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IoT-Enabled Individual Cell Monitoring System for 3S Lithium-Ion Battery Pack Using ESP32 and INA219 Sensors

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ABSTRACT

This paper presents the design and implementation of an IoT-enabled smart Battery Management System (BMS) for a 3S lithium-ion battery pack. The system employs three INA219 current/voltage sensors, SPDT relays, an ESP32 microcontroller, and a 16x2 LCD display to achieve real-time individual cell monitoring. Key battery parameters — voltage, current, State of Charge (SOC), and State of Health (SOH) — are computed for each cell and simultaneously displayed on a local LCD and a Wi-Fi hosted web dashboard. A fault detection mechanism identifies overvoltage, undervoltage, overcurrent, and cell imbalance conditions, triggering relay-based cell isolation and real-time alerts. The proposed system provides a low-cost, scalable, and practical solution for battery monitoring in Indian EV, solar storage, and UPS applications.

Index Terms — *Battery Management System, ESP32, INA219, Lithium-ion, SOC, SOH, IoT, Cell Monitoring, SPDT Relay, Electric Vehicles.*

I. INTRODUCTION

The rapid proliferation of lithium-ion batteries in electric vehicles (EVs), solar energy storage, uninterruptible power supplies (UPS), and consumer electronics has created an urgent need for reliable and intelligent Battery Management Systems (BMS). In India, this demand is further intensified by national initiatives such as the FAME India Scheme, which accelerates EV adoption, and

IV. FIRMWARE DESIGN

A. Initialization Sequence

On power-on, the firmware initializes the I2C bus, instantiates three INA219 objects at their respective addresses, configures the LCD, sets relay GPIO pins as outputs (default: closed), establishes Wi-Fi connectivity, and starts the HTTP server. If Wi-Fi is unavailable, the system continues in local-only mode.

B. Data Acquisition Loop

The main loop executes every 500ms using millis()-based non-blocking timing. For each of the three cells, the firmware reads: getBusVoltage_V(), getCurrent_mA(), and getPower_mW() from the corresponding INA219. Values are stored in arrays indexed by cell number.

C. SOC Estimation

SOC is estimated using a hybrid approach. A voltage-to-SOC lookup table, derived from the cell's discharge characteristic curve, provides an initial reference. Coulomb Counting (integrating I × Δt) dynamically updates SOC between cycles. The lookup table recalibrates Coulomb Counting at rest states (low current) to minimize drift error.

$$\mathbf{SOC(t) = SOC_0 - (1/Q_n) \int I(t)\,dt}$$

where Q_n is the nominal cell capacity in Ah and SOC_0 is the initial SOC.

D. SOH Estimation

SOH is calculated at the end of each charge-discharge cycle by comparing the measured deliverable capacity against the rated capacity:

$$\mathbf{SOH\ (\%) = (C_n^{0\frown} / C_r^{aTIRED}) \times 100}$$

the Ministry of New and Renewable Energy's solar energy drive [1].

A multi-cell lithium-ion battery pack — particularly in series configurations — poses significant monitoring challenges. In a 3S (three-cells-in-series) pack, each cell operates at a different voltage reference relative to ground, making simultaneous direct measurement impractical without isolation circuits. Furthermore, manufacturing tolerances, aging, and unequal thermal conditions cause cells to behave differently over time, leading to cell imbalance, reduced pack performance, and potential safety hazards such as thermal runaway [2].

Conventional BMS designs typically measure only the aggregate pack voltage and total current, which is insufficient for detecting cell-level faults. This limitation can allow undetected issues — such as a single weak cell drawing disproportionate current — to degrade or destroy the entire pack. Advanced BMS solutions capable of per-cell monitoring, SOC/SOH estimation, and fault isolation are therefore critical for safety and longevity [3].

This paper presents an ESP32-based individual cell monitoring BMS for a 3S lithium-ion pack. The key contributions of this work are: (i) dedicated INA219 sensors per cell using unique I2C addresses for simultaneous measurement, (ii) SPDT relay switching for cell isolation under fault conditions, (iii) hybrid SOC estimation combining Coulomb Counting and voltage-based lookup, (iv) real-time local display via LCD, and (v) an IoT web dashboard hosted on the ESP32 for remote monitoring and alert management.

II. LITERATURE REVIEW

Several researchers have investigated BMS designs for lithium-ion batteries. Plett [4] established foundational algorithms for SOC estimation using Extended Kalman Filters (EKF), which, while accurate, require significant computational resources unsuitable for low-cost embedded systems. Lu et al. [5] reviewed BMS architectures and highlighted that cell-level monitoring is essential for detecting early-stage degradation in series-connected packs.

A SOH below 80% triggers a maintenance alert, indicating the cell should be inspected or replaced.

E. Fault Detection

The fault detection module continuously evaluates each cell's parameters against thresholds defined in Table II. Upon threshold violation, the corresponding relay is opened and alerts are dispatched to both the LCD and IoT dashboard.

TABLE II. Fault Thresholds and System Responses

Fault	Condition	Response
Overvoltage	>4.2V	Relay open + alert
Undervoltage	<2.8V	Charge cutoff
Overcurrent	>2C rate	Relay open + alert
Imbalance	ΔV>0.2V	Warning alert
Low SOH	<80%	Maint. alert

V. IOT WEB DASHBOARD

The ESP32 hosts a lightweight HTTP server on port 80. The dashboard is a single-page web application built with HTML5, CSS3, and JavaScript. It polls the /data endpoint via the Fetch API every 1 second, receiving a compact JSON payload containing per-cell voltage, current, SOC, SOH, and fault flags.

The dashboard displays: (i) color-coded metric cards per cell (green: normal, yellow: caution, red: fault), (ii) rolling trend charts for the last 60 readings using Chart.js, (iii) a timestamped fault event log, and (iv) manual relay toggle buttons for maintenance. The system is accessible from any device on the local Wi-Fi network, requiring no external cloud services.

VI. RESULTS AND DISCUSSION

The system was tested under three load conditions: no-load, 0.5A constant load, and 1.2A constant load. Voltage measurements from the INA219 sensors were compared against a calibrated

IoT-enabled BMS designs have gained considerable attention in recent years. Gabbar et al. [6] proposed a cloud-connected BMS using Wi-Fi communication, demonstrating the feasibility of remote battery monitoring. However, their system relied on external cloud infrastructure, increasing cost and dependency. In contrast, the proposed system hosts the dashboard directly on the ESP32, eliminating cloud dependency.

Regarding SOC estimation, the Coulomb Counting method combined with open-circuit voltage (OCV) lookup remains a practical and computationally efficient approach for embedded systems [7]. The INA219 sensor has been validated in several embedded energy monitoring applications for its accuracy and I2C compatibility [8]. The use of SPDT relays for cell switching in series BMS configurations has been demonstrated as a cost-effective alternative to analog multiplexers [9].

The proposed work addresses gaps in existing literature by integrating per-cell INA219 sensing, relay-based fault isolation, and a self-hosted IoT dashboard into a unified, low-cost system tailored for Indian energy applications.

III. SYSTEM DESIGN

A. Hardware Architecture

The hardware system comprises five functional subsystems: (1) the 3S lithium-ion battery pack with voltage tap points, (2) three INA219 current/voltage sensor modules, (3) three SPDT relay circuits with transistor drivers, (4) an ESP32 microcontroller, and (5) a 16x2 I2C LCD display. A buck converter (12V to 5V) supplies regulated power to the ESP32 and peripherals.

The 3S pack produces a nominal voltage of 11.1V (fully charged: 12.6V). Voltage measurement tap points between each cell allow individual cell monitoring. The battery positive terminal is connected through the relay network, and the negative terminal is connected to common ground.

B. INA219 Sensor Configuration

Three INA219 bidirectional current/power monitor ICs are used — one per cell. Each is configured with a unique I2C hardware address via digital multimeter. Table III summarizes the accuracy observed.

TABLE III. Measurement Accuracy (INA219 vs. Multimeter)

Parameter	Actual	Measured	Error
Cell 1 Voltage	3.92V	3.91V	0.26%
Cell 2 Voltage	3.87V	3.88V	0.26%
Cell 3 Voltage	3.75V	3.76V	0.27%
Current (0.5A)	500mA	498mA	0.40%

Fault detection was verified by simulating overvoltage (injecting 4.25V) and cell imbalance ($\Delta V = 0.25V$). In both cases, the system correctly identified the fault, opened the relay within one monitoring cycle (500ms), and displayed alerts on both the LCD and the web dashboard. The IoT dashboard consistently updated within the 1-second polling window across all test conditions.

SOC estimation accuracy was evaluated by comparing Coulomb-Counting-derived SOC with the voltage-lookup reference at rest. The maximum observed SOC deviation was ±3.5%, which is acceptable for the intended applications.

VII. CONCLUSION

This paper presented the design and implementation of a low-cost, IoT-enabled BMS for a 3S lithium-ion battery pack using the ESP32, INA219 sensors, and SPDT relays. The system successfully achieves individual cell-level monitoring of voltage, current, SOC, and SOH with measurement accuracy within 0.4%. The fault detection mechanism reliably identifies and isolates overvoltage, overcurrent, and cell imbalance conditions. The self-hosted IoT dashboard eliminates cloud dependency while providing real-time remote monitoring and alert logging.

The proposed system is cost-effective, scalable, and well-suited for deployment in Indian EV battery packs, solar energy storage systems, and industrial UPS applications. Future work will explore integration of temperature sensing (NTC thermistors), active cell balancing circuits, and machine learning-based SOH prediction models.

its address pins (A0, A1), as shown in Table I. A 0.1Ω shunt resistor is used for current sensing. The sensors share the ESP32's SDA/SCL lines, enabling simultaneous per-cell measurement without switching.

TABLE I. INA219 I2C Address Configuration

Cell	A0 Pin	A1 Pin	I2C Addr
Cell 1	GND	GND	0x40
Cell 2	VCC	GND	0x41
Cell 3	GND	VCC	0x44

C. SPDT Relay and Driver Circuit

Three SPDT relays provide cell isolation under fault conditions. Since relay coils draw ~70mA — exceeding ESP32 GPIO limits — NPN transistors (BC547) act as driver switches between GPIO and coil. A 1N4007 flyback diode suppresses inductive voltage spikes. During normal operation, all relays remain closed. Upon fault detection, the ESP32 opens the corresponding relay to disconnect the affected cell.

D. Voltage Divider for ADC Safety

The ESP32 ADC accepts a maximum of 3.3V. A resistive voltage divider (R1 = 100kΩ, R2 = 10kΩ) scales the pack voltage (up to 12.6V) to approximately 1.15V, providing a safe margin. Individual cell voltages are primarily read via INA219 bus voltage registers, which handle the differential measurement internally.

E. *Block Diagram of Proposed System*

The block diagram of the proposed Battery Management System represents the overall architecture of the system. It consists of a 3S lithium-ion battery pack, INA219 sensors, ESP32 microcontroller, SPDT relay modules, LCD display, and IoT communication interface.

Each battery cell is connected to an individual INA219 sensor for voltage and current measurement. The sensors communicate with the ESP32 microcontroller through the I2C protocol. The ESP32 processes the acquired data to estimate SOC and SOH, and controls relay operation for fault isolation.

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The processed data is displayed locally on an LCD and transmitted to a web-based IoT dashboard via Wi-Fi. The system continuously monitors battery parameters and ensures safe and efficient operation.

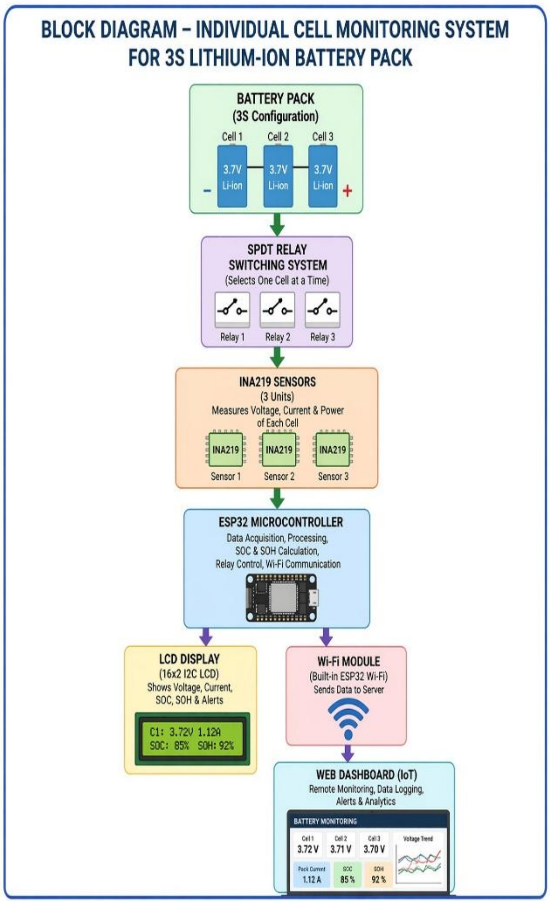

Fig. 1 shows the block diagram of the proposed system.

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