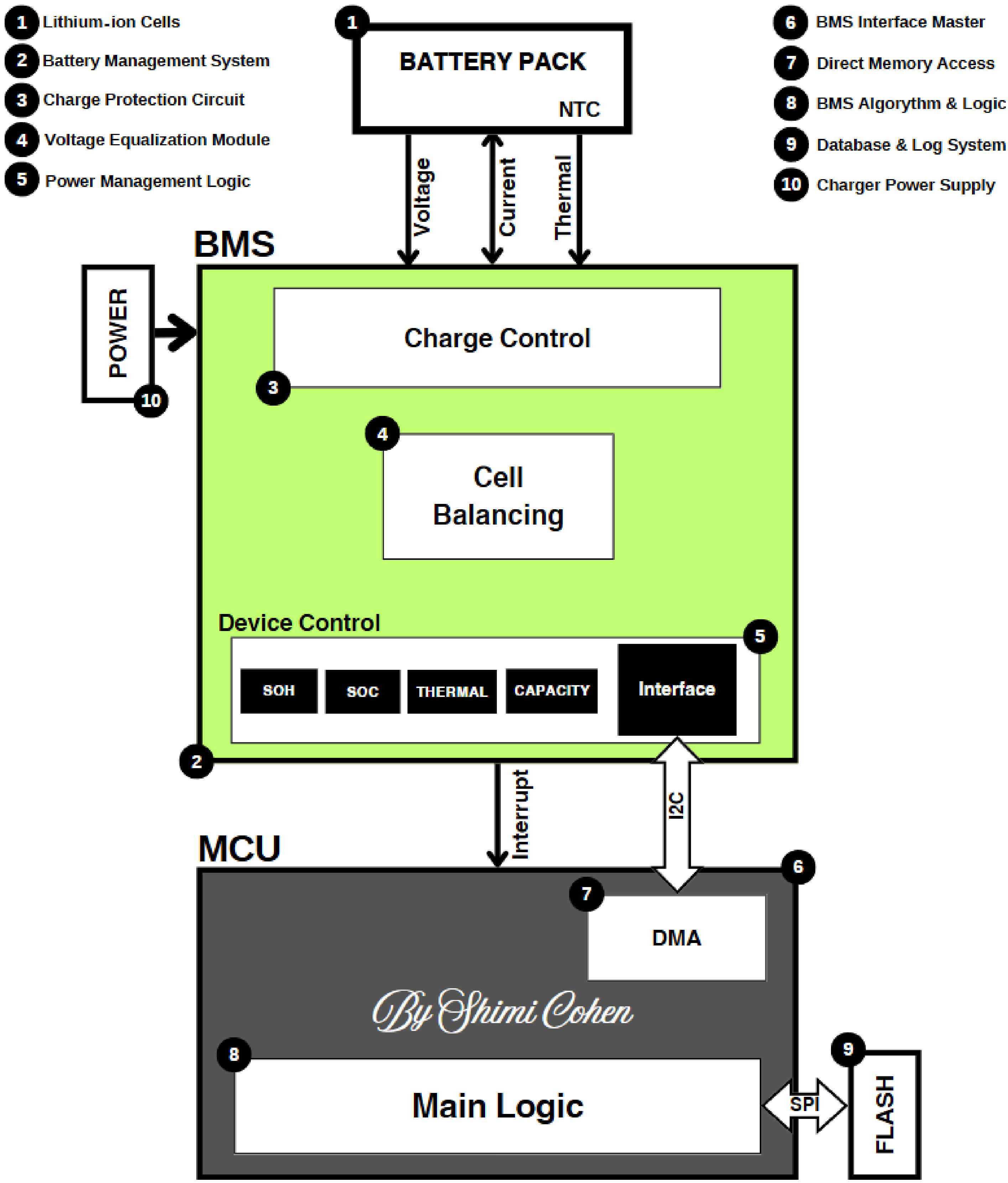
Hardware Engineer's Guide

Battery Management



LITHIUM CELLS

This Guide discusses Lithium-ion batteries for small devices (1-3 cells).

CORE PARAMETERS

Parameter	Li-ion NMC	Li-ion LFP	Li-ion NCA	Li-ion LMO	Li-Poly
Nominal[V]	3.6-3.7V	3.2-3.3V	3.6V	3.7-3.8V	3.7V
Min[V]	2.5-3.0V	2.0-2.5V	2.5-3.0V	2.5-3.0V	3.0V
Max[V]	4.2V	3.65V	4.2V	4.2V	4.2V
Energy[Wh/kg]	200-260	90-160	220-300	100-150	130-250
Power Density	300-1500	300-2500	250-500	800-2000	300-1500
Cycles	1000-3000	2000-7000	500-1500	500-1000	500-1000
Self-Discharge	1-3%	1-3%	2-4%	2-5%	3-5%

SAFETY PARAMETERS

Type	Thermal Stability	Short Circuit	Venting	Fire Risk
Li-ion NMC	Moderate	10-20C	CID, PTC	High
Li-ion LFP	High	10-15C	CID, PTC	Low
Li-ion NCA	Low	10-20C	CID, PTC	Very High
Li-ion LMO	Moderate	10-20C	CID, PTC	Moderate
Li-Polymer	Low	10-15C	Pouch swell	High

CELL AGING

Cell Type	Calendar Aging	Shelf Life	Life-Limiting Factor
Li-ion NMC	2-3%/yr capacity	5-8 yrs	SEI growth, Li loss
Li-ion LFP	1-2%/yr capacity	8-12 yrs	SEI growth, Min Li loss
Li-ion NCA	3-4%/yr capacity	4-7 yrs	Cathode dissolution
Li-ion LMO	3-5%/yr capacity	4-6 yrs	Mn dissolution
Li-Polymer	2-3%/yr capacity	5-8 yrs	Like Li-ion

BATTERY MANANGEMENT SYSTEM

DEFINITION AND CORE FUNCTIONS

Battery Management Systems (BMS) for IoT and small lithium-ion battery packs serve as the intelligence behind efficient and safe battery operation. Unlike large-scale systems used in electric vehicles or grid storage, small-scale BMS solutions focus on optimizing performance within significant size, cost, and power constraints.

BMS Purpose

- Extend battery life through proper charge/discharge management
- Prevent unsafe operating conditions
- Maximize runtime from limited capacity
- Provide accurate state information for system decision-making
- Optimize performance in varying environmental conditions

FUNCTIONAL BLOCKS

Block	Primary Functions
Cell Monitoring	Measures individual cell voltages and temp.
Current Sensing	Tracks charge/discharge current
Protection Circuitry	Provides hardware-level safety mechanisms
SOC Calculation	Determines remaining capacity
SOH Monitoring	Assesses battery health
Cell Balancing	Equalizes charge between cells
Thermal Management	Monitors and controls temperature
Communication	Interfaces with host system

CHARACTERISTICS

- Voltage monitoring precision requirements
- Temperature monitoring strategy
- SOC estimation algorithm selection
- Cell balancing approach
- Safety protection thresholds

CELL MONITORING

PROTECTION MECHANISMS

Protection circuits prevent operation outside safe limits:

Protection Type	Implementation Method	Thresholds (Li-ion)
Overvoltage	Hardware + software cutoff	4.2-4.3V per cell
Undervoltage	Load disconnection	2.5-3.0V per cell
Overcurrent (charge)	Current limiting, FET control	0.5-1C
Overcurrent (discharge)	Current limiting, FET control	2-10C
Over-Temperature	Cooling, current limiting	45-60°C
Under-Temperature	Heating, charging prohibition	0-10°C
Short-circuit	Fuse, fast-acting cutoff	>3-10× rated current

Multi-level protection approach:

- Software protection - Primary response with configurable thresholds
- Hardware protection - Secondary independent circuit (fail-safe)
- Mechanical protection - Physical disconnection (circuit breaker, fuse)

VOLTAGE MONITORING

Accurate voltage measurement is fundamental to BMS operation.

Measurement Requirements:

- Lithium-ion cells: ±5mV (typical)
- Lead-acid: ±20mV (typical)
- Resolution: 12-16bit ADC recommended
- Adequate sample time

Voltage measurement employs:

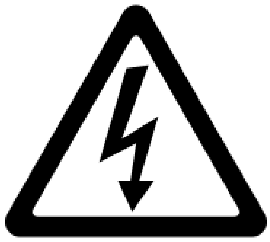
- Low-pass filtering to reduce noise
- Multiplexed inputs for multi-cell systems
- Precision voltage references (0.1% or better)
- ADC Module (External or Integrated in MCU)

OVER-VOLTAGE PROTECTION (OVP)

OVP implementation uses comparators with precise reference voltages that trigger FET switches to disconnect the charging path when thresholds are exceeded.

OVP prevents cell damage from excessive charging:

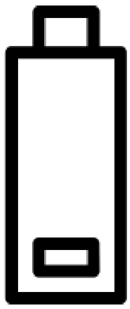
Element	Typical Implementation
Threshold	4.2-4.35V (chemistry dependent)
Hysteresis	50-200mV
Response	Disconnect charging circuit
Recovery	Automatic or manual reset



UNDER-VOLTAGE PROTECTION (UVP)

UVP prevents deep discharge damage:

Element	Typical Implementation
Threshold	2.5-3.0V (chemistry dependent)
Hysteresis	100-300mV
Response	Disconnect discharge circuit
Recovery	Requires charging to restore



OVER-CURRENT PROTECTION (OCP)

Over current prevents damage from excessive current.

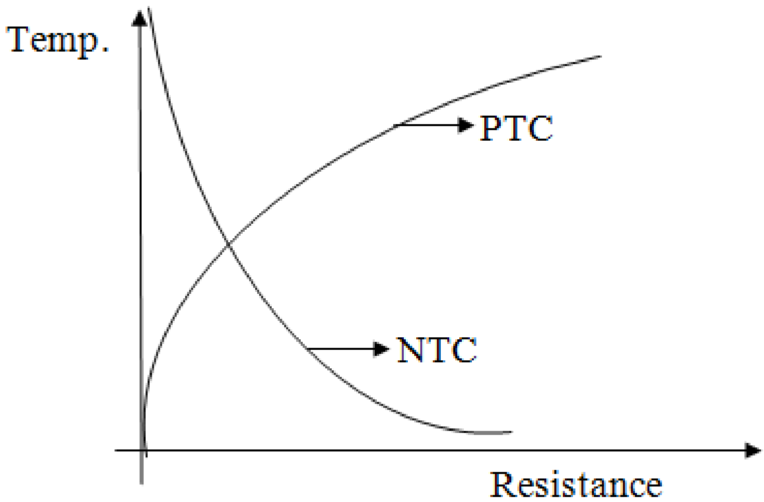
Direction	Threshold Range	Response Time
Charge	0.5C to 2C	1-100ms
Discharge	1C to 5C	1-100ms
Short Circuit	>10C	<10µs

TEMPERATURE MONITORING

Temperature monitoring prevents operation in unsafe conditions:

Condition	Typical Thresholds	Action
Low Temperature Charging	0°C to 10°C	Reduce charge current
Low Temperature Cutoff	-20°C to 0°C	Disable charging
High Temperature Warning	45°C to 50°C	Reduce current
High Temperature Cutoff	55°C to 60°C	Disable all operations

Sensor Type	Advantages	Disadvantages	Accuracy
NTC Thermistor	Low cost, simple	Nonlinear response	±1-3°C
PT100/PT1000	High accuracy, linearity	Higher cost	±0.5-1°C
Digital Sensors	Calibrated output	Higher cost, complexed	±0.5-2°C
Infrared	Non-contact measurement	View factor limitations	±2-5°C



CELL BALANCING

OPERATING PRINCIPLE

- Connect resistor in parallel with cells that have higher voltage
- Energy converted to heat until voltages equalize
- Typically activated near end of charge

Parameter	Typical Values	Design Impact
Balancing Current	50-200mA	Heat dissipation, balancing time
Balancing Resistance	20-100Ω	Current flow, power rating
Duty Cycle	10-100%	Thermal management
Balance Threshold	10-50mV	Balancing frequency, energy loss

BALANCING ALGORITHMS

1. Voltage-based Balancing:
   - Activates when voltage difference exceeds threshold
   - IF $(V_{max} - V_{min}) > V_{thresh}$ THEN balance
2. SOC-based Balancing:
   - Uses estimated SOC instead of voltage
   - More accurate for chemistries with flat voltage curves
   - IF $(SOC_{max} - SOC_{min}) > SOC_{thresh}$ THEN balance

3. Predictive Balancing:
   - Uses cell models to anticipate future imbalance
   - Proactively balances to minimize overall energy loss

Decision Criteria:

Parameter	Description	Typical Values
Voltage Threshold	Minimum to trigger balancing	20-50mV
SOC Threshold	SOC difference triggering	3-10%
Priority Selection	Which cells to balance first	Highest voltage / highest SOC
Timing Strategy	When to perform balancing	During charge/rest, continuous

STATE OF CHARGE (SOC)

State of Charge represents the remaining energy in the battery as a percentage of its capacity, functioning as the "fuel gauge" for the system. SOC Calculation Methods:

Method	Principle	Advantages
Voltage-Based	Maps OCV to SOC	Simple, low resource
Coulomb Counting	Integrates current over time	Accurate for short term
Kalman Filter	Statistical approach	Adaptive, self-correcting
Combined	Fusion of multiple methods	More accurate

Voltage-Based SOC

For resource-constrained IoT devices, voltage-based SOC is common:

$SOC = f(OCV, temperature)$

Implementation:

1. Measure battery voltage (allow relaxation period)
2. Apply temperature compensation
3. Map to SOC using calibrated curves

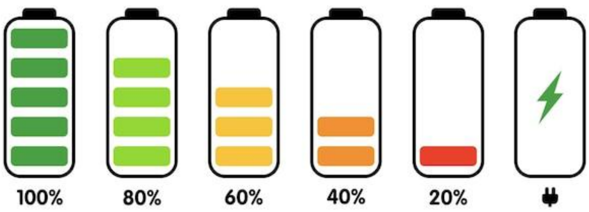
Coulomb Counting Implementation

Coulomb counting tracks charge flow in and out of the battery:

$SOC(t) = SOC(0) + \int (i(t) \times \eta/Qmax)\, dt$

Implementation Challenges:

- Current measurement accuracy
- Efficiency variations
- Self-discharge not accounted for



SOC Reporting and Uncertainty

Small-scale BMS typically implements:

- SOC smoothing for user interface stability
- Confidence metrics to indicate estimation quality
- Adaptive algorithms that self-calibrate during full charge cycles

STATE OF HEALTH (SOH)

SOH quantifies battery aging and capacity degradation, enabling predictive maintenance and appropriate application behavior adjustments. SOH Parameters:

Parameter	Description	Implementation
Capacity Fade	Reduction in capacity	Periodic full cycle
Internal Resistance	Increase in resistance	Pulse load tests
Self-Discharge Rate	Loss when idle	Long-term voltage monitoring
Charge Acceptance	Ability to accept charge	Charge curve analysis

SOH Calculation Techniques

Common SOH calculation methods for small systems:

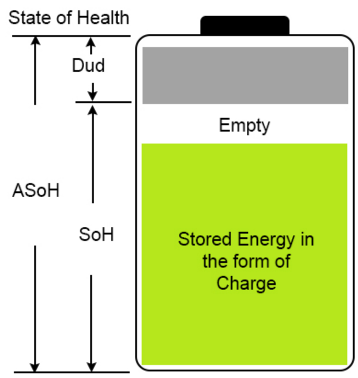
Capacity-Based: $SOH = (Current\_Capacity / Rated\_Capacity) \times 100\%$

Resistance-Based: $SOH = (Init\_Resistance / Current\_Resistance) \times 100\%$

Simplified SOH Estimation for IoT

Resource-constrained implementations often use:

- Charge/discharge cycle counting
- Voltage recovery rate monitoring
- Charge time tracking
- Temperature exposure history



SOH Data Utilization

SOH information enables:

- Predictive replacement notifications
- Dynamic power management adjustments
- Charge current optimization
- Runtime estimation refinement

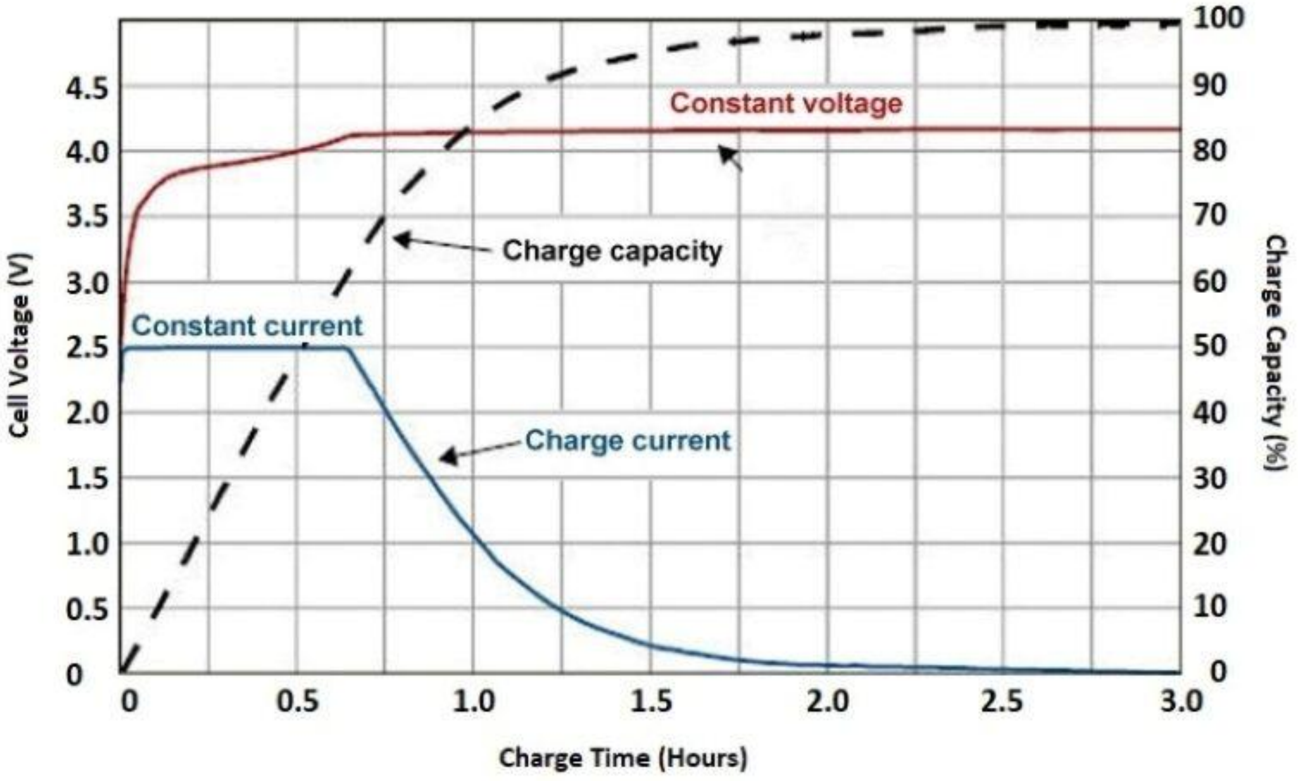
CHARGING MANAGEMENT

Charging management optimizes battery longevity and safety.

CC-CV CHARGING PROFILE

Constant Current – Constant Voltage Process:

Stage	Description	Termination
Trickle	Low current for cells (<3.0V)	Cell voltage >3.0V
Constant Current	Fixed current charging	Cell voltage reaches Vmax
Constant Voltage	Hold @ Vmax while current drops	Current drops below TH
Termination	Charging complete	Current <0.05-0.1C



FAST CHARGING IMPLEMENTATION

Fast charging for IoT devices typically involves:

Technique	Implementation	Considerations
Higher Current	Increased CC phase	Additional thermal monitoring
Multi-Stage	Dynamic current	Complex control algorithm
Optimized Transition	Earlier CV transition	Balance of speed vs. capacity

Fast Charge Decision Logic:

- Temperature window verification
- User or application priority settings
- Available input power assessment

LOW-POWER CHARGING

For energy-harvesting or constrained-power applications:

Aspect	Implementation
Input Power Management	Boost/buck conversion for optimal transfer
Charge Prioritization	Power system vs. charge battery
Minimal Overhead	Ultra-low quiescent current
Dynamic Adjustment	Adapt to available input power

COMPONENTS (INTEGRATED CIRCUITS)

There are many options to choose from, each option may carry unique feature.

COMPONENT SELECTION

IC Model	Comm.	Alerts/Protection	Unique Features
BQ76952	I2C/SPI	OV/UV/OC/OT/Short	Integrated ADC, AFE
LTC6811	SPI	OV/UV/Fault/Temp.	Stackable, high accuracy
MAX17852	SPI	OV/UV/OC/OT/Fault	Daisy-chain, diagnostics
ISL94212	I2C	OV/UV/OC/OT/Fault	Standalone, high integration
MC33771C	SPI	OV/UV/OC/OT/Fault	Scalable, advanced comm.
S-8254A	None	OV, UV, OC, OT	Simple, low cost, compact
BQ40Z50-R2	SMBus	OV/UV/OC/OT/Fault	Fuel gauge, battery auth.
LTC6804	SPI	OV/UV/Fault	Stackable, high voltage
MAX14921	SPI	OV/UV/OC/OT	High voltage, diagnostics
BQ76930	I2C	OV/UV/OC/OT/Fault	Integrated ADC, diagnostics

Solutions by Family (TI):

Series	Primary Focus	Applications
BQ25xxx	Charging management	Single-cell applications
BQ27xxx	Fuel gauging	monitoring
BQ29xxx	Cell protection	Multi-cell protection
BQ34xxx	Cell balancing	Multi-cell packs
BQ40zxx	Complete BMS solutions	Integrated systems

COMMUNICATION INTERFACES

BMS systems communicate with host processors.

Common Protocols:

Protocol	Characteristics	Typical Use Case
I2C	2-wire, multi-device	Most common for IoT BMS
SPI	Higher speed, more pins	Performance-critical apps
1-Wire	Single data line	Ultra-simple interfaces
UART	Serial communication	Legacy systems
SMBus	I2C variant with defined commands	Smart Battery systems

Smart Battery Data

Some IoT BMS implement a subset of Smart Battery Data (SBD) specifications:

Parameter	Register	Unit	Access
Voltage	0x09	mV	Read
Current	0x0A	mA	Read
Temperature	0x08	0.1K	Read
SOC	0x0D	%	Read
Full Capacity	0x10	mAh	Read
Cycle Count	0x17	count	Read
Status	0x16	flags	Read

Alert Mechanisms

BMS alert implementations:

- Dedicated interrupt pin (active low)
- Status register flags
- Programmable thresholds
- Maskable interrupts

PRACTICAL IMPLEMENTATION

DESEIGN GUIDES

This section outlines the practical steps for implementing a small-scale BMS solution.

BMS Selection Criteria:

Parameter	Considerations
Cell Configuration	Series/parallel arrangement
Capacity Range	Expected battery capacity
Current Requirements	Peak charge/discharge needs
Size Constraints	Available PCB area
Power Consumption	Quiescent current budget
Feature Requirements	SOC, balancing, protections
Communication	Interface with host system

Cell Connection Considerations

Critical aspects of cell connection:

- Low-impedance power paths
- Kelvin connections for voltage sensing
- Thermal considerations in layout
- Protection device placement
- Connector selection and rating

Firmware Configuration

Key firmware configuration steps:

1. Cell chemistry parameters setting
2. Protection threshold configuration
3. SOC algorithm calibration
4. Temperature compensation setup
5. Communication protocol configuration
6. Alert and status reporting setup

TESTING AND VALIDATION

Proper testing ensures BMS reliability and performance in field conditions.

ELECTRICAL VALIDATION

Test	Purpose	Method
Voltage Accuracy	Verify precision	Compare with Measured
Current Accuracy	Validate current sensing	Use loads comparison
Protection Response	Verify safety functions	Controlled fault injection
Balancing Verification	Check balancing	Intentional imbalance test
Power Consumption	Measure current	Various operating modes

ALGORITHM VALIDATION

Methods to validate BMS algorithms:

SOC Testing:

- **Controlled discharge tests at various rates**
- **Temperature variation testing**
- **Aging effect simulation**

SOH Validation:

- **Accelerated aging tests**
- **Impedance measurement correlation**
- **Capacity verification testing**

ENVIRONMENTAL TESTING

Condition	Test Parameters	Verification
Temperature	-20°C to 60°C typical	Full functionality across range
Humidity	Up to 95% non-condensing	No performance degradation
Vibration	Application-specific	Connection integrity
EMI/EMC	Regulatory requirements	Operation during interference

REAL-WORLD EXAMPLES

WEARABLE DEVICE BMS

Application Requirements:

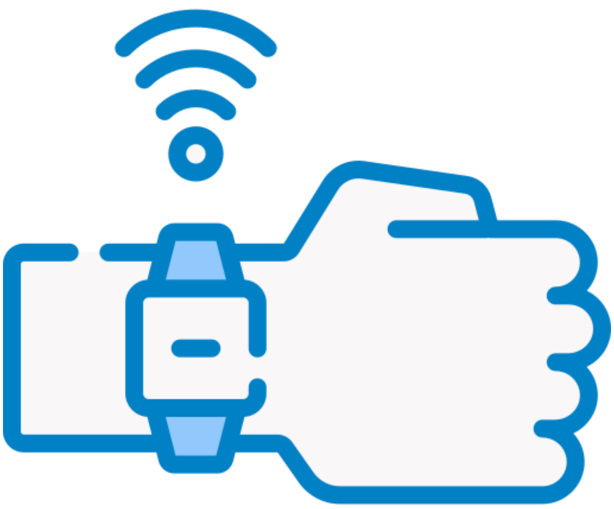
- 100-300mAh single-cell LiPo
- Ultra-low power consumption (<10μA average)
- Minimal PCB footprint (<25mm²)
- Basic fuel gauging
- USB charging support

Solution Implementation:

- BQ25120 integrated charger + fuel gauge
- 3.9V-4.35V/2.5V protection thresholds
- Voltage-based SOC with temperature compensation
- 25mΩ sense resistor for 200mA max charging
- I2C interface to main MCU at 100kHz

Performance Metrics:

- 5μA quiescent current
- ±3% SOC accuracy at steady state
- 65 minutes to full charge
- 4mm × 4mm total solution size



IOT SENSOR NODE BMS

Application Requirements:

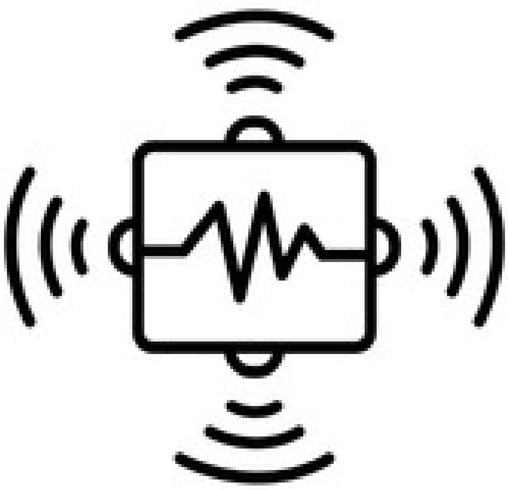
- 2-cell 18650 configuration (2S1P)
- Energy harvesting input
- Extended temperature operation
- 5+ year lifetime
- Weekly reporting cycle

Solution Implementation:

- BQ29330 protection IC
- BQ34Z100 fuel gauge
- BQ25570 energy harvesting PMIC
- Active cell balancing circuit
- Low-frequency sampling for power conservation

Performance Metrics:

- 3.5μA sleep current
- 98% charge efficiency
- ±5% SOC reporting accuracy
- Operating temperature range: -30°C to +75°C



TROUBLESHOOTING

Common problems encountered in BMS implementations and their solutions.

SOC INACCURACY ISSUES

Symptom	Potential Cause	Solution
SOC jumps	Voltage-only limitations	coulomb counting
Drift over time	Cumulative errors	Periodic recalibration
Temperature-related errors	Insufficient compensation	Enhance model
Different discharge rates	Rate-dependent capacity	Implement rate factor

PROTECTION PROBLEMS

Issue	Causes	Resolution
False OVP	Voltage spikes, noise	Add filtering, debounce
Nuisance OCP	Transient loads	Adjust timing, thresholds
UVP oscillation	Recovery bounce	Add hysteresis
Thermal shutdown	Sense location issue	Relocate sensor, improve cooling

COMMUNICATION FAILURES

Symptom	Potential Causes	Solutions
No response	Address conflict, bus issues	Verify address, check pullups
Corrupted data	Noise, clock issues	Add filtering, check timing
Intermittent connection	EMI susceptibility	Improve routing, shielding
Lockups	Clock stretching issues	Timeout handling, recovery

CHARGING ABNORMALITIES

Issue	Possible Causes	Fixes
Premature termination	Incorrect thresholds	Adjust parameters
Excessive charge time	Worn cells, high resistance	Check connections, cells
Oscillating charge	Thermal regulation	Improve thermal design
No charging initiation	Protection state	Implement recovery

SAFETY STANDARDS

REGULATORY FRAMEWORK

BMS designs must comply with applicable safety standards based on application domain.

Key Safety Standards:

Standard	Scope	Key Requirements
IEC 62133	Cell safety	Overcharge, short circuit, crush tests
UL 1642	Lithium batteries	Cell-level safety requirements
UL 2054	Battery packs	Pack construction, protection circuits
UL 2271	Light mobility	Environmental, electrical safety
UL 2580	Electric vehicles	Comprehensive system testing
IEC 61508	Functional safety	SIL levels, systematic capability
ISO 26262	Automotive safety	ASIL levels, safety lifecycle
DO-311A	Aerospace	Rigorous environmental testing

TESTING AND VALIDATION

Comprehensive testing ensures BMS reliability and safety across operating conditions.

Test Categories:

Test Type	Parameters	Standards
Electrical	Accuracy, response time, isolation	IEC 61010
Environmental	Temperature, humidity, altitude	IEC 60068
EMC	Emissions, immunity	IEC 61000
Mechanical	Vibration, shock, drop	IEC 60068-2
Safety	Overload, short circuit, thermal	UL 2580, IEC 62619

GLOSSARY

Battery Management System (BMS) Terminology Glossary

Term	Description
BMS	Battery Management System; monitors and protects rechargeable batteries
SOC	State of Charge; percentage of remaining battery capacity
SOH	State of Health; measure of battery's current condition
OCV	Open Circuit Voltage: battery voltage when no load is connected
CC-CV	Constant Current-Constant Voltage; standard lithium-ion battery profile
OVP	Over-Voltage Protection; prevents cell damage from excessive charging
UVP	Under-Voltage Protection; prevents excessive discharge below safe threshold
OCP	Over-Current Protection; prevents damage from excessive current flow
OTP	Over-Temperature Protection; prevents operation outsidetemperature range
DOD	Depth of Discharge; percentage of battery capacity that has been discharged
PCM	Protection Circuit Module: hardware that implements battery protection
Cell Balancing	Process of equalizing the charge level between cells in multi-cell battery packs
Coulomb Count	SOC determination method based on current integration over time
C-Rate	Charge or discharge rate relative to battery capacity (1C = full in 1 hour)
PMIC	Power Management Integrated Circuit
SBD	Smart Battery Data; standardized protocol for battery data communication
Passivation	Formation of resistive layer on electrode surfaces
IR	Internal Resistance; opposition to current flow within the battery
Self-Discharge	Gradual loss of stored charge when battery is not in use
CID	Current Interrupt Device; safety mechanism that permanently breaks circuit
LCO	Lithium Cobalt Oxide; common lithium-ion battery cathode chemistry
NTC	Negative Temperature Coefficient thermistor; sensor for battery temperature
ESR	Equivalent Series Resistance: total resistance in series with battery
Pre-charge	Low-current charging phase for deeply discharged cells before charging