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Battery Management System

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ABSTRACT :

This work shows the design and implementation of a low-cost, effective Battery Management System (BMS) with an ESP32 microcontroller, ACS712 current sensor, TP4056 charging module, and a 3.7V Li-ion battery. The system tracks critical parameters like voltage, current, and temperature to provide safe and optimal battery operation. It features MOSFET-based protection for overvoltage, undervoltage, and overcurrent conditions. Taking advantage of the ESP32's Wi-Fi feature, the BMS features real-time remote monitoring and smart power management. The solution is IoT-capable, suitable for IoT devices, portable electronics, and small-scale energy storage systems.

INTRODUCTION

In the modern technology era, batteries
find tremendous applications in driving portable electronics, electric vehicles, IoT devices, and renewable energy systems. Of different types of batteries, Lithium-ion (Li-ion) batteries are the most popular because of their high energy density and long life. Yet, they are vulnerable to overcharging, deep discharging, overheating, and short-circuiting. A Battery Management System (BMS) is necessary for their safe and effective usage
A BMS monitors key battery parameters, guards the battery against faults, and maximizes its operating life Conventional BMS solutions tend to be complicated and costly, which makes them less ideal for small-scale or low-budget projects With the availability of affordable microcontrollers like the ESP32, it is now possible to design and build a low-cost, reliable, and feature-rich BMS.

Literature Review

Hannan, M. A. – Battery Management System for Electric Vehicles The paper provides a detailed description of Battery Management Systems (BMS) for electric vehicle applications, stressing their importance in maintaining battery safety, performance, and longevity. It points out how BMS combines different functionalities such as state-of-charge estimation, fault detection, and thermal management. The paper also addresses issues such as algorithm complexity and hardware reliability, which prompt innovation in developing smart BMS.

Piller, S. – Methods for State-of-Charge Estimation This article assesses several methods of state-of-charge (SoC) estimation for batteries, which is a central task of any BMS. It contrasts the traditional voltage-based approaches with more sophisticated model-based estimations and highlights the compromise between accuracy and computational expense. The research highlights SoC estimation as a prerequisite for real-time battery health monitoring.

Zhang, S. S. – Effect of Charging Protocols on Battery Life The study focuses on how varying charging protocols affect lithium-ion battery cycle life. It highlights the fact that intelligent BMS has to learn optimized charging strategies in order to avoid degradation and prolong battery life, particularly under different environmental and load conditions.

Hu, X. – Equivalent Circuit Models in BMS This paper compares various equivalent circuit models applied to model battery behavior for real-time usage.

It determines the most apt models for precise prediction and control to facilitate intelligent decision-making in BMS systems.

Ning, G. – Cycle Life Modeling for Battery Packs degradation of lithium-ion cells over time. The article gives insights into predictive maintenance practices, which enable BMS system to look ahead in anticipating failure and planning replacements.

Kim, I. – Adaptive SOC Estimation Using Kalman Filter Proposes an adaptive Kalman filter-based approach to SoC estimation under variable operating conditions. It makes the BMS more reliable and robust, especially in dynamic load and temperature operating conditions.

Wang, Q. – Thermal Management in Battery Systems Examines thermal runaway hazards in battery packs and addresses thermal management techniques. It emphasizes how BMS needs to regulate and monitor temperature distribution to maintain safety and efficiency, particularly in high-power applications.

Hossain, E. – Smart BMS Using IoT and Cloud Monitoring Suggests an IoT-based BMS architecture for remote monitoring and data analysis. The paper illustrates how cloud-based BMS can enable predictive analytics, enhance energy efficiency, and lower maintenance expenses in large-scale battery deployments.

He, H. – Fault Diagnosis in Lithium-Ion Batteries The research suggests an adaptive estimation method for battery fault detection, such as overcharging, thermal runaway, or cell imbalance. This is highly relevant to failure prevention and is the basis of contemporary protective features in intelligent BMS architectures.

Zhang, Y. – Prognostics and Health Monitoring of Batteries Investigates sophisticated diagnosis tools and machine learning models for battery health estimation.

This work promotes the embedding of AI in BMS to make real-time analytics and early warning systems available.

Research Questions:

1. What is the effect of real-time data logging and wireless transmission on the analysis of battery health and remote diagnosis?
2. Can the machine learning algorithm be incorporated into BMS for fault detection and predictive maintenance?
3. How do environmental conditions like temperature and load variation influence battery performance, and how can a BMS counteract these effects?
4. What are the essential safety safeguards that a low-cost BMS should have to avoid overcharging, over-discharging, and thermal runaway?
5. How can a low-cost BMS design meet cost, performance, and reliability requirements for scalable IoT and embedded systems?
6. What are the compromises of analog vs. digital sensors in battery monitoring applications?
7. How can a BMS be designed for energy efficiency to maximize battery life in portable systems?
8. What are the difficulties of implementing wireless communication modules in a small BMS, and how do they get around them?
9. How does modular BMS architecture accommodate multiple battery chemistries and configurations with minimal design changes?
10. How can the BMS based on a microcontroller effectively monitor real-time single-cell Li-ion battery parameters?

METHOLOGOY:

1.Research Design -

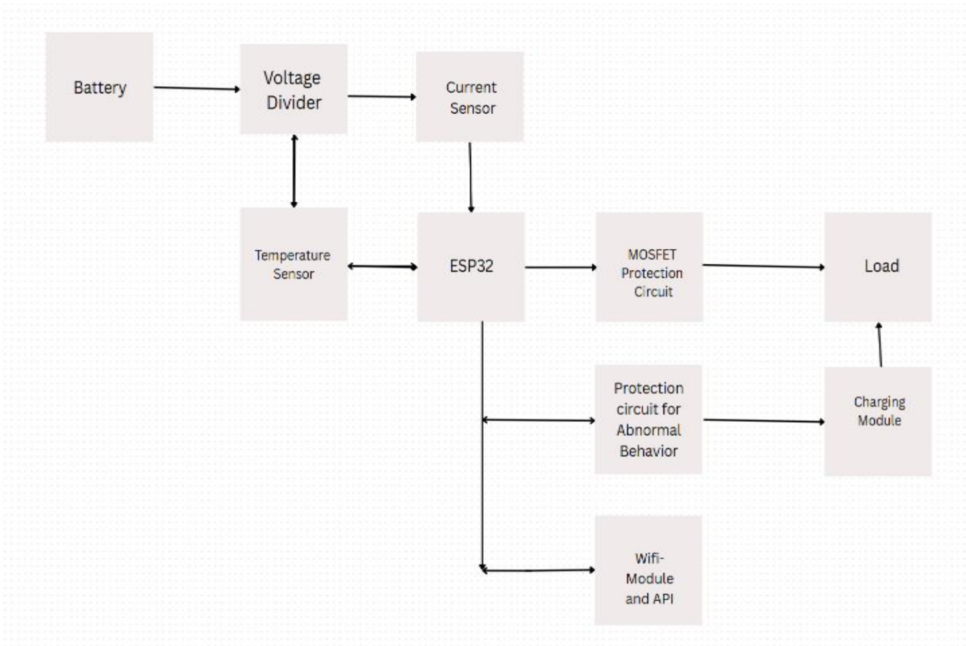
The project involves the design and development of an Intelligent Battery Monitoring and Optimization System based on an ESP32 microcontroller. It aims to monitor the most important parameters of the battery, namely voltage, current, and temperature, and prevent the battery from any dangerous conditions including overvoltage, undervoltage, overcurrent, and overheat

The system comprises:

- ESP32 Control and Communication Board
- ACS712 Real-Time Current Sensor.
- Voltage Divider Circuit for voltage sensing.
- DHT11 Environmental Temperature Sensor.
- MOSFET Protection Circuit for load or charger disconnection when faults happen.
- TP4056 Charging Module to charge the battery safely
- Filter Capacitors and TVS Diodes for protection against voltage spikes
- Wi-Fi Module (integrated in ESP32) for real-time wireless data transmission.

The system was developed and tested on a breadboard, with all components wired appropriately. The block diagram of the design helps visualize the architecture and signal flow between components.

Block Diagram –



2.Data Collection :

The system continuously collects three types of data:

- Voltage: Measured via a voltage divider and read using ESP32's analog pin.
- Current: Measured by the ACS712 current sensor and converted to readable values.
- Temperature: Measured by the DHT11 sensor

These values are read in real-time by the ESP32 and shown using the Serial Monitor or sent wirelessly via Wi-Fi. The ESP32 employs a loop to read data at regular intervals implement basic filtering (averaging or smoothing), and compare values with with predefined safety thresholds.

If any abnormal behavior is detected, such as:

Voltage going below/above safety levels Current exceeding limits Temperature rising above threshold ...the ESP32 sends a signal to the MOSFET circuit to disconnect the load or charger, ensuring protection.

3.Data Analysis

The collected data was analyzed both manually via the Serial Monitor and automatically by the ESP32 firmware to make decisions in real-time. Key aspects of analysis included:

- Voltage Trends: Monitoring for signs of overcharging or deep discharging.
- Current Patterns: Identifying load spikes or short circuits.
- Temperature Monitoring: Ensuring the battery operates within safe thermal limits.

Threshold values were programmed into the ESP32. When a parameter went beyond its threshold value, the system acted immediately by triggering the protection circuit. Real-time response under various test cases (e.g., charging, discharging, fault simulation) was monitored to confirm the system's decision-making accuracy and reliability.

The system was tested by operating it through various cycles of operation (charging, discharging, load variation).

Logs and plots (if prolonged) can reveal information about the behavior of the battery over a period of time and how well the system guards against failures.

RESULT AND DISCUSSION

Results -

The Intelligent Battery Monitoring and Optimization System was successfully designed, installed, and tested. The system was capable of: Correctly measure real-time voltage, current, and temperature of a 3.7V Li-ion battery by utilizing the ESP32 microcontroller and sensors (ACS712, DHT11, and voltage divider).

Detect and respond to abnormal conditions, such as:

- Overvoltage (above 4.2V)
- Undervoltage (below 3.0V)
- Overcurrent (above 5A)
- Overtemperature (above 40°C)

MOSFET-based trigger protection circuits to cut off the charger or load when thresholds were reached.

Wirelessly transmit sensor data through the ESP32's onboard Wi-Fi, enabling remote monitoring using a web-based dashboard or API.

Log data through Serial Monitor for debugging and testing.

The system reacted to faults in real-time. For instance, when the battery voltage fell below 3.0V, the ESP32 immediately disconnected the load to avoid deep discharge. Likewise, when the battery temperature rose above the set limit, charging was suspended to prevent overheating

Discussion -

The results show that this system can protect and monitor a battery effectively. Some important points are:

- Reliable performance: The protection circuits worked well during all tests.
- Low cost: All the parts used were affordable, making the system good for small projects and simple devices
- Can be improved: Right now, the system only works with a single battery. In the future, it can be upgraded to work with more batteries and add features like battery health check.
- Even though it doesn't have advanced features like battery health tracking, this system gives a strong base for safe battery use and monitoring

CONCLUSION :

In this project, a low-cost and effective Battery Monitoring and Protection System was successfully developed and tested on the ESP32 microcontroller. The system was capable of monitoring important battery parameters such as voltage, current, and temperature in real-time, ensuring safe and reliable use of batteries.

Through the aid of sensors and protective circuits, the system was able to sense hazardous conditions including overvoltage, undervoltage, overcurrent, and temperature. When any of these conditions were detected, the system would act rapidly by disconnecting the charger or load through MOSFETs in order to protect the battery.

The Wi-Fi-based data transmission feature through wireless enabled monitoring of battery condition remotely, rendering the system apt for IoT projects and handheld electronics. The configuration was tested on various conditions and proved to operate correctly and functionally

In general, the project creates a solid foundation for smart battery control in mini-sized systems. Subsequently, there are more and advanced features in the form of battery wellness predictions, multimeter support, and improved analysis for data enhancement so that it may become all the more intelligent and beneficial in the future..

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