

The BMS for solar power plants was designed using Proteus software and the setup is shown in Fig. 13, allowing for simulation to obtain various results, including battery voltage, current, and temperature. The design process comprised several key steps, as outlined below.

- **Defining System Requirements**: This step involved specifying the requirements for the BMS, including voltage, current, and capacity specifications. Additionally, it included determining the type of batteries to be used, specifically lithium-ion (Li-ion) batteries.
- **Circuit Design**: The circuit design was created using Proteus software, integrating various components such as microcontrollers, voltage sensors, current sensors, temperature sensors, a LCD, and a virtual terminal.

- **Software Programming**: An Arduino code was developed to manage the battery charging and discharging processes. This code implemented algorithms for SoC estimation and thermal management.
- **Simulating the Designed System**: The written code was compiled and verified, after which the hex file was transferred to the Proteus controller, and the simulation was executed. The results were then displayed on the LCD and observed in the serial monitor, as shown below.

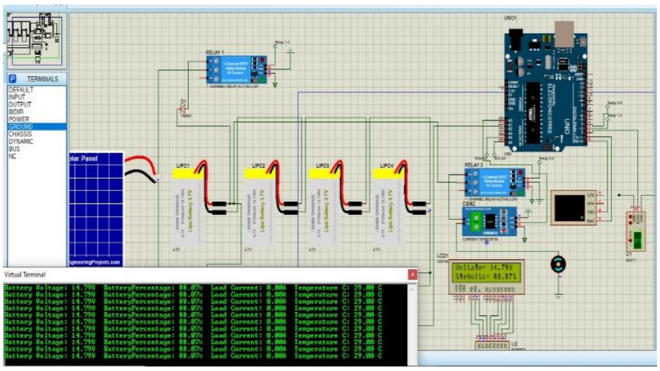

Fig. 13. Proteaus professional 8 simulation of the system.

3.5.1 Arduino code for the designed system

The Arduino code developed for the BMS is crucial for efficiently managing the battery pack in the solar power plant. Key components of the code include:

- **Initializing the components:** This step involves setting up the pins and libraries for the sensors and other components.
- **Reading sensor data:** Functions are implemented to read voltage, current, and temperature data from the sensors.
- **Implementing control logic:** Algorithms are developed to manage the charging and discharging of the battery pack, as well as to monitor battery temperature, ensuring safety and efficiency.
- **Displaying data:** An LCD is used to show real-time data from the battery system. Additionally, parameters such as depth of discharge and state of charge are displayed on a created ThingSpeak channel, enabling real-time monitoring of the system from anywhere in the world.

Together, these components facilitate effective control and monitoring of the battery management operations within the solar power system. Fig. 14 displays a portion of the code written in Arduino.

```
Denis_BMS_RealFinal_code.ino
#include <ESP8266WiFi.h>
#include "DHTesp.h"
#include "DHT.h"
#include "ThingSpeak.h"
#include <LiquidCrystal_I2C.h>

#define DHTPIN D3
#define DHTTYPE DHT11     //DHT11
#define LoadRelayPin D6     //declaring the relay pin.
#define SolarRelayPin D7

const int muxSIG = A0; // Connect to the multiplexer SIG pin
const int muxS0 = D8;
const int muxS1 = D9;
const int muxS2 = D10;
const int muxS3 = D11;
float Vout;
float Vin = 0.0;
float R1 = 30000.0;
float R2 = 7500.0;
int value = 0;
float max_voltage = 16.8;
float BatteryPercentage;

LiquidCrystal_I2C lcd(0x27, 16, 2); // declaring an object of type lcd
float humidity, tempC;
int setupTime=500;
int delayTime= 15000;
```

```
DHT dht(DHTPIN, DHTTYPE);
WiFiClient client;

char ssid[] = "Ssembalirwa's Galaxy A24";   //Your network SSID (name)
char pass[] = "Rexkhan..1";  //Your network password (use for WPA, or use as key for WEP)
unsigned long myChannelNumber = 2588980;
const char *myWriteAPIKey = "STJ7ACB3ZJY3TJI4";
//==========================================================================================

void setup() {
  // put your setup code here, to run once:
   pinMode(muxSIG, INPUT);
   pinMode(muxS0, OUTPUT);
   pinMode(muxS1, OUTPUT);
   pinMode(muxS2, OUTPUT);
   pinMode(muxS3, OUTPUT);
   Serial.begin(115200);
   delay(setupTime);
   pinMode(LoadRelayPin,OUTPUT);  //Setting relay pin as output.
   pinMode(SolarRelayPin,OUTPUT);

   lcd.begin();      // initialize the LCD
   lcd.backlight();   //Turn on the back light and print a message
   lcd.clear();
   lcd.print("BMS Battery");
   lcd.setCursor(0,1);
   lcd.print("Parameters");
   WiFi.begin(ssid, pass);
```

Fig. 14. Part of the code written in Arduino.

3.6 System Architecture

Following the design of the system, the various components were tested individually to verify that each one worked correctly before they were integrated into the system. The components were first assembled and connected on a breadboard to ensure that the intended system would reliably serve its purpose. The connected components are shown in Fig. 15.

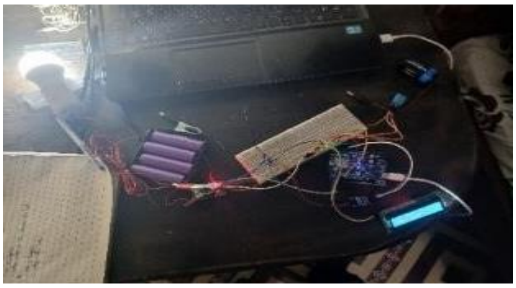

Fig. 15. Connection of the Breadboard.

After testing the components on the breadboard, they were meticulously transferred and soldered onto the veroboard to create a stable and durable setup. This process ensured secure connections and was executed with care to avoid short circuits and loose connections, which are essential for the effective operation of the battery management system. The arrangement on the vero board is depicted in Fig. 16.

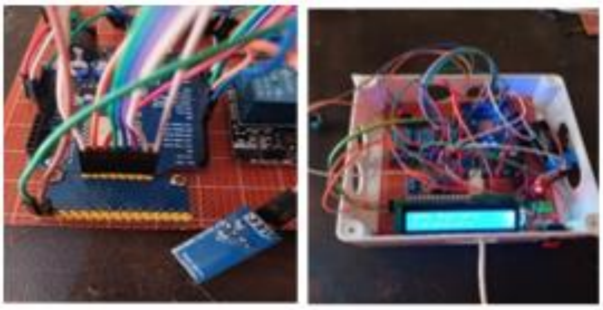

Fig. 16. Connnection of components on the vero board

3.7 Implementation of the System Architecture

In modern solar power applications, effective battery management is crucial for ensuring longevity, efficiency, and reliability. This study presents an IoT-based BMS that enables real-time remote monitoring and intelligent control of battery operations. The implementation and its contributions to the system's functionality are outlined as follows:

- IoT Technology Implementation: The system employs an IoT-based architecture to enable real-time remote monitoring of battery performance. A microcontroller interfaces with the BMS to collect key parameters such as voltage, current, and temperature. This data is transmitted via a Wi-Fi module (ESP8266 chip) to a cloud-based platform, where it can be accessed globally through a user-friendly interface. Real-time monitoring enables the immediate detection of abnormal conditions, such as temperature rises or excessive current levels, and sends alerts to the user, facilitating proactive system management.
- Intelligent Algorithms: The BMS utilizes intelligent algorithms to optimize battery charge and discharge cycles. These algorithms analyze real-time battery parameters, including SoC, load current, and temperature, to dynamically adjust charging rates and prevent overcharging or deep discharging. For instance, when the SoC reaches 100%, the algorithm triggers a cutoff to prevent overcharging. Similarly, if the temperature exceeds a set threshold (30 ℃), the system disconnects the battery to prevent overheating. Additionally, the algorithms optimize discharge cycles to enhance battery efficiency, extend lifespan, and improve overall energy management.

By integrating IoT for remote monitoring and intelligent algorithms for dynamic charge/discharge control, the proposed BMS significantly enhances battery performance, extends lifespan, and ensures greater system reliability compared to traditional battery management solutions.

4. Result and Discussion

In the course of the project, several results were obtained during both the simulation and the complete prototype. The battery pack voltage, percentage voltage, load current, and battery pack temperature were displayed for effective monitoring using a liquid crystal display and IoT, also known as ThingSpeak. The results are as follows:

4.1 Simulation Results

The simulation results were obtained using Proteus 8.0, which was utilized to link the design components effectively. The system was initially designed in the Proteus software, involving the installation of libraries for various components, including solar panels, lithium-ion batteries, relays, voltage sensors, current sensors, DHT11 temperature and humidity sensors, and LCDs. These components were connected to create a complete system. The results of the simulation were displayed on both the serial monitor and the LCD, as shown in Fig. 17.

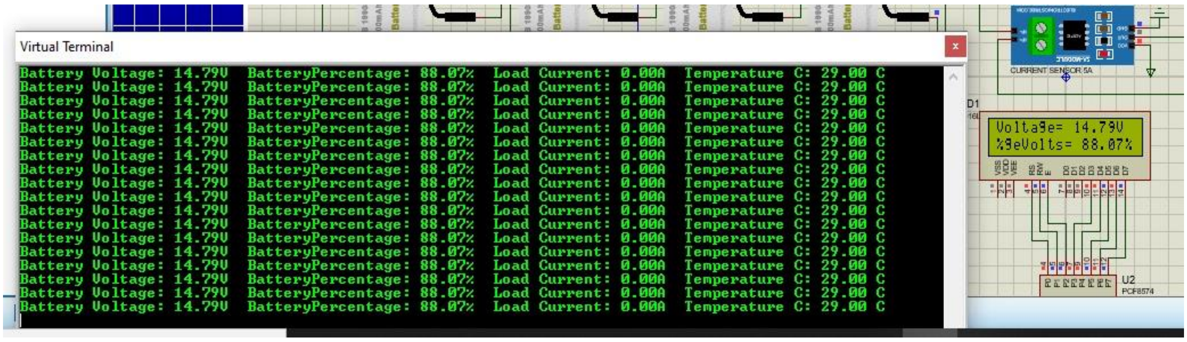

Fig. 17. Simulation results

4.2 Prototype Results

The complete prototype of the designed system is presented in Fig. 18, showcasing the arrangement and integration of various components such as the solar panels, battery pack, loads and etc. This prototype demonstrates the functionality and operational capabilities of the Battery Management System, illustrating how each component contributes to the overall performance and efficiency of the solar power plant. The visual representation highlights the meticulous assembly and the connections made to ensure reliable operation.

Fig. 18. Prototype of the system.

The results of the prototype were displayed on a liquid crystal display, enabling easy monitoring of the battery parameters by any system attendant. This allows for a fast response to undesirable conditions that could cause damage to the battery pack, either immediately or in the long run. Furthermore, IoT capabilities were utilized through the ESP8266 on the Wemos D1 R1 board to display the results over the internet on a created ThingSpeak channel called ‘Denis.BMS.’ This was intended to provide real-time monitoring of the battery parameters from anywhere in the world, as shown in Fig. 19.

Fig. 19. Display of system data over the internet/cloud.

The system has been designed to enable automatic control of the charging and discharging states of the battery pack. It continuously monitors the SoC and DoD using the installed sensors, particularly the voltage sensor. Relays have been connected between the solar panels and the battery pack, as well as between the battery pack and the loads, to facilitate automatic connection and disconnection of the battery pack from the charging system (solar panels) and discharging loads.

For example, when the batteries reach a full charge (100%), Relay 1 (the relay between the charging system and the battery pack) automatically opens to isolate the batteries from the charging system. Similarly, when the battery level drops to 10%, Relay 2 (the relay between the battery pack and the loads) automatically opens to disconnect the battery pack from the loads. This automated control protects the batteries against overcharging and over-discharging, thereby enhancing the efficiency, longevity, and reliability of energy storage systems, and ultimately improving the performance of solar power plants.

A manual override has also been incorporated into the system, allowing for manual control in the event of a fault in the automatic system, during maintenance, or in case of an emergency.

4.3 Analysis of the Battery Pack Configuration and Load Management

In the design of the system, four lithium-ion batteries, each rated at 3.7V (with a maximum voltage of 4.2V), were connected in series to create a simple battery pack. This configuration yields a total maximum voltage of 16.8V, which corresponds to a battery voltage percentage of 100%. At this voltage level, the system automatically isolates the battery pack from the solar panel, thereby protecting the batteries from overcharging. Conversely, when the battery voltage drops to 10%, the system automatically disconnects the battery pack from the load, preventing over-discharging of the battery pack.

Two DC lamps each of 1W and 12V have been used in this design. These provide a total current of 0.16A as calculated mathematically below.

$$Power\ (P) = Voltage\ (V) \times Current\ (I) \tag{1}$$

For one lamp:

$$P = 1\ W\ and\ V = 12\ V$$
$$1\ W = 12\ V\ \times I$$
$$I = \frac{1\ W}{12\ V} \approx 0.0833\ A$$

For two lamps:
The Total Current is given as:

$$Total\ current\ (I) = 2 \times 0.0833\ A \approx 0.16\ A$$

Therefore for two loads:

$$current\ (I) = 0.08 \times 2 \approx 0.16\ A$$

This calculation confirms that the total current drawn by the two lamps is approximately 0.16A.

With proper calibration, the designed system is expected to measure current levels under normal conditions around 0.16A. If the current rises significantly above this value while the load is connected, it may indicate a fault, most commonly a short circuit. In such cases, the system is designed to automatically isolate the load, prompting immediate attention from the responsible personnel.

Given that the batteries are located in an environment with an ambient temperature of approximately 25 ℃, and considering that the battery temperature should not exceed an increase of 3 ℃, the system has been configured to disconnect the load and charging system if the battery temperature surpasses 30 ℃. This automatic disconnect operation is intended to protect the battery pack and provides a clear reason for the action, ensuring that immediate response is taken by the concerned individuals.

Note: In the event of the automatic isolation of the load and the charging system from the battery pack, the system provides a clear indication of the cause for the action, allowing the operator to address the specific issue promptly. Once the conditions return to normal, the system automatically reconnects the loads and the charging system back to the battery pack. Moreover, the manual override is meant to enable manual operation of the system in case of any fault, or during maintenance.

We organize the remaining section of this research work as follows: In section two (2), we described the basic model and its properties; in section three (3), we present the model analysis and in section four (4), we discussed the numerical simulation and results of the proposed mathematical model.

4.4. Limitations and Potential Biases

The proposed IoT-enabled BMS enhances monitoring and control of solar power storage but has some limitations. Sensor accuracy affects SoC and DoD estimations, while network connectivity issues may disrupt real-time monitoring. The system's scalability to larger applications remains untested, and reliance on relays introduces potential failure points. The charge/discharge optimization algorithm may not fully adapt to varying battery conditions, and manual overrides carry risks of human error.

To address these limitations, future improvements should focus on enhancing sensor accuracy through calibration techniques, implementing alternative communication methods for greater reliability, improving the system's scalability for larger applications, exploring more durable switching mechanisms, and incorporating AI-driven adaptive control for smarter energy management. These advancements will further improve the efficiency, longevity, and reliability of solar power storage systems.

5. Conclusion

This study successfully designed and prototyped a customized BMS for solar power plants in Uganda, offering significant benefits to both the local energy sector and broader sustainable development goals. By continuously monitoring and regulating critical battery parameters such as SoC, discharge current, and temperature, the BMS ensures optimal performance, longevity, and efficiency of the energy storage system. Additionally, the integration of an advanced charging and discharging algorithm improves battery lifespan while minimizing energy losses, delivering both economic and environmental advantages. One of the standout features of the proposed system is its real-time monitoring capabilities, enabling remote oversight of battery performance and facilitating immediate detection of any issues through automated alerts. This proactive approach to energy management is a crucial advancement in enhancing the reliability and sustainability of solar power infrastructure in Uganda, especially in regions with limited access to advanced technology. The successful deployment of this intelligent BMS represents not only a technical achievement but also a strategic contribution to Uganda's renewable energy landscape. It supports the country’s ongoing efforts to promote sustainable energy and reduce dependence on conventional power sources, thereby strengthening its long-term energy resilience. Future improvements of this work should aim at improving sensor accuracy, exploring better communication methods for remote areas, and addressing scalability to handle larger storage systems. Enhancing the durability of switching components and integrating AI-driven adaptive control can further optimize efficiency and reliability. These improvements will support the development of more sustainable and resilient energy solutions.

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