



# 12 V-Class 3S Li-Ion Charger, BMS and IoT-Based Battery Monitoring System

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## Abstract—

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This paper presents the design of a 12 V-class, three-series (3S) lithium-ion battery system that integrates a constant-current/constant-voltage (CC-CV) charger, a protection and cell-balancing battery management system (BMS) built around the Texas Instruments BQ76920 analog front-end (AFE), and an ESP32-based Internet-of-Things (IoT) telemetry layer. The pack is rated 11.1 V nominal (12.6 V full charge) with a capacity of approximately 6 Ah. Unlike single-cell fast-charge integrated circuits, which cannot terminate correctly on a multi-cell stack, the proposed architecture routes all charge current through the BMS charge field-effect transistor (FET) so that per-cell over-voltage cutoff and passive balancing remain active throughout the charge cycle. The ESP32 polls the AFE over an I<sup>2</sup>C bus, computes state of charge (SOC) using coulomb counting with open-circuit-voltage (OCV) fallback, and publishes pack telemetry to a cloud dashboard over MQTT, with an optional local OLED read-out. Design calculations for charge time, coulomb-counter resolution and balancing current are derived from the component data sheets and cross-checked against the target capacity and C-rate. The resulting architecture concentrates protection, balancing and telemetry read-out in a single AFE, reducing bill-of-materials count relative to discrete comparator-based designs while remaining implementable with hobbyist-accessible modules.

**Keywords—** Battery management system; Lithium-ion battery; BQ76920; CC-CV charging; State of charge; Internet of Things.



## I. INTRODUCTION

Lithium-ion (Li-ion) batteries are the dominant energy-storage technology for portable electronics, power tools, light electric vehicles and battery-backed IoT devices because of their high energy density and low self-discharge relative to lead-acid and nickel-based chemistries. This advantage comes with a narrow safe-operating window: individual cells can be permanently damaged, or in the worst case become thermally unstable, if charged above roughly 4.2 V, discharged below approximately 3.0 V, or operated outside a bounded temperature range [1]. When cells are connected in series to obtain a practical pack voltage, cell-to-cell manufacturing tolerance and self-discharge variation cause individual cell voltages to drift apart over repeated cycles — a problem that single-cell protection alone cannot address.

A battery management system (BMS) therefore has three closely related responsibilities: (i) hardware protection against over-voltage, under-voltage, over-current and short-circuit events; (ii) active or passive balancing to keep series-connected cells at a common state of charge; and (iii) telemetry, so that the host system, and increasingly a remote operator, can observe pack health in real time [2], [3]. Many hobbyist-grade BMS boards implement only the first responsibility using discrete comparators, giving no visibility into individual cell behaviour and no path to remote monitoring.

This paper documents the design of a 3S, 12 V-class Li-ion system that combines a CC-CV charger, a BQ76920-based AFE for protection and balancing, and an ESP32 microcontroller that reads the AFE over I<sup>2</sup>C and republishes pack telemetry to an MQTT broker for dashboarding and alerting. The contribution of this work is not a new IC or estimation algorithm, but a coherent, bill-of-materials-conscious system architecture together with the design calculations — charge-time budgeting, coulomb-counter resolution and balancing-current sizing — that a practitioner needs to take such a system from a data sheet to a working prototype. Section II reviews related approaches to Li-ion protection and IoT battery monitoring. Section III describes the proposed methodology and each subsystem in detail. Section IV presents the design-stage results, including the simulated charge profile and coulomb-counter resolution analysis. Section V concludes the paper and lists open items for the build phase.

## II. LITERATURE REVIEW

Early Li-ion protection circuits relied on discrete over-voltage/under-voltage comparators driving a charge/discharge FET pair — a topology still common in low-cost single-cell power banks. Haq et al. [5] describe an early cell-monitoring and protection BMS built on this comparator philosophy and note its limited scalability as cell count grows. Integrated analog front-ends such as the TI BQ769x0 family fold this comparator network, the balancing-FET drivers and the coulomb-counting ADC into a single I<sup>2</sup>C-addressable device, the approach adopted in this work; the BQ76920 variant supports three-to-five series cells with a 14-bit cell-voltage ADC and a separate 16-bit coulomb-counter ADC [4].

On the monitoring side, several recent papers pair a battery-monitor front-end with a Wi-Fi-capable microcontroller. Friansa et al. [3] developed an IoT-based battery monitoring system for a smart microgrid that streams pack parameters to a cloud back-end for fleet-level visibility. Aspilli [2] combined a photovoltaic-sourced BMS with real-time IoT monitoring for an electric-vehicle context, emphasising remote fault visibility over local display. Paiva-Peredo [8] used an ESP32 with current and voltage sensing to manage and monitor Li-ion recharging over MQTT and Node-RED, reporting that the added telemetry improved charge-time and energy-cost visibility without materially increasing hardware complexity. MQTT/Node-RED pipelines of this kind recur across the literature [6] because both components are open source and self-hostable, avoiding recurring cloud fees. Ma et al. [7] separately show that temperature strongly affects both charge acceptance and long-term degradation, motivating a thermistor input in the monitoring layer rather than treating temperature as optional telemetry.

A gap that recurs across this literature is that most IoT-monitoring papers instrument an existing, separately protected pack — protection and telemetry are designed and reported independently. Fewer papers document the charger, the AFE-based protection/balancing stage and the IoT layer as a single, jointly designed system with explicit sizing calculations for each stage. This paper targets that gap for a specific, reproducible 6 Ah, 3S design point, using the coulomb-counter and cell-ADC specifications published in the BQ76920 data sheet [4] to derive expected SOC-estimation resolution rather than assuming it.



### III. METHODOLOGY

The system is decomposed into four subsystems that are designed together but can be validated independently: the battery pack, the BMS/AFE protection-and-balancing stage, the CC-CV charger, and the ESP32 IoT telemetry layer. Fig. 1 shows the overall block diagram and the signal/power flow between these subsystems.

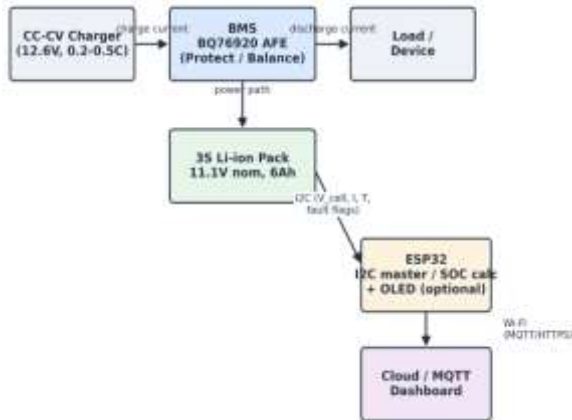


Fig. 1. System block diagram of the 3S Li-ion charger, BMS and IoT monitoring layer.

#### A. Battery Pack

The pack is configured as 3S1P or 3S2P using matched 18650/21700 cells, giving a nominal voltage of 11.1 V (3.7 V/cell), a full-charge voltage of 12.6 V (4.2 V/cell) and a discharge cut-off of 9.0 V (3.0 V/cell). Table I summarises the pack-level specification used throughout this paper. Cells are joined with spot-welded nickel strips; direct reflow soldering on cell tabs is avoided because the associated heat can damage the internal separator and accelerate self-discharge.

Table I: Battery Pack Specification

| Parameter           | Value                     |
|---------------------|---------------------------|
| Configuration       | 3S1P or 3S2P, 18650/21700 |
| Nominal voltage     | 11.1 V (3.7 V/cell)       |
| Full-charge voltage | 12.6 V (4.2 V/cell)       |
| Discharge cut-off   | 9.0 V (3.0 V/cell)        |
| Capacity            | ≈6 Ah (2–3 Ah/cell)       |
| Cell joining        | Spot-welded Ni strips     |

#### B. BMS: Protection, Balancing and Telemetry Front-End

Protection, balancing and readout are centred on the BQ76920, a three-to-five-series-cell Li-ion/LiFePO<sub>4</sub> battery monitor [4]. The device integrates a 14-bit cell-voltage ADC, a separate 16-bit coulomb-counter ADC for pack current, hardware over-voltage (OV), under-voltage (UV), over-current-in-discharge (OCD) and short-circuit-in-discharge (SCD) protection, integrated

cell-balancing FET drivers, and low-side N-channel FET drivers for the charge (CHG) and discharge (DSG) paths — all accessible over a single I<sup>2</sup>C bus. Fig. 2 shows the internal signal flow from the cell taps to the pack terminal.

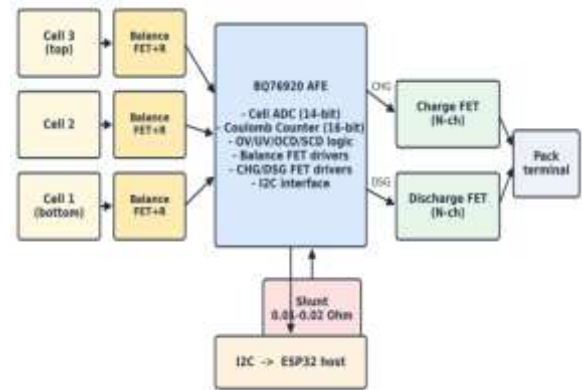


Fig. 2. BMS internal architecture: cell taps, balancing FETs, BQ76920 AFE, shunt and CHG/DSG FET drivers.

Two back-to-back N-channel MOSFETs (e.g., AO3401/AO3400-class parts, paralleled and sized to the peak current) implement the charge and discharge switches, driven directly by the BQ76920 CHG/DSG outputs. A 0.01–0.02 Ω shunt in the pack return path feeds the internal coulomb counter for current sensing and state-of-charge accumulation. External balance resistors on each cell tap provide passive balancing, which the AFE enables selectively near the top of charge.

Table III: BMS Key Component Values

| Item                | Value / Part                         |
|---------------------|--------------------------------------|
| AFE                 | TI BQ76920 (3–5S)                    |
| CHG/DSG FETs        | AO3401/AO3400-class N-ch, paralleled |
| Current shunt       | 0.01–0.02 Ω                          |
| Cell ADC            | 14-bit, 382 μV LSB                   |
| Coulomb-counter ADC | 16-bit, 8.44 μV LSB                  |

#### C. CC-CV Charger

A 3S Li-ion stack requires 12.6 V termination, so single-cell charge ICs such as the TP4056 are not applicable — they terminate at a single-cell voltage and have no per-cell awareness on a multi-cell stack. Charging is therefore always routed through the BMS charge FET rather than directly to the pack, so the BQ76920 retains per-cell over-voltage cut-off and balancing authority throughout the charge cycle. Table II compares the two charger options considered: an adjustable buck module used in CC-CV mode, and a dedicated multi-cell charge IC. The buck-module



option was selected for the initial prototype because it is adjustable, inexpensive and widely available, while still being gated by the BMS charge-enable signal for safety.

Table II: Charger Options Compared

| Option                                | Notes                                                       |
|---------------------------------------|-------------------------------------------------------------|
| CC-CV buck (XL4015/LM2596-class)      | 12.6 V out, 0.2–0.5C limit; simplest, adjustable, BMS-gated |
| Multi-cell charge IC (BQ24610/CN3789) | Native 3S CC-CV termination; BMS-enable gated               |

#### D. ESP32 IoT Monitoring Layer

The ESP32 acts as the I<sup>2</sup>C master for the BQ76920, polling per-cell voltage, pack current, pack temperature (via an added NTC thermistor) and fault flags on a fixed sample period. State of charge is estimated primarily by coulomb counting — integrating measured current over time and dividing by rated capacity — with an open-circuit-voltage (OCV) look-up used as a coarse fallback when the pack has been at rest, which corrects for the long-term drift that coulomb counting alone accumulates. Telemetry is published over Wi-Fi using MQTT to a broker such as Node-RED or HiveMQ for logging and alerting, with a direct Blynk/ThingSpeak path available for a quicker dashboard; an optional local SSD1306 OLED gives an on-device read-out independent of network connectivity. Fig. 3 details the charge-control and protection logic executed by the BMS/charger pair, and Fig. 4 details the ESP32 firmware loop that produces the published telemetry.

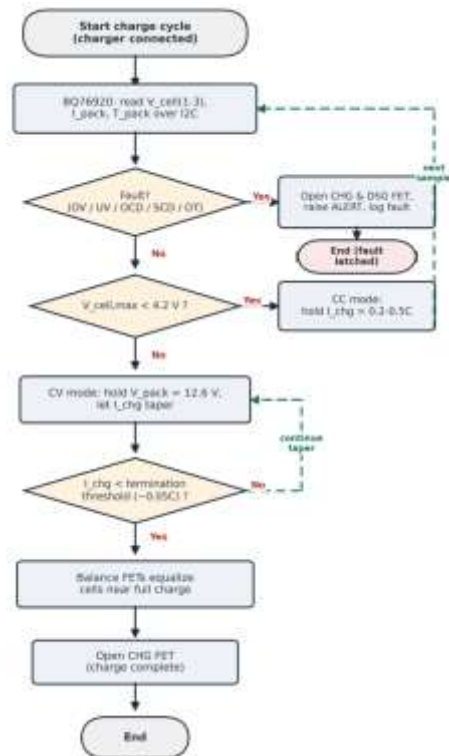


Fig. 3. Charging-control and protection flowchart (BMS/charger interaction).

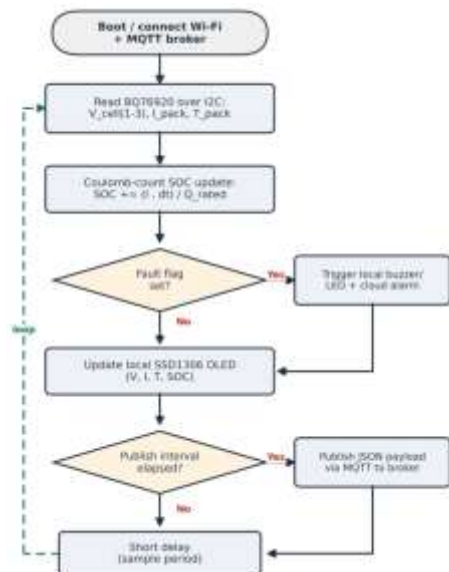


Fig. 4. ESP32 firmware flowchart: I<sup>2</sup>C read, SOC update, fault check, OLED and MQTT publish.

## IV. RESULTS AND DISCUSSION

Because the system is at the design and simulation stage — the open items in Section V include finalising peak current and confirming the 3S1P/3S2P split — the results below are analytical and simulated outcomes derived directly from the design parameters in Tables I–III and the BQ76920 data-sheet specifications, rather than measurements from an assembled pack. They are intended to validate that the chosen component values meet the target charge time and telemetry resolution before hardware is committed.



### A. Simulated CC-CV Charge Profile

Fig. 5 shows the calculated pack voltage and charge current for a representative 0.35C charge rate ( $I_{CC} \approx 2.1$  A for the 6 Ah pack), using the CC-CV thresholds in Table I and a lumped pack internal resistance typical of matched 18650 cells in this capacity class. The constant-current stage carries the pack from an assumed rested voltage of 9.9 V to the 12.6 V constant-voltage set-point in approximately 2.4 h; the constant-voltage stage then tapers the current exponentially until it falls below the 0.05C ( $\approx 0.30$  A) termination threshold, for a total calculated charge time of about 5.4 h. This is consistent with the general rule of thumb that a CC-CV Li-ion charge at C/3-class current completes in 1.3–1.5 times the nominal 1/C-rate time once the CV taper is included.

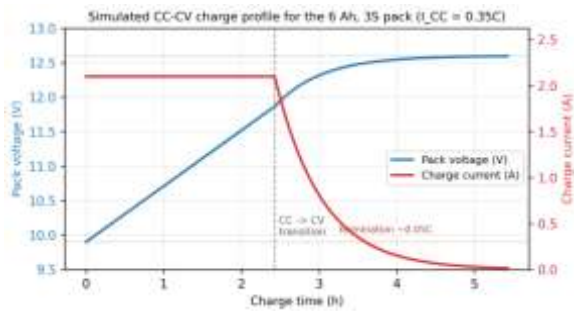


Fig. 5. Simulated CC-CV charge profile for the 6 Ah, 3S pack ( $I_{CC} = 0.35C$ ).

### B. Coulomb-Counter and Cell-ADC Resolution

The BQ76920 coulomb counter is a 16-bit integrating ADC with a full-scale input range of  $\pm 270$  mV and an LSB of  $8.44 \mu\text{V}$  [4]. Dividing this voltage LSB by the shunt resistance gives the smallest current step the AFE can resolve: with the  $0.01 \Omega$  shunt specified in Table III, the current resolution is  $8.44 \mu\text{V} / 0.01 \Omega \approx 0.84$  mA; with the larger  $0.02 \Omega$  shunt option, resolution improves to  $\approx 0.42$  mA. Both values are more than adequate for coulomb-counting a 6 Ah pack, where the charge and discharge currents of interest are in the hundreds of milliamps to low amps range — the resolution error contributes negligibly to SOC drift compared with the ADC offset and gain error terms in the data sheet. The 14-bit cell-voltage ADC, with a  $382 \mu\text{V}$  LSB [4], likewise resolves the 3.0–4.2 V per-cell operating window to roughly 3,100 discrete steps, which is well within the precision needed to enforce the  $\pm 25$  mV protection thresholds used by the OV/UV comparators.

Table IV summarises these calculated figures alongside the corresponding design targets, and Table

V lists the indicative bill of materials for the complete system.

Table IV: Calculated Design Figures

| Quantity                                 | Calculated value           |
|------------------------------------------|----------------------------|
| CC-stage current (0.35C)                 | $\approx 2.1$ A            |
| CV termination current (0.05C)           | $\approx 0.30$ A           |
| Estimated total charge time              | $\approx 5.4$ h            |
| Current resolution (0.01 $\Omega$ shunt) | $\approx 0.84$ mA          |
| Current resolution (0.02 $\Omega$ shunt) | $\approx 0.42$ mA          |
| Cell-voltage resolution                  | $382 \mu\text{V}$ (14-bit) |

Table V: Indicative Bill of Materials

| Item              | Part / Spec                     | Qty |
|-------------------|---------------------------------|-----|
| Cells             | 18650/21700 Li-ion, matched     | 3–6 |
| BMS AFE           | TI BQ76920                      | 1   |
| CHG/DSG FETs      | AO3401/AO3400-class, paralleled | 4–6 |
| Current shunt     | $0.01\text{--}0.02 \Omega$      | 1   |
| Charger module    | XL4015-class CC-CV buck         | 1   |
| MCU               | ESP32 dev board                 | 1   |
| Temp sensor       | NTC thermistor                  | 1   |
| Display (opt.)    | SSD1306 OLED                    | 1   |
| Balance resistors | Per-cell, per target $I_{bal}$  | 3–5 |

### C. Discussion

The calculations above indicate that the selected shunt and ADC combination gives more than adequate current and voltage resolution for a 6 Ah pack, so the coulomb-counting SOC estimate is expected to be dominated by ADC offset/gain error and by the accuracy of the assumed rated capacity, rather than by quantisation. This matches the general finding in the literature that periodic OCV re-anchoring, not finer ADC resolution, is the main lever for improving long-run SOC accuracy in coulomb-counting systems [3], [8]. The 5.4 h calculated charge time is a reasonable design point for an overnight or workday-cycle charge; raising the CC-stage current toward the 0.5C upper bound in Table I would shorten this at the cost of higher peak FET and shunt dissipation, which is why FET and shunt sizing remains an open item pending a confirmed target current (Section V).

### V. CONCLUSION

This paper presented the design of a 12 V-class, 3S Li-ion charger, BMS and IoT monitoring system built around the BQ76920 analog front-end and an ESP32 telemetry layer. Routing all charge current through the BMS charge FET keeps per-cell over-voltage protection and passive balancing active throughout



charging, addressing a limitation of single-cell fast-charge ICs on multi-cell stacks. Design-stage calculations show that the chosen 0.01–0.02  $\Omega$  shunt and the AFE's 16-bit coulomb-counter ADC give sub-milliamp current resolution, and that a representative 0.35C charge profile completes in approximately 5.4 h, both consistent with the target 6 Ah, 3S design point. Remaining open items before hardware validation are: finalising the peak charge/discharge current to size the FETs and shunt; confirming the 3S1P-versus-3S2P split based on the target discharge current and enclosure space; and selecting the cloud back-end (MQTT broker versus Blynk/ThingSpeak) based on the desired dashboard and alerting feature set. Future work will report measured charge curves and coulomb-counter drift from an assembled prototype against the calculations presented here.

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