Real-Time Battery Monitoring and Control for EV Applications

Mahesh Ganesh Jalgaonkar[1], Dr. Santosh C. Wagaj[2]
[1] JSPM's, Rajarshi Shahu College of Engineering, Department of Electronics and Telecommunication Engineering.
Email: maheshjalgaonkar@hotmail.com
[2] HOD, JSPM's, Rajarshi Shahu College of Engineering, Department of Electronics and Telecommunication Engineering.
Email: scwagaj@gmail.com

Abstract
The battery is an essential component of electric vehicles and represents a step toward sustainable mobility. Electric and hybrid vehicles rely largely on Battery Management Systems (BMS) to operate effectively. The battery management system (BMS) assures the battery's safety and consistency. Battery management systems keep batteries safe by monitoring status, managing charge, and balancing cells. Battery performance varies according to the operating and ambient conditions. Implementing battery-powered tasks may be difficult due to their unpredictable performance. Battery management systems (BMS) must assess a battery's state of charge, health, and lifecycle. Battery management systems (BMS) must evaluate a battery's state of charge, health, and life cycle. This research of battery status evaluation approaches predicts future challenges for BMS. This study examines the operation, topologies, and future technologies of BMS, including wireless BMS.
Keywords: Battery Management System, Electrical Vehicle, Microcontroller, Load, Voltage Sensor, Current Sensor.

I. INTRODUCTION

Battery management systems (BMS) are essential for the security, reliability, and optimal performance of rechargeable batteries. Strong BMS solutions are becoming increasingly important as the demand for cutting-edge technology rises, especially in industries like electric vehicles (EVs). Modern electric vehicles (EVs) are increasingly coming equipped with advanced driver assistance systems (ADAS), climate control, entertainment systems, and improved lighting. Although these capabilities improve the user experience, most BMS systems do not adapt to changing power demands. This emphasises the need for innovative solutions because it frequently leads to energy waste, a decreased driving range, and battery degradation.

The proposed system includes an LCD, MQTT IoT technologies, DC motors, rechargeable batteries, and an efficient BMS with ESP modules to enhance functionality. The system intends to overcome these obstacles in order to offer a balanced power supply, extend battery life, and enable real-time monitoring and control. The ESP8266/ESP32 is the primary controller for collecting data and communicating with the MQTT IoT panel. This enables the real-time transmission of critical data, such as battery voltage and current, to a user interface for remote control and monitoring.

The primary energy source is a rechargeable battery, such as two 3.7V lithium-ion cells connected in parallel or series, depending on the load. The BMS prevents short circuits, overcharging, and excessive battery depletion during charging and draining. To simulate high-power applications, the system connects relays or MOSFET-driven DC motors to the ESP module.

When used with a broker like Mosquitto, the MQTT IoT panel enables remote operations, improving real-time data transfer and monitoring capabilities. Users can utilise a simple smartphone interface to control connected loads and check battery characteristics, including voltage, current, and remaining charge. To help users collect vital information, an LCD (16x2 or 20x4) displays key metrics for local monitoring, such as battery voltage and charging current.

Various criteria are difficult for conventional systems to handle, particularly in high-demand applications like electric automobiles. This sophisticated battery management method addresses the difficulties stated previously. The effort supports sustainability by reducing energy waste and increasing system efficiency using a practical and reliable technique.

II. LITERATURE SURVEY

According to one study, a modular, decentralised system can improve scalability and fault tolerance while lowering expenses. Additional issues were hardware stability over time and performance at extremely high temperatures. Using machine learning algorithms to accurately anticipate battery health and charge level is another option to extend battery life. However, because of its high processing requirements, its application in EV systems with limited resources has been limited. Basic circuit designs. Reduced complexity and system costs, but accuracy is compromised by ageing batteries or dynamic load fluctuations. [1].

The study used a unique modelling technique to evaluate battery performance under dynamic grid conditions, resulting in improved charge-discharge control. Despite providing accurate system performance estimations, the model's high processing resource needs made it unsuitable for real-time use. Another way is to develop energy management algorithms to improve efficiency and battery life. Although this strategy improved overall system reliability, it was difficult to scale across various grid topologies and battery chemistries [2].

As the worldwide fleet of electric vehicles grows, researchers and manufacturers must focus on improving battery performance, efficiency, and safety. This article goes thoroughly into the most recent advances in lithium-ion (Li-ion) and other next-generation battery chemistries, which provide higher energy density, faster charging, and longer cycle life to meet the growing demands of today's electric vehicles. More realistic electrochemical, thermal, and data-driven models have allowed for detailed simulations of battery performance across a wide variety of operating circumstances, resulting in substantial advances in battery modelling. These models must calculate SOC, SOH, and lifespan while obtaining the highest energy efficiency [3].

Energy storage devices are needed to meet energy demands and preserve grid stability since renewable energy sources, such as photovoltaics, are incorporated into power networks in an unpredictable and unequal manner. High-power and high-energy batteries are widely employed in hybrid battery systems. They provide a practical method of improving energy distribution and storage strategies. The proposed paradigm for energy management is hierarchical in structure. It is most effective when it focuses on PV capacity firming, which involves the hybrid storage system balancing changes in PV production while continually sending power to the grid. Spot market trading, which uses real-time market pricing to maximize energy discharge and profit from arbitrage possibilities, is handled by lower-level management [4].

The primary objectives are to improve prediction accuracy, real-time monitoring, and overall battery performance, particularly for grid energy storage and electric vehicle (EV) applications. The Digital Twin, which uses information from the BMS, is a dynamic virtual model of the real battery that is continuously updated. Critical battery conditions are anticipated and simulated, including state of charge (SOC), state of health (SOH), and remaining useful life (RL). The system evaluates the battery's operating state in a variety of

scenarios by employing physics-based battery models, strong machine learning algorithms, and data-driven models [5].
This study looks into a digital twin structure to improve battery management systems (BMS) in electric vehicles (EVs). The approach predicts the state of charge (SOC) and state of health (SOH) of lithium-ion batteries using Extreme Gradient Boost (XGBoost) and Extended Kalman Filter (EKF), addressing challenges such as ageing and performance degradation. The method increases battery life and improves EV performance by increasing situational awareness, which allows for more accurate estimation of SOC and SOH [6].
The study focuses on the use of explainable, data-driven digital twins to forecast battery states in electric vehicles, namely state of charge (SOC) and state of health (SOH), in order to optimize battery performance. Deep neural networks and long short-term memory (LSTM) networks are examples of artificial intelligence models that improve prediction accuracy. However, because AI is opaque, explainable methods such as SHAP and LIME are required. The LSTM-based digital twin surpassed the others in terms of dependability [7].
This survey employed digital twins, deep learning, and machine learning to forecast the health of electric car batteries. These data-driven approaches solve the drawbacks of conventional methodologies by revealing nonlinear relationships between battery metrics and health conditions. While domain expertise improves interpretability, innovation broadens real-time applications. With a focus on studies published between 2021 and 2023, the study examines the problems, developments, and potential future paths in optimizing battery performance, safety, and affordability [8].
This study illustrates the role of battery management systems (BMS) in ensuring the efficient operation of electric vehicles (EVs). It analyses lithium battery cell models with one and two RC equivalent circuits, employing MATLAB simulations to assess charging current, terminal voltage, state of charge (SOC), and battery current. The study highlights the importance of battery types and addresses future BMS enhancements to improve EV performance and reliability [9].
The Battery Management System (BMS) is critical for improving the performance and safety of electric vehicles (EVs). To minimize overcharging, overheating, and other issues, BMS monitors temperature, voltage, current, and state of charge (SOC). Maintaining constant performance, enhancing energy efficiency, and extending battery life all rely on a functional BMS. As EV technology advances, ongoing research is being conducted to extend BMS capabilities for improved integration and efficiency [10].

III. METHODOLOGY

The method creates a reliable, efficient, and user-friendly rechargeable battery management system by combining hardware and software components. The structure of the technique consists of the following steps:
Startup Phase: Initially, the system configures the sensors, ESP module, and Battery Management System (BMS). The ESP module serves as the primary controller, connecting to the MQTT broker to facilitate real-time data exchange. To ensure seamless operation, each component has been functionally checked.
Data Acquisition: Voltage and current sensors continuously monitor battery characteristics and record real-time data. The ESP module uses this information to determine the battery's state of charge (SOC). An LCD displays the computed figures, which provide information on the local and current battery statuses.
Data Transmission: The ESP module publishes voltage and current measurements to MQTT topics. These topics are handled by an Internet of Things application that allows consumers to remotely monitor the status of their batteries. Customers can utilise this feature to see the most recent critical metric and system health information.

Load Control: The MQTT IoT application allows users to communicate commands to connected loads, such as DC motors. The ESP module receives these commands and activates the GPIO pins required to carry them out. This capability extends battery life by making it easier to control power-hungry devices.
Safety Checks: The device periodically checks the voltage levels of the batteries to prevent harm. The BMS will immediately switch off the load if the battery voltage falls below 3.7 volts. This safeguard prevents deep depletion and extends the battery's lifespan.

IV. BLOCK DIAGRAM

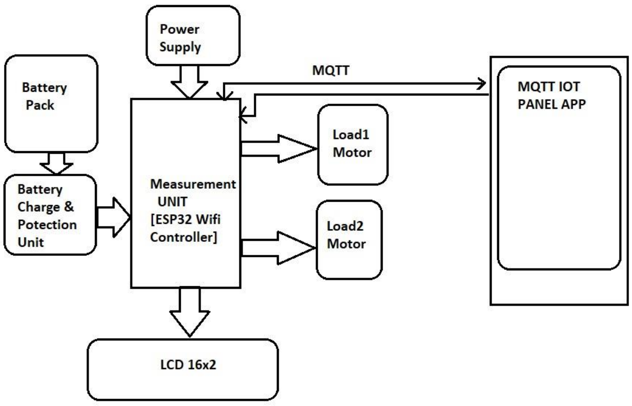

Fig: Block Diagram of Battery Management System

The block diagram depicts an ESP32 Wi-Fi controller-based battery management system (BMS) for monitoring and maintaining battery activity. The system's first component is a power-generating battery pack, which is protected by a charge and protection module. This extends battery life and improves safety by reducing short circuits, overcharging, and excessive discharge. The measuring unit is the system's primary component, which is controlled by the ESP32 controller. It continuously monitors battery parameters such as voltage, current, and charge level while drawing power from an external source.
Load1 and Load2, two motor-powered devices, work with the ESP32. These loads are created based on power consumption and system availability. The ESP32's ability to wirelessly transfer real-time data via the MQTT protocol to an MQTT panel app based on the Internet of Things enables remote monitoring and control. Critical battery information is displayed locally on a 16x2 LCD panel, allowing users to respond swiftly.
The battery pack connects to the charging and protection unit, which supplies power to the ESP32. The motors are attached to the ESP32's GPIO pins, and the LCD is connected to either the I2C or GPIO pins. This comprehensive strategy promotes effective communication, energy management, and operational safety. This integrated system improves energy economy, communications, and operational safety.

3.1 Hardware Requirement:
ESP8266/ESP32 module: The system's primary controller is the ESP8266/ESP32. It controls communication with the MQTT IoT panel, as well as data gathering and processing.
Two Li-ion batteries at 3.7V. Depending on the load, two 3.7V lithium-ion batteries can be wired in series or parallel (7.4V total). Tests all cell voltages for safety.
Battery Management System (BMS): Prevents deep discharge, short-circuiting, and overcharging of batteries. maintains an equilibrium between battery charging and draining.

DC Motors: Determine the system's power-hungry components. Controlled via relays or MOSFETs attached to the ESP module.
MQTT IoT Panel: Mosquito is a name given to a MQTT broker that allows real-time communication. The app interface displays battery voltage and current and allows for remote load control.
LCD Display: A 16x2 or 20x4 LCD displays important information such as charging current and battery voltage.

V. FLOWCHART

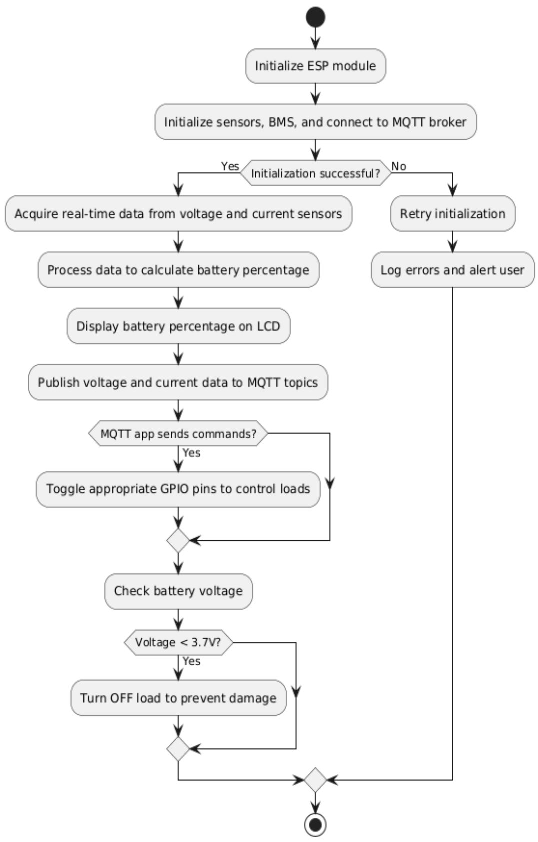

Fig: Flowchart of BMS

The ESP module is initially set up, and an MQTT broker connection is made. Following that, the system connects to the MQTT broker and configures the sensors and BMS. If the initialisation is successful, the system will collect real-time data from the voltage and current sensors. The battery percentage is then computed by analysing this information. After sending voltage and current data to MQTT topics, an LCD shows the determined battery %. The system manages the load by toggling the appropriate GPIO pins in response to MQTT application requests. Finally, the system monitors the battery's voltage. If the voltage goes below 3.7 volts, the load is turned off to prevent harm.
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VI. RESULT AND DISCUSSION

1. Voltage Measurement Accuracy

Issue:
Voltage divider circuits for battery voltage monitoring sometimes provided inaccurate readings.
The ESP ADC pins have limited resolution and are sensitive to noise.

Root Cause:
Poor calibration of the voltage divider. Inconsistent resistor tolerances and ADC non-linearity.
Solution:
Used precise resistors with low tolerance (1% or better). Applied smoothing filters or oversampling techniques in the firmware.

2. Current Measurement Instability
Issue:
The current sensor output fluctuated, causing inconsistent current readings.
Root Cause:
Noise and interference from motor operations. Insufficient sensor bandwidth for dynamic loads.
Solution:
Added decoupling capacitors near the current sensor. Implemented software filtering (moving average or exponential smoothing).

3. Battery Protection Challenges
Issue:
The BMS module didn't always disconnect the load at low voltages. Over-current scenarios damaged MOSFETs/relays controlling the motors.
Root Cause:
Delayed response from the BMS protection circuit. Insufficient current ratings of relays or MOSFETs.
Solution:
Selected a BMS module rated for the specific battery chemistry and load current. Upgraded relays/MOSFETs to handle peak current.

4. Load Control via MQTT
Issue:
Delays or failed commands when turning loads ON/OFF via the MQTT app.
Root Cause:
Network latency or unstable Wi-Fi connectivity.
MQTT broker disconnections.
Solution:
Added retry and reconnect logic for MQTT communication in the ESP firmware.
Configured Quality of Service (QoS) level 1 for reliable message delivery.

5. Battery Voltage Drop During Load
Issue:
Battery voltage dropped significantly under heavy motor load, causing premature load cutoff.
Root Cause:
Internal resistance of the batteries and insufficient capacity.
Solution:
Used higher-capacity batteries with lower internal resistance.
Implemented a hysteresis mechanism to prevent rapid cutoff during brief voltage dips.

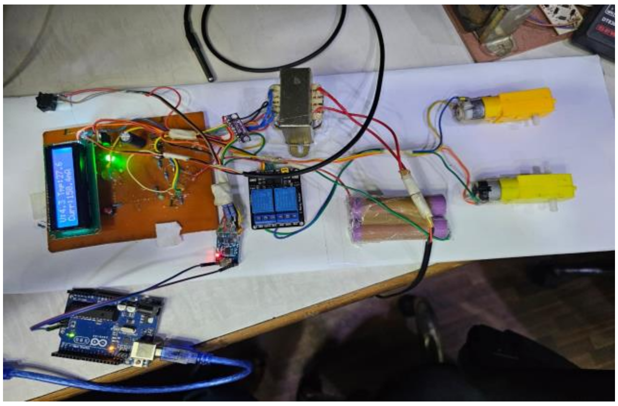

Fig: Result

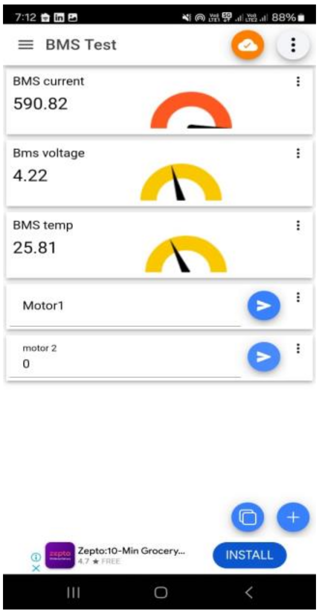

Fig: Mobile App Interface

VII. CONCLUSION

In conclusion, the concept of a Battery Management System (BMS) is useful for both energy management and battery monitoring. The ESP32 Wi-Fi controller is a vital component for real-time data collection, processing, and transmission. The system's charge and protection mechanism safeguard the battery from deep discharge, overcharging, and other potential risks.

Customers get immediate responses from the BMS's 16x2 LCD display, which also allows for local monitoring of crucial parameters like voltage and current. Furthermore, the system employs the MQTT protocol for wireless access, which enables real-time data transfer to an IoT-based MQTT panel application. This capability makes the system suitable for a variety of applications and allows for remote monitoring and management. The addition of two load motors (Load1 and Load2) demonstrates the system's ability to efficiently regulate power distribution. The project's architecture, which focuses on scalability and integration, is perfect for Internet of Things-based applications in electric vehicles, renewable energy, and other industries that require extensive battery management skills. This BMS improves battery performance and longevity while also enabling intelligent control and remote operation. When everything is said and done, the system prioritises safety, dependability, and connection while providing a comprehensive solution to modern energy management challenges.

Future research on effective EV battery management should concentrate on developing sophisticated algorithms for real-time load prioritisation, improving state monitoring through multi-sensor integration, creating innovative thermal management systems, researching next-generation battery technologies, and customising user interfaces.

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