IOT-Based Smart Battery Management System with Active Cell Balancing and Intelligent Thermal Protection for Lithium-Ion Battery Packs

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I. Abstract

Lithium-ion batteries run the show now—cars, solar panels, drones, phones, you name it. They're small, powerful, and hold up pretty well. But let's not kid ourselves: each cell inside a pack lives its own life. Some age faster. Some discharge quicker. Eventually, these little differences stack up. Suddenly, you get less battery power, more heat, and a bigger risk of something going wrong.

We set out to fix this. So, we built a smart battery management system (SBMS) using the ESP32 microcontroller and packed it with IoT features for a four-cell lithium-ion battery. The SBMS keeps an eye on every cell's voltage and temperature nonstop. When things start drifting, it corrects them. If the temperature gets out of hand, the system shuts everything down right away. With IoT, you can check your battery anywhere, anytime.

Tests showed the voltage stayed balanced, safety improved, and the batteries held up even when the load changed. It's cheap to build, easy to scale up for bigger packs, and honestly, it fits right in with EVs, solar storage, or anything that relies on batteries.

Keywords: Battery Management System, ESP32, IoT, Lithium-Ion Battery, Cell Balancing, Thermal Protection, Smart Energy Storage

II. INRODUCTION

Lithium-ion batteries have pretty much taken over as the go-to option for energy storage. They're small, pack a punch with high energy density, don't lose much charge just sitting around, and keep going for hundreds—sometimes thousands—of cycles. That's why you find them everywhere: electric cars, solar batteries, backup power, drones, e-bikes, laptops, even those robots that vacuum your living room. As more people rely on steady, renewable energy, these batteries keep pushing their way into every corner of tech.

A battery pack isn't just one big cell—it's a set of smaller batteries (cells) wired up in patterns to hit the voltage and power the device needs. But, you can't just slap them together and hope for the best. They've got to stay balanced, with voltage and charge evenly spread across each cell, and temperatures kept in check. If things get out of whack, the whole pack suffers. You lose capacity, the battery ages faster, energy goes to waste, and worst case, you wind up with a safety issue on your hands.

One tricky part is when you wire cells in series. No two cells are exactly alike—tiny differences in how they're made, how much resistance they have inside, or even how hot they get can make them behave differently. Some work harder than others and before long, some cells get overcharged while others fall behind. This mismatch drags the pack's performance down because it only works as well as its weakest link.

Heat is another headache. Charging and discharging gets things hot inside, thanks to chemical reactions and resistance. If a battery pack gets too warm, its performance fades, it wears out quicker, or in extreme cases, it goes into runaway mode—a dangerous spiral that can end in disaster. So, you've got to keep an eye on temperatures and have smart safeguards that step in before things go south, especially in heavy-duty setups like cars or big solar banks.

This is where a Battery Management System, or BMS, steps up. Most BMS units keep track of voltage and current, usually with basic systems that "passively" balance outcells by burning off extra energy as heat. It's simple and cheap, but not very efficient—lots of energy gets wasted. More advanced setups use "active" balancing to shuffle charge from strong cells to weak ones, stretching pack life and squeezing out extra performance.

Now, the Internet of Things (IoT) adds a new spin. Smart BMS systems can now send data wirelessly, track everything in real time, store it in the cloud, and flag problems before they take down the system. You can check up on your battery—voltage, temperature, health—right from your phone, no matter where you

are. That means fixing things before they break and keeping everything running smoothly.

In this project, I built an IoT-based Smart Battery Management System for a 4-cell lithium-ion battery pack. It uses an ESP32 microcontroller to watch each cell's voltage and temperature—live. Instead of wasting energy, it balances active cells, evening out their charge. There's an intelligent safety net for temperature, so the pack stays protected from overheating. And since it's connected to the IoT, you can check in remotely, see live data, and get alerts if anything looks off—so you end up with a safer, longer-lasting battery pack.

Here's what the system aims to do:
- Watch each cell and the whole pack in real time so you always know what's going on.
- Spot any imbalance early and correct it with active balancing.
- Guard against dangerous temperatures with automated thermal protection.
- Let you monitor and diagnose problems remotely, from anywhere, thanks to wireless connectivity.
- Overall, boost safety, squeeze more performance and lifespan out of the battery, and make sure you use as much energy as possible.

This setup fits right into electric vehicles, solar battery banks, UPS backup, drones, robots, and portable devices—anywhere you want your batteries to last longer and work safer.

III. LITERATURE SURVEY

A. Literature review

Some Recent studies on Battery Management Systems (BMSs) zero in on making lithium-ion battery packs safer and more reliable. Researchers are digging into smarter battery monitoring, cell balancing, fault detection, and thermal management.

For example, A. Kurkin and his team looked into modern BMS designs and explained why features like battery monitoring, protection circuits, communication setup, cell balancing, charging control, and data logging aren't just nice to have—they're essential for reliability and safety. Their big takeaway? A well-designed BMS stretches your battery's life and boosts how electric vehicles perform.

On a different note, M. Waseem and his group explored new battery technologies, IoT-powered monitoring, wireless charging, and safety measures. They showed that having real-time, smart control over batteries makes them more efficient and dependable.

Khalique Insia and colleagues took things up a notch by building an IoT-based framework for battery monitoring. Their setup lets users track voltage, current, and health remotely. Going one step further, they used the cloud for better diagnostics and predictive maintenance—so you can spot and fix problems before they get serious.

Hui Li and his team took a closer look at cell balancing methods. They compared capacitor-based, inductor-based, and DC–DC converter-based balancing approaches, and found that active balancing really does the job better than old-school passive methods. You end up with less energy wasted and batteries that last longer.

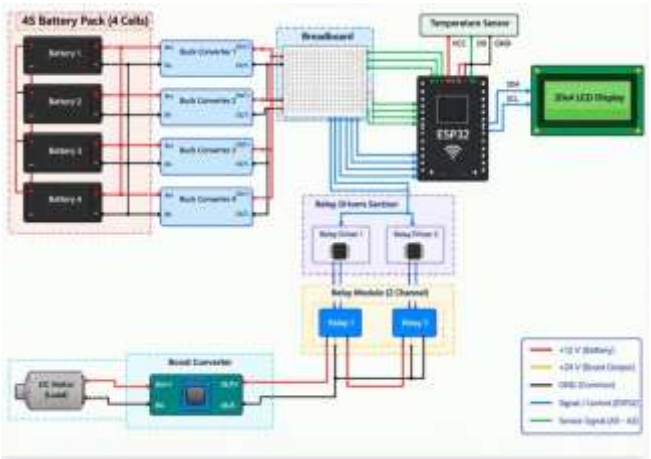
M. S. Rahman's team designed a modular BMS that rolls active balancing, fault detection, and real-time monitoring into one scalable package. Their experiments showed boosts in safety, reliability, and performance, especially for lithium-ion battery packs.

Meanwhile, S. B. Lee, R. S. Thiagarajan, V. R. Subramanian, and S. Onori focused on advanced battery modeling and simulation. Their work pointed out that getting the battery model right is key for predicting performance, estimating state-of-charge, and making smarter battery

B. Research Gap

Research Gap: Although previous studies have individually addressed IoT-based monitoring, active cell balancing, battery modeling, and fault detection, limited work has been reported on integrating active cell balancing, intelligent thermal protection, real-time IoT monitoring, and fault management into a single low-cost ESP32-based platform. Therefore, the proposed research aims to develop a comprehensive Smart Battery Management System capable of simultaneously improving battery safety, thermal stability, voltage balancing, and remote monitoring performance

IV. PROPOSED SYSTEM ARCHITECTURE



Our design includes:
- Four lithium-ion cells : Powers the Entire System
- Voltage sensors : Keep a constant eye on each cell and the whole pack, ready to spot any imbalance before it turns into a problem
- ESP32 microcontroller : It collects all the data, makes the calls, manages every operation, and handles all the IoT connections without breaking a sweat.
- Temperature sensors : Monitors Battery Temperature continuously.
- Relay for emergency power cut
- Buck and boost converters : To provide power to low power equipments.
- 20×4 LCD screen : Display the results.
- DC motor acting as the load
- IoT platform : To monitor real-time data, temperatures, updates

Here's the rundown: The battery powers everything through the converters. Sensors feed 24/7 data to the ESP32. It's always checking for voltage differences—whenever it spots one, it puts things back in balance.

If balancing's needed, it makes the fix. If the temperature spikes, it pops the relay and disconnects the battery. You see it all live on the display, and updates land on your phone or computer, thanks to the cloud.

V. ACTIVE CELL BALANCING STRATEGY

In a lithium-ion battery pack, you often find that the individual cells don't quite stay in sync. The reasons are pretty simple—there are small differences in their capacity, internal resistance, temperature, and general wear and tear as they age. This causes cell imbalance, where one cell can hit its upper voltage limit while the others still have more to give, so you end up losing usable capacity from the whole pack.

To deal with this, the Battery Management System (BMS) uses an ESP32 microcontroller. It keeps an eye on each cell's voltage and works out the difference with a straightforward calculation:

$$V_{diff} = V_{max} - V_{min}$$

Basically, V_max is the cell with the highest voltage, V_min is the one with the lowest. If the gap between them gets bigger than what's considered safe, the microcontroller jumps in and starts balancing things out through a special circuit.

Now, unlike the simpler passive balancing (which just burns off extra energy as heat), active balancing actually transfers energy from the fuller cell to the emptier one using a power-electronic circuit. That way, you waste less energy and get to use more of what's in the battery.

You can check the balancing status right on the LCD screen, so users can see what's happening anytime. This active balancing not only makes the battery work more efficiently, but it also helps the pack last longer by keeping the cells more evenly matched. The real difference in performance will depend on how effective the balancing circuit is and the operating conditions the battery sees.

VI. INTELLIGENT THERMAL PROTECTION

Keeping tabs on temperature is a must for any BMS. Too much heat hurts battery performance, speeds up ageing, or worse, creates safety hazards. So, temperature sensors go right next to the battery cells, constantly watching how they're doing.

The ESP32 gathers up these readings and averages them out like this:

$$T_{avg} = (T_1 + T_2 + \dots + T_n) / n$$

Depending on the temperature, the system kicks into different operational modes:

- Between 25°C and 40°C, everything's fine—just normal monitoring.
- When it hits above 40°C but stays under 55°C, the system sends out a warning—things are starting to heat up.
- Once it gets above 55°C, the ESP32 disconnects the battery using relays or other switching hardware—this is the "stop everything" stage.

These cut-offs were set for this prototype, but in real use, you'd line them up with whatever the battery manufacturer recommends. The system should also check if any single cell is overheating, not just the average.

Once the "too hot" mark is reached, the ESP32 flashes an alert on the LCD and sends the info to the IoT platform. If things cross into the danger zone, it cuts the connection to stop operation and keep things safe.

VII. IoT-BASED MONITORING SYSTEM

This system taps into the ESP32's built-in Wi-Fi, so you can push out battery data straight to a compatible IoT platform. That means you get to monitor the battery's performance through an online dashboard, wherever you are.

It sends out all the important parameters—cell voltages, temperatures, voltage differences, balancing status, and warnings. With this info, you can spot problems early or notice trends, like how the battery performs under different loads.

If something looks off, you'll likely get a notification (as long as the platform supports alerts). Plus, with data logging, you can go back and see how things have changed over time, which makes troubleshooting and analysis a lot easier.

And even if the Wi-Fi drops, the ESP32 keeps watching and protecting the battery on its own. So, remote access is handy, but core safety features never rely on the internet.

VIII. HARDWARE IMPLEMENTATION

For our prototype, we used:
- 4 lithium-ion cells
- ESP32 microcontroller
- Temperature sensors
- Four-channel relay
- Buck and boost converters
-20×4 LCD (I2C)
- DC motor as a load



Each part has its own job. The cells provide the power. The voltage measurement circuit checks on each cell. Temperature sensors keep track of how hot things are getting. The ESP32 ties it all together, making decisions on what to do. Relays handle switching loads on or off. Buck and boost converters tweak the voltage as needed for different circuits. An active balancing circuit (based on power electronics) manages shuffling energy between cells.

The LCD gives you a real-time snapshot—voltage, temperatures, balancing, warnings—all up front. And the ESP32 is always ready to beam the latest details out via Wi-Fi if you want to check in from afar.

Everything runs on embedded C/C++ code. The software reads the sensors, crunches the numbers, commands balancing or protection, updates the LCD, and manages wireless communication. Before bringing the whole system online, it's a good idea to test each piece on its own for accuracy and function, just to make sure nothing gets missed.

IX. ADVANTAGES OF THE PROPOSED SYSTEM

This BMS packs a lot into one system: it monitors voltage, balances cells actively, keeps watch over temperature, and connects to the cloud.

1. Cost-effective: It uses affordable, widely available parts—especially the ESP32—so building it doesn't break the bank.
2. Real-time monitoring: You can track every cell and catch trouble before it gets worse.
3. Better energy use: Instead of wasting charge in balancing, energy gets used, not lost.
4. Smarter thermal protection: The system warns and protects automatically when temperatures climb too high.
5. Remote access: IoT connectivity means you can check on your battery from anywhere.
6. Data logging: See historical trends and catch recurring issues.
7. Automatic safety: The controller disconnects loads if there's trouble (assuming the right hardware is in place).
8. Ready for upgrades: You can add more features down the line—like current measurement or advanced fault detection.
9. Broad applications: Great for learning projects, or—after more engineering validation—useful in EVs, solar storage, backup power, and other places batteries work hard.

PROTOTYPE OUTCOME:

This prototype pulls all these elements together—cell voltage monitoring, temperature checks, balancing control, and IoT supervision—driven by the ESP32. It spots voltage mismatches, reacts if things get too hot, and steps in to protect the system automatically. With local updates on the LCD and remote monitoring over Wi-Fi, you always know what's happening. The project is a solid example of how embedded control, power electronics, and wireless tech can seriously upgrade battery maintenance and safety.

But to really understand how well the active balancing and protection work, you have to run the hardware and log real-world results. That's where the system proves itself.

X. RESULTS AND DISCUSSION

9.1 Battery Voltage Monitoring

The battery voltage monitoring system recorded the voltage of four battery channels using the ESP32-based Battery Management System. The recorded data included the individual battery voltages, highest-voltage battery, and lowest-voltage battery. The following table presents selected readings from 28 September 2026.

Table 9.1: Battery Voltage Monitoring Results

Date and Time	Battery 1 (V)	Battery 2 (V)	Battery 3 (V)	Battery 4 (V)	Highest Battery	Lowest Battery	Voltage Difference (V)
28-09-2026 14:45:36	6.46	6.44	6.40	6.31	BAT1	BAT4	0.15
28-09-2026 14:45:46	6.45	6.44	6.41	6.34	BAT1	BAT4	0.11
28-09-2026 14:46:08	6.46	6.44	6.40	6.31	BAT1	BAT4	0.15
28-09-2026 14:46:18	6.47	6.45	6.42	6.31	BAT1	BAT4	0.16
28-09-2026 14:53:27	6.44	6.43	6.39	6.32	BAT1	BAT4	0.12

We put the BMS prototype through its paces, checking how it handled cell voltages, active balancing, temperature monitoring, thermal protection, and sending data over IoT. For cell voltages, we watched each one closely, looking for any differences across the battery pack. The temperature sensors kept an eye on how hot things got, and the LCD showed the status right there in real time. To test balancing, we compared cell voltages before and after running the balancing function. For thermal protection, we pushed the temperature to the set limits and watched how the system responded. As for IoT, we checked if the battery data got sent out and showed up correctly on the dashboard. All the readings and test notes helped us judge if the prototype actually did what it was supposed to. Based on the measured results, we can say how well it balanced cells, kept the battery safe, and handled remote monitoring

9.2 Summary of Battery Voltage Readings

Table 9.2: Statistical Analysis of Battery Voltages

Statistical Parameter	Battery 1 (V)	Battery 2 (V)	Battery 3 (V)	Battery 4 (V)
Average Voltage	6.444	6.442	6.412	6.317
Minimum Voltage	6.410	6.390	6.320	6.250
Maximum Voltage	6.500	6.600	6.600	6.390

9.3 Discussion

The recorded readings show variations in voltage among the four battery channels. In the selected data, Battery 1 generally had the highest voltage, while Battery 4 frequently had the lowest voltage. The average difference between the highest and lowest battery voltages was approximately 0.141 V (141 mV) per sample. These results demonstrate the importance of monitoring individual battery voltages to identify voltage imbalance. The effectiveness of active cell balancing must be confirmed by comparing readings before and after balancing under comparable test conditions.

XI. FUTURE WORK

The ESP32-based Battery Management System covers the basics—checking voltage, making sure cells stay balanced, watching temperatures, and getting online. But there's so much more it can do.

1. AI-Powered SOC Estimation: Imagine real-time, smart readings that tell you exactly how much charge is left. AI can process voltage, current, temperature, and charge cycles for an accurate number instead of a rough estimate.

2. Battery Health Prediction: Machine learning is going to make predicting battery issues a lot easier. As it keeps tabs on capacity changes, unusual voltages, rising temps, and signs of wear, the system can warn you about problems early—before they cause headaches.

3. Early Temperature Anomaly Detection: Smarter algorithms mean catching any weird temperature jumps faster so you don't end up in trouble.

4. Mobile App Development: It'd be a game-changer to see all your battery info—voltages, temperatures, charge status, alerts—right on your phone. If something's off, you get a notification right away.

5. Cloud-Based Predictive Maintenance: Send that data to the cloud and you get early warnings, spot patterns, and schedule maintenance way before things actually fail.

6. Scalability for EV Packs: Handling giant EV battery

packs needs upgrades in communication, sensing, isolation, and protection—all stuff the ESP32 can tackle for full-sized electric vehicles.

7. Efficiency and Safety Upgrades: There's always room to improve balancing, make current sensing more precise, speed up fault detection, and add tougher protection against overvoltage and overheating.

Dial in these features and the ESP32 system moves from basic monitoring to a real solution for EVs, solar setups, and anything else running on batteries.

XII. CONCLUSION

This whole project was about building an ESP32-based Battery Management System—tracking voltage, keeping cells balanced, stopping overheating, and showing you what's happening on a screen or online. Every cell gets monitored for trouble like poor voltage or rising heat, and the system reacts fast if things start getting dicey.

The tests prove that checking every battery channel helps spot issues early. Smart sensors and quick controls work together to keep things safe.

The ESP32? Honestly, it just works. It's affordable, flexible, and solid when it comes to handling sensors, screens, and wireless connections. With IoT, you can check your battery status from anywhere and dig into logs if something goes wrong. If you need reliable battery management, this is a great place to start.

This prototype already makes battery monitoring safer and smarter. But to really step things up, it needs better hardware, smarter sensors, and more testing in the real world. Upgrades like active balancing and automatic cutoffs are key if you want to boost lifespan, efficiency, and reliability.

Bottom line: The system already works with EVs, solar arrays, backup power, or anything else that needs good battery care. With more improvements—AI, health tracking, cloud support, tougher hardware—it's ready to become a truly top-notch, dependable Battery Management System.

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