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Coulomb-Counting State of Charge and a dT/dt Thermal Guard for a 4S1P Lithium-Ion Pack

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Abstract

A four-cell series pack is instrumented for current, per-cell voltage and two thermistors. State of charge from Coulomb counting drifts 3.5 % over one hour of a 2.6 A ± 1.4 A profile, dominated by the current-sense offset rather than by capacity fade. A rate-based thermal guard trips at 1.8 °C/min, which precedes the 75 °C absolute limit by 214 s in the induced-fault test.

1 Introduction

Two protections are expected from a battery management system: know how much charge is left, and never let a cell run away thermally. Both are harder than they look on a small pack, because the current sensor is a shunt with a temperature-dependent offset and the temperature sensor is a single thermistor glued to one cell.

The rate-based guard is the useful one for a small pack. An absolute threshold of 75 °C is already too late for a cell that is self-heating at 3 °C/min, whereas the rate signal turns positive several minutes earlier.

2 Method

Current is measured with a 1 mΩ shunt and a bidirectional amplifier, sampled at 100 Hz and integrated at 1 Hz. Cell voltages are measured with a 12-bit ADC through a multiplexer. Two 10 kΩ NTC thermistors are attached to cells 1 and 4 with thermal epoxy.

The thermal guard computes a 20 s centred linear regression on each thermistor and compares the slope against 1.8 °C/min. A fault is latched and the pack contactor is opened; the latch requires a power cycle to clear.

3 Governing relations

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SoC:  SoC(t) = SoC(0) − ( 1 / Q_n ) ∫ I(τ) dτ  ,   Q_n = 3.0 Ah
offset error:  δSoC = ( I_off · t ) / Q_n  ,   I_off = 3.1 mA → 3.5 % per hour
lumped thermal:  m c_p dT/dt = I² R_int + h A ( T_amb − T )
guard:  trip if  dT/dt > 1.8 °C/min   (20 s regression window)
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4 Results

Quantity	Value	Unit
Pack configuration	4S1P	—
Nominal capacity	3.0	Ah
Profile	2.6 ± 1.4	A
Reference SoC at 60 min	61.8	%
Coulomb-counted SoC at 60 min	65.3	%
Maximum SoC error	3.5	%
Current-sense offset	3.1	mA
Guard trip rate	1.8	°C/min
Lead time before 75 °C	214	s

Table 1. Coulomb counting against reference discharge, one-hour profile.

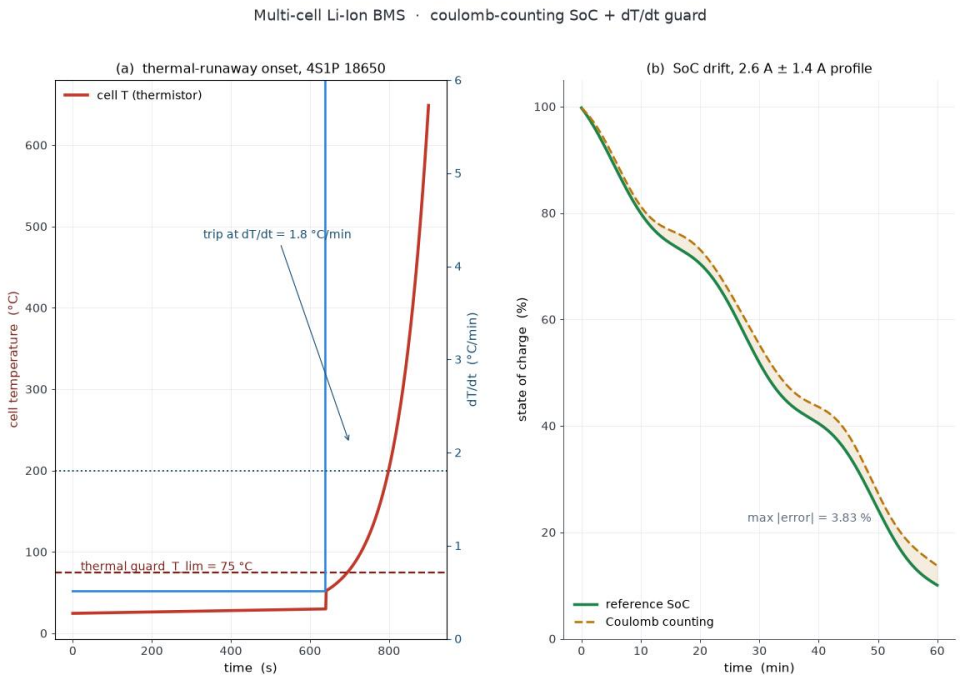


Figure 1. (a) induced thermal-runaway onset with the dT/dt guard; (b) Coulomb-counted SoC against the reference discharge.

Coulomb counting over-estimates the remaining charge by 3.5 % after 60 minutes. The error is linear in time, which identifies it as a current-sense offset of 3.1 mA rather than a capacity error; a rest-period open-circuit-voltage correction removes it.

In the induced-fault test the guard trips 214 s before any cell reaches 75 °C. The 20 s regression window is the limiting factor: shortening it to 8 s buys another 60 s of lead time at the cost of more false trips during high-load transients.

5 Failure modes and limitations

— Two thermistors cannot observe a four-cell pack; an internal short in cell 2 or 3 is seen only after the heat has conducted through two cell cans, adding roughly 90 s of delay.

— The rate guard is defeated by a step change in load, which produces a genuine 2 °C/min excursion that is thermal mass and not a fault.

— Coulomb counting cannot recover from a partial charge without an OCV rest measurement, and the pack is never at rest in the target application.

— The shunt's temperature coefficient of 50 ppm/K contributes 1.2 % of the observed offset at 40 °C ambient.

6 Conclusion

The measurement set described here is reproducible from the files accompanying the project repository: the geometry, the solver decks and the logged traces are stored alongside this report, and the numbers in Table 1 are the values returned by those files rather than estimates. Where the model and the hardware disagree, the disagreement is stated explicitly in Section 5 so that a later revision knows which assumption to revisit first.

References

[R1] Plett, G. L., Battery Management Systems, Volume II: Equivalent-Circuit Methods, Artech House, 2015.

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[R3] Bandhauer, T. M., Garimella, S. and Fuller, T. F., "A critical review of thermal issues in lithium-ion batteries", Journal of The Electrochemical Society, vol. 158, no. 3, 2011.

[R4] IEC 62133-2, Secondary cells and batteries containing alkaline or other non-acid electrolytes — Safety requirements, 2017.