ENERGY EFFICIENT BATTERY MANAGEMENT SYSTEM

A PROJECT REPORT

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by

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CERTIFICATE

This is to certify that the project work titled ***"ENERGY EFFICIENT BATTERY MANAGEMENT SYSTEM"*** submitted by ***BHAGAVATULA SAI PRANAV, NOMULA RISHITH, SREENIKETH DASAM*** is in partial fulfillment of the requirements for the award of the degree of **BACHELOR OF TECHNOLOGY**, is a record of bonafide work done under my guidance. The contents of this project work, in full or in parts, have neither been taken from any other source nor have been submitted to any other Institute or University for award of any degree or diploma and the same is certified.

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The thesis is satisfactory / unsatisfactory

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ABSTRACT

This project focuses on the design and development of an energy-efficient Battery Management System (BMS) that optimizes the State of Charge (SOC) for batteries used in electric vehicles and renewable energy systems. With the increasing demand for sustainable energy solutions, it is crucial to enhance battery performance and extend battery life. The proposed BMS will incorporate advanced machine learning (ML) algorithms to improve battery performance, particularly in low charge conditions. These algorithms will enable the system to predict and adapt to the battery's behavior, optimizing charging cycles, cell voltage, and current. Additionally, the BMS will integrate thermal control techniques to manage temperature variations, ensuring safe and efficient operation across a wide range of operating conditions. By optimizing these critical parameters, the system will significantly improve the overall performance, reliability, and longevity of the battery.

The BMS will employ advanced predictive algorithms and real-time data analysis to continuously adapt to the battery’s state, ensuring optimal charging and discharging patterns. This will reduce wear and tear on the battery and enhance its efficiency, which is particularly important for applications in renewable energy systems and electric vehicles where energy conservation is vital. Moreover, the integration of machine learning allows for a more intelligent approach to battery management, improving operational efficiency and minimizing the environmental impact. This project aims to contribute to a cleaner, more sustainable energy future by enabling more effective use of renewable energy sources, reducing the overall carbon footprint, and supporting the shift towards environmentally friendly technologies.

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ABBREVIATIONS AND NOMENCLATURE

BMS	Battery Management System
ML	Machine Learning
XGBOOST	Extreme Gradient Boosting Algorithm
GBDT	Gradient Boosting Decision Tree
MSE	Mean Square Error
MAE	Mean Absolute Error
R-Squared	Coefficient of determination
EV	Electric Vehicles

CHAPTER I

1. INTRODUCTION

1.1 INTRODUCTION

The transition to sustainable energy solutions has placed a significant emphasis on the development of efficient energy storage systems, particularly in applications such as electric vehicles (EVs) and renewable energy. Central to the effective operation of these systems is the Battery Management System (BMS), which ensures optimal performance by monitoring and controlling various parameters, including charging cycles, cell balancing, and thermal regulation. By optimizing these factors, a BMS helps to reduce energy waste, extend the lifespan of batteries, and enhance overall system reliability.

This report focuses on designing and implementing an advanced battery management strategy to improve the energy efficiency of battery-operated systems. The primary objective is to develop a system that not only tracks key battery parameters—such as voltage, current, and temperature. Temperature, current, and voltage sensors are integrated to measure the battery's condition, and a relay is employed to disconnect the load in response to any abnormal fluctuations in battery temperature or voltage, thereby protecting the system from potential damage.

1.1.1 Motivation

The motivation for this project stems from the critical role batteries play in modern technology and the challenges associated with their energy efficiency and lifespan. With the rapid adoption of electric vehicles and renewable energy systems, there is a pressing need for solutions that can manage battery power more effectively. Inefficient battery use not only leads to higher costs and more frequent replacements but also impacts on the environment due to increased resource consumption and waste. By focusing on energy-efficient battery management, this project seeks to improve battery sustainability, minimize energy waste, and promote more responsible use of resources, aligning with global efforts toward a greener future.

1.1.2 Objectives

The primary objectives of this project are:

1. **To design and implement a Battery Management System (BMS)** that effectively monitors the battery's State of Charge (SOC) using temperature, current, and voltage sensors.
2. **To ensure the protection and safety of the battery** by integrating a relay mechanism that disconnects the load in the event of abrupt changes in battery temperature or voltage, preventing potential damage or failures.
3. **To optimize the SOC calculation** through the application of machine learning models, aiming to improve the accuracy and efficiency of SOC estimation, thereby enhancing the overall performance of the battery management system.
4. **To evaluate and compare different machine learning models** to determine the most suitable approach for optimizing battery performance and extending battery lifespan.
5. **To contribute to the development of sustainable energy solutions** by improving the efficiency, reliability, and longevity of energy storage systems used in electric vehicles and renewable energy applications.

1.1.3 Scope of the Work

This project focuses on designing and implementing an energy-efficient battery management system (BMS) tailored to optimize battery performance and extend lifespan. The scope includes developing algorithms for efficient charging cycles, cell balancing, and thermal control. Predictive modeling and real-time data analysis will be incorporated to enhance system efficiency and reliability. Testing and validating the system's performance will also be part of the scope, with an emphasis on reducing energy waste and supporting applications in renewable energy and electric vehicles. This work aims to contribute to sustainable energy practices by improving battery efficiency and resilience.

CHAPTER II

2. PROJECT DESCRIPTION

2.1 OVERVIEW OF PROJECT

This project was designed to give an energy-efficient BMS that would minimize energy waste and extend the life of the battery for renewable energy and electric vehicle applications. It is possible to visualize and manage the performance of the battery in real time, integrating different sensors and modules with the help of the ESP32 microcontroller as the main central processing unit. The BMS can measure voltage, current, and temperature parameters for better optimization of charging cycles and balancing the cell voltages for achieving higher efficiency. The optimization of state of charge will be done with the help of ML algorithms In this project, practically a demonstration of how to achieve better battery management using both hardware aspects and software algorithms will be done.

1. Modules of the Project

The BMS has several key modules, each designed to accomplish a specific function to achieve optimal battery performance. These modules are interconnected, taking data from sensors and applying control algorithms to maintain battery health.

1.1. Module 1: Hardware configuration

In this Battery Management System (BMS) project, we used an ESP32 microcontroller along with essential components like the ACS712 DC current sensor (0-10A), a DC voltage sensor (25V), and a 3.7V 3000mAh rechargeable battery. By measuring the battery's voltage, current, and temperature in real time, we could determine the State of Charge (SOC) and ensure optimal battery performance.

The system also includes a relay that disconnects the load under conditions of high temperature or voltage to protect the battery. To enhance SOC prediction, we analysed various machine learning models based on sensor data, allowing for a more accurate and optimized SOC estimation. All sensor readings and SOC values are displayed on the Arduino IoT Cloud with live graphs and gauges, providing a real-time view of the battery's health and operational state.

The TP4056 charging module is configured to safely and efficiently charge single-cell lithium-ion batteries, especially those rated at 3.7V. The module operates in two primary modes: Constant Current (CC) and Constant Voltage (CV). In CC mode, it provides a steady current to the battery, charging it safely and quickly until the voltage nears 4.2V. At this point, the module transitions to CV mode, where it holds the voltage at 4.2V while gradually reducing the current as the battery approaches full capacity, preventing overcharging and protecting battery longevity.

1.2. Module 2: Software configuration

For the software configuration, data from the sensors was first collected and stored in the Arduino IoT Cloud, allowing for easy access to historical and real-time battery performance metrics. The dataset, which includes voltage, current, and temperature readings, was then used to train several machine learning models to predict the State of Charge (SOC) accurately. Various models were tested, the XGBoost algorithm was chosen due to its superior performance. Key parameters displayed to assess the models included Mean Squared Error (MSE), Mean Absolute Error (MAE), and the R^2 value, which helped identify XGBoost as the optimal model for high-accuracy SOC prediction.

2.2 TASKS AND MILESTONE

- **Integration of Sensors:** The initial task involved setting up sensors for voltage, current, and temperature to monitor the battery's state. Each sensor was calibrated and connected to the ESP32 microcontroller to ensure accurate and reliable data collection.
- **Displaying in IoT Cloud:** After sensor integration, data transmission to the Arduino IoT Cloud was configured, allowing for real-time visualization. Key battery parameters such as voltage, current, temperature, and State of Charge (SOC) were displayed with live graphs and gauge meters for an accessible overview.
- **Integration of TP4056 Charging Module:** The TP4056 module was then integrated into the circuit to manage battery charging efficiently using its

constant current/constant voltage (CC/CV) charging algorithm. This addition enables safe, automated charging for the lithium-ion battery.

- **Calculation of SOC from Sensor Data:** Using the data collected from voltage and current sensors, the SOC was calculated to provide an estimate of the remaining battery life. This SOC determination was essential for battery management and ensuring optimal battery performance.
- **Machine Learning Model for SOC Prediction:** Various machine learning models were trained on the collected sensor data to enhance SOC prediction accuracy. After testing linear and polynomial regression as well as Support Vector Regression (SVR), the XGBoost algorithm was selected as the final model, achieving optimal predictive accuracy for SOC.
- **Relay Addition for Safety:** A relay was added to the circuit to protect the battery under extreme conditions. The relay automatically disconnects the load when the battery temperature or voltage exceeds safe limits, safeguarding the battery and system components.

CHAPTER III

3. DESIGN OF BATTERY MANAGEMENT SYSTEM

3.1 DESIGN APPROACH

In the design approach of this BMS, the ESP32 microcontroller is used in combination with a set of important sensors and charging module to ensure successful battery monitoring and management. Using a TP4056 charging module with 3.7V, combined with ACS712 current as well as voltage sensors, this design will handle the real-time monitor of voltage, current, and temperature. Arduino programming was used to code the ESP32. This ensured thorough measurements and control functions for safe, efficient discharge of the battery.

3.1.1 Circuit Diagram

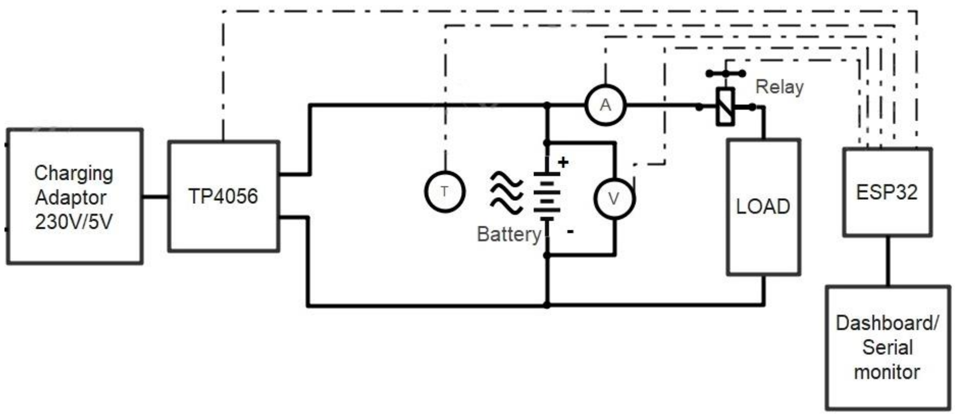

Figure 1: Circuit diagram of Battery Management System.

1. **Charging Adaptor:** This component takes the 230V AC input and converts it to a 5V DC output suitable for charging the battery.
2. **TP4056:** This is an integrated circuit (IC) used for battery charging. It regulates the charging process, ensuring the battery is charged safely and efficiently.
3. **Battery:** This is the main energy storage component, typically a lithium-ion battery pack in an electric vehicle (EV). It stores the energy supplied by the charging adaptor.

4. **Relay:** A relay is an electromechanical switch that is controlled by a low-voltage signal from the ESP32. It can be used to switch the battery connection to the load or disconnect it, depending on the charging status or other conditions.
5. **ESP32:** This is a powerful microcontroller that acts as the "brain" of the BMS. It monitors various parameters like battery voltage, current, temperature, and state of charge (SOC). It also controls the charging and discharging processes based on these parameters.
6. **Load:** This represents the devices or components that consume power from the battery, such as the electric motor in an EV.
7. **Dashboard/Serial Monitor:** This is a user interface that displays information about the battery's status, such as voltage, current, and SOC. It can also be used to control the charging process or other functions.
8. **A180185 Voltage sensor:** A voltage divider circuit with R1=30kΩ and R2 = 7.5kΩ is used to measure battery voltage up to 5V, scaled for accurate ADC input on the ESP32.
9. **ACS712 Current Sensor:** This Hall-effect-based sensor is employed for precise measurement of current up to ±5A, providing an analog voltage proportional to the current flow.

Circuit Flow:

1. **Charging:**
   - The adaptor converts the AC power to 5V DC.
   - The 5V DC is supplied to the TP4056 IC.
   - The TP4056 regulates the charging current and voltage, ensuring the battery is charged safely.
   - The ESP32 monitors the charging process and controls the relay to connect the battery to the charging circuit.
2. **Discharging:**
   - The ESP32 monitors the battery's SOC and load demand.
   - If the battery has sufficient charge and the load requires power, the ESP32 controls the relay to connect the battery to the load.
   - The battery supplies power to the load, such as the electric motor.

- The ESP32 continues to monitor the battery's SOC and adjusts the power output as needed.

3.1.2 Practical Constraints

The following constraints were encountered during the project:

- Technical Limitations: Many parts like the module TP4056 do not go well with the ESP32; hence, wired and pin allocation had to be adjusted. Again, the ACS712 current sensor was not that accurate and requires careful adjustment, particularly when the load changes.
- Resource Limitations: The use of specific sensors and modules obliged certain design modifications that even scaled up the overall system architecture.
- Temperature Control: To ensure that the lithium-ion battery is not thermally sensitive and thus call for effective temperature monitoring to avoid overheating, hence safety is enhanced.

3.1.3 Options and Tradeoffs

During this design cycle, various options and tradeoffs were considered

- Microcontroller Selection: Although the ESP32 was chosen due to its versatility and being cheap. The ESP32 was finally selected because of its board integrated capabilities of Wi-Fi and machine learning, which would have made it energy efficient.
- Charging Module: The TP4056 module was picked as a reliable and minimalist option for lithium-ion charging.
- Sensor Selection: Given the cost aspect, the ACS712 current sensor was chosen. There had to be compromises on the side of accuracy in measurement by calibration and coding manipulation.

3.2 DESIGN SPECIFICATIONS

The BMS was designed to meet the following specifications:

- Voltage Monitoring: A180185 voltage sensor was integrated to monitor the battery voltage and keep it within the range that provides safety during operation.
- Current Monitoring: The current was monitored using the ACS712 sensor, mainly while discharging and avoiding the possibility of causing overcurrent conditions.
- Temperature Monitoring: A temperature sensor was also integrated to ensure thermal stability and alert the system when this becomes unusual.
- Charging Module: It provides a TP4056 module to ensure the efficient and safe charging of the 3.7V battery.
- Coding and Integration: Custom Arduino code was developed to control the ESP32, along with actual pin assignment and tasks, which enabled data collection accurately from the sensors with real-time feedback from each.

CHAPTER IV

4. PROJECT DEMONSTRATION

4.1 INTRODUCTION

The demonstration of the energy-efficient BMS confirms the realization of its design objectives and demonstrates functionality. Through meticulous planning, hardware integration, and iterative testing, the BMS monitors and manages important battery parameters such as voltage, current, and temperature in an efficient and safe mode of operation. This chapter presents analytical, simulation, and hardware results, which attest that the system functions reliably and fulfills all the specifications put forward.

4.2 HARDWARE RESULTS

After the hardware assembling and integration of all elements, which includes the ESP32, TP4056 charging module, ACS712 current sensor, voltage sensor, and temperature sensor, comprehensive testing was done on the BMS. Most primary configuration errors have been sorted out through crucial calibration of sensor values, correct pin setting, and perfect code writing in Arduino IDE.

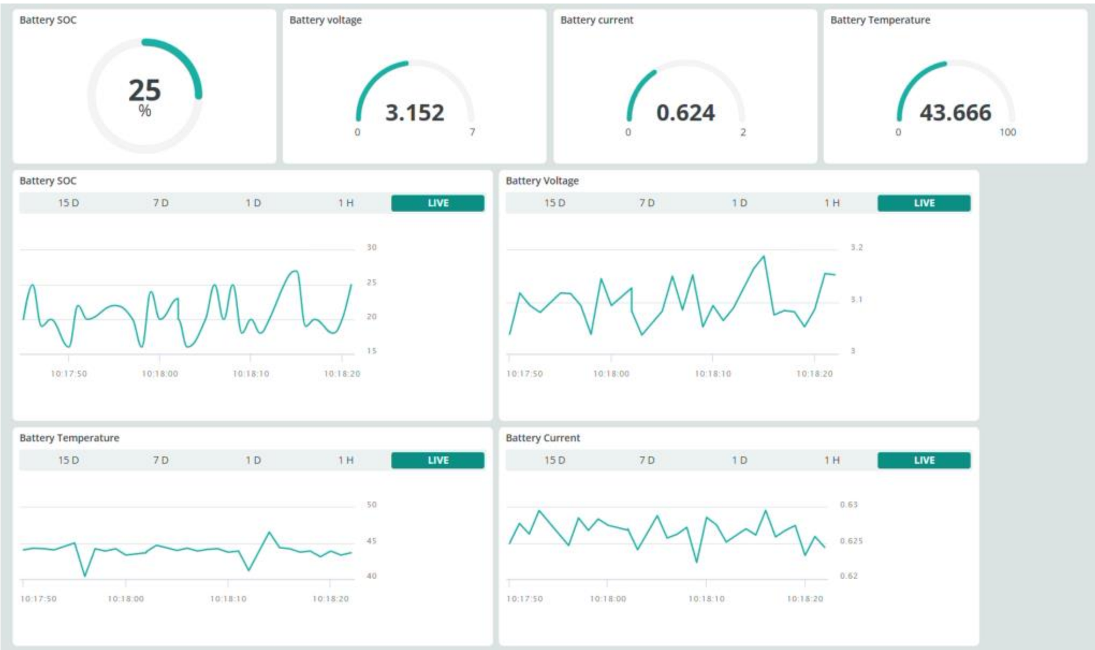

Figure 2: BMS output displayed on cloud dashboard.

The system robustly measured and presented voltage, current, and temperature data of the battery. All the sensors operated consistently within their prescribed parameters, and the ESP32 predictive algorithms kept correcting towards optimal use of energy. This successful demonstration confirmed that the BMS not only met design expectations but certainly exceeded it by providing a robust solution for efficient energy delivery from battery management with practical applicability in renewable energy as well as electric vehicle systems.

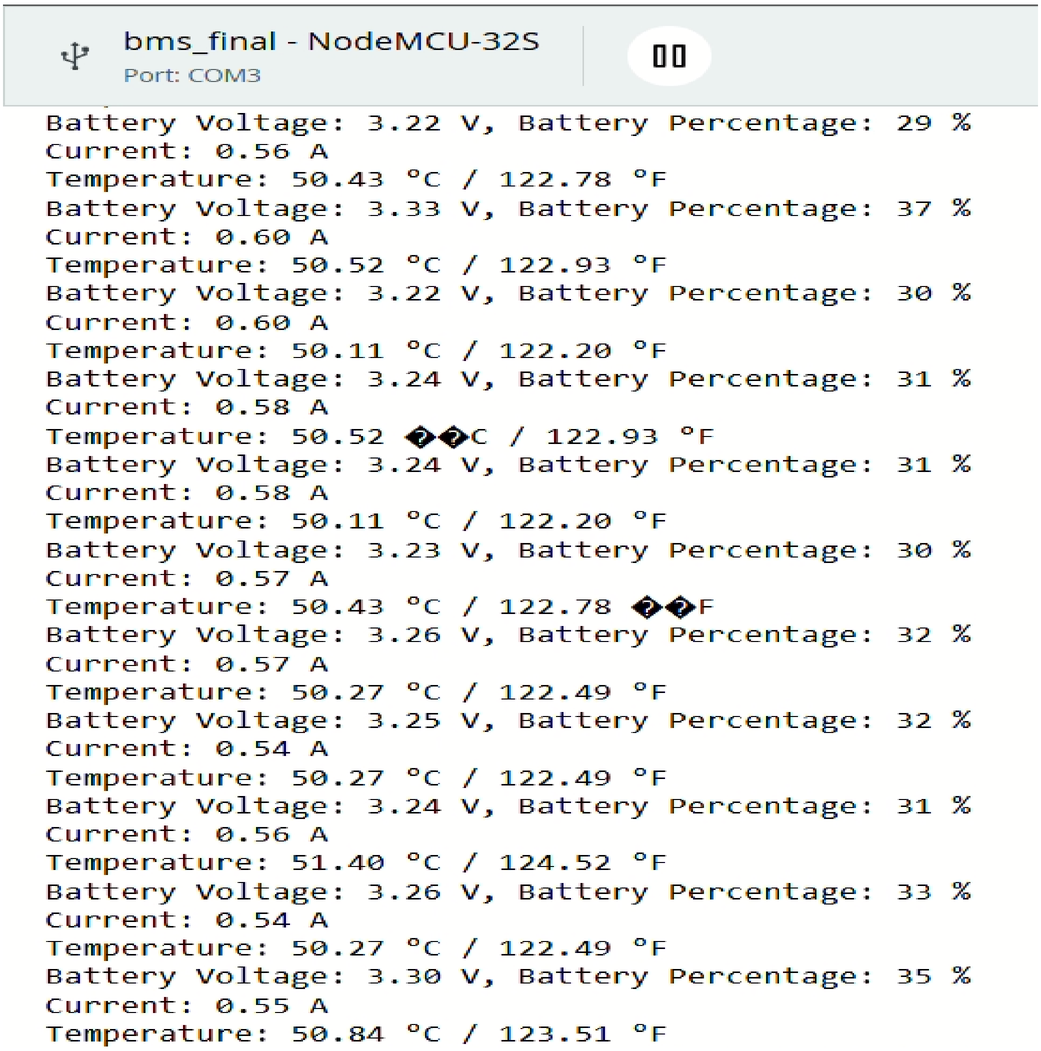

Figure 3: Serial monitor display.

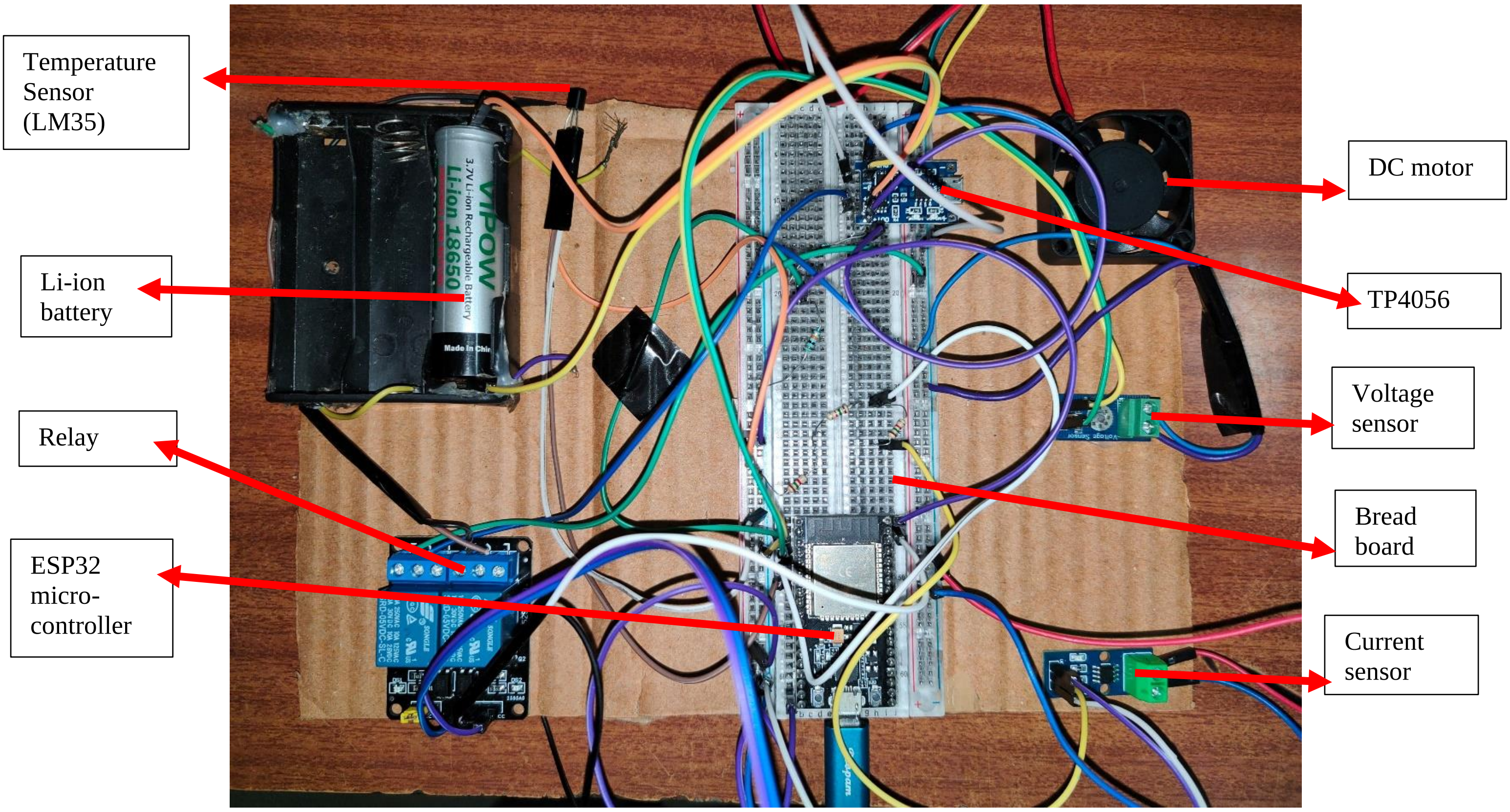

Figure 4: Hardware design specification of BMS.

4.3 SOFTWARE RESULTS

This script showcases the development of a predictive model designed to estimate the State of Charge (SOC) of a battery system. It utilizes the XGBoost Regressor, a powerful gradient boosting framework, to examine the relationships between sensor inputs (voltage, current, and temperature) and the SOC. The process involves the following steps:

Data Preprocessing:

- A dataset with 2000 entries was used for training and evaluation.
- Rows containing zero values were removed to ensure the integrity of the data.

Feature and Target Selection:

- Input features: Voltage (V), Current (A), and Temperature (°C).
- Target variable: State of Charge (SOC) (%).

Model Training and Evaluation:

- The dataset was split into 80% training data and 20% testing data.
- An XGBoost Regressor model was trained with the following hyperparameters:
    - n_estimators = 15: Number of boosting rounds.
    - learning_rate = 0.17: Higher rate for faster convergence.
    - max_depth = 3: Limits tree depth to prevent overfitting.
- The model's performance was evaluated using:
    - R^2 Score (Training & Testing): Indicates how well the model explains the variability in SOC.
    - Mean Squared Error (MSE): Measures the average squared difference between predicted and actual SOC.
    - Mean Absolute Error (MAE): Measures the average magnitude of prediction errors.

Results Summary:

- The model achieved a Training R^2 of 0.994 and a Testing R^2 of 0.991, indicating excellent generalization and minimal overfitting.
- The low MSE (1.12) and MAE (0.79) highlight the model's accuracy in predicting SOC values.

Visualization:

- A bar chart was plotted to visualize the metrics (Training R^2, Testing R^2, MSE, MAE), allowing for an intuitive understanding of the model's performance.

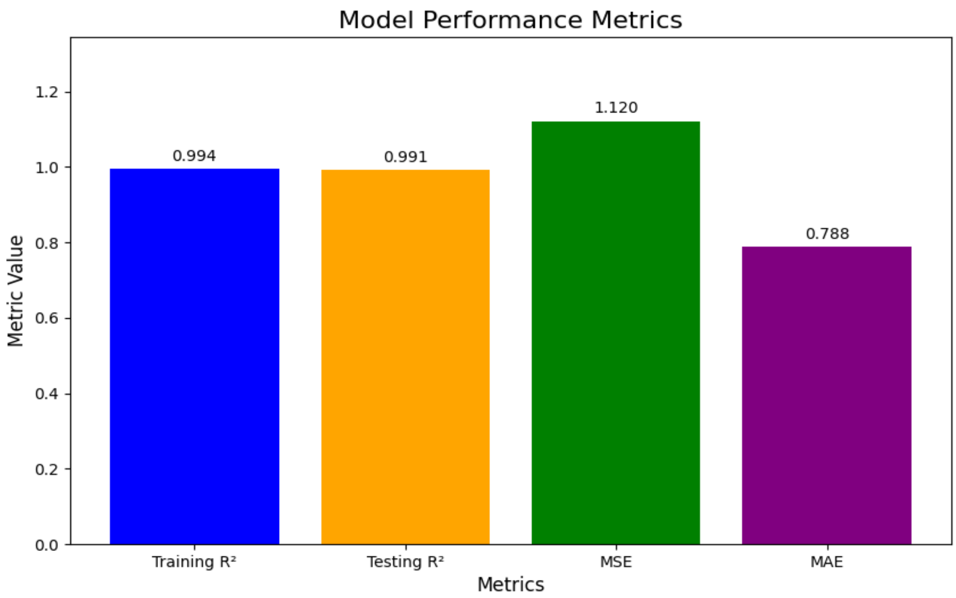

Figure 5: Graphical representation of XGBoost model outputs for BMS.

SoC (%)	Current (A)	Voltage (V)	Temperature (°C)
100	6.295602322	4.39252758	43.66699219
100	5.727472305	4.450549603	43.50585938
99	4.84505415	4.39413929	43.66699219
87	4.808790684	4.374798775	43.42529297
89	3.841757774	4.39252758	43.58642578
86	4.482417107	4.400586128	43.66699219
91	4.978022575	4.397362709	43.34472656
89	5.485713482	4.39413929	43.828125
88	5.292305946	4.400586128	43.26416016
82	5.364832878	4.407032967	37.86621094
88	6.924173832	4.304395676	32.2265625
86	5.497801304	4.19318676	28.68164063
88	3.636262417	4.022344112	26.34521484
87	4.023075104	4.030403137	24.89501953
89	3.599998951	4.049743652	23.68652344
87	3.926372528	4.017508984	24.57275391
88	3.430769444	4.083589554	24.4921875
78	3.9747262	4.05941391	24.00878906
69	3.636262417	4.032014847	24.4921875
71	3.394503593	4.033626556	26.90917969
75	4.095602036	3.953040361	24.41162109
77	4.204397202	4.033626556	24.4921875
86	3.684613705	4.043296814	24.08935547
88	4.035162926	4.004615307	24.33105469
84	4.240658283	4.043296814	24.25048828

Figure 6: Dataset used for Training ML model to predict SoC.

CHAPTER V

5.CONCLUSION

5.1 COST ANALYSIS

COMPONENT NAME	COMPONENT TYPE	COMPONENT RATING	QUANTITY	COST (In Rs.)
ESP32	Microcontroller	-	1	349.00
TP4056	Charging module	4.12V,1A	1	75.00
ACS712	Current Sensor	0-10A	1	90.00
A180185	Voltage Sensor	0-25V	1	50.00
VIPOW Li-ion battery	Battery	3.7V,3000mAh	1	95.00
DC motor	Load		1	70.00
Resistors	Resistance	1kΩ, 10kΩ	3,2	5.00
Wires	Male to Male wires	-	50	50.00
LM35	Temperature sensor	-55˚C - 150˚C	1	70.00
Relay Module	Electronic switch	5V, 10A	1	100.00
TOTAL:				**974.00**

Table 1: Cost analysis of the components used for project.

5.2 SCOPE OF WORK

This project demonstrates that a BMS can be designed and implemented in such a way to monitor and maintain such crucial parameters for ensuring critical lifetime in batteries and total energy wastage. Furthermore, it would be feasible to bring some enhancement with the upcoming upgrades like remote monitoring over Wi-Fi or Bluetooth, some advanced algorithmic controls, or the adaptability towards higher-capacity battery systems. This feature would help it find its place in the larger-scale applications in energy storages and advanced electric vehicles, which in turn would eventually promote the policy of sustainable energy.

5.3 CONCLUSION

This project successfully developed a reliable and energy-efficient Battery Management System (BMS), designed to monitor voltage, current, and temperature through the strategic integration of sensors and components, supported by optimized algorithms. Analytical, simulation, and hardware results demonstrated strong alignment, validating the system's effectiveness. The work lays a foundation for more sustainable battery management practices, contributing to clean energy initiatives and the advancement of renewable-powered applications. However, certain limitations were identified during the development process. The accuracy of sensors occasionally affected data precision, while loose connections impacted system reliability. Challenges in consistent and reliable data logging led to errors in the machine learning model, affecting its predictive accuracy. Additionally, minor difficulties in seamless cloud integration were encountered, and wear and tear of hardware components over time posed potential risks to long-term system reliability.

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