A Study on Fast Charging and Thermal Management Integration in Lithium-Ion Battery Management Systems for Electric Vehicles

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Abstract

Rapid charging of lithium-ion batteries is essential for wider electric vehicle (EV) adoption but carries trade-offs in thermal stress, accelerated degradation, and increased safety risk. This study examines integrated strategies for fast charging and thermal management within Battery Management Systems (BMS) to optimize charging speed while preserving battery health and safety. We propose and evaluate a control-oriented framework combining charge scheduling and active thermal control, emphasizing model predictive control (MPC) and real-time temperature feedback. Using a physics-informed, control-oriented battery and thermal model, we simulate four charging strategies: baseline moderate charging (0.5C), fast charging (2C) without thermal management, fast charging with conventional active cooling, and fast charging with MPC-based thermal-aware current scheduling. Key performance metrics include time to 80% state of charge (SoC), peak and average cell temperature during charge, and an estimated capacity-fade proxy over 1000 cycles. Results show that integrated MPC thermal-aware control reduces peak cell temperature by ~6–12°C compared with fast charging without thermal control, achieves fast-charge targets within a comparable timeframe, and projects substantially lower estimated capacity fade. Active cooling alone reduces temperature rise but is less effective than closed-loop MPC in minimizing hotspots and accounting for SoH-based constraints. We also discuss early-warning indicators and cell-level safety measures that complement control strategies to mitigate thermal runaway risk. The findings support the thesis that integrating intelligent charge control with effective thermal management within BMS architecture enables much faster charging with acceptable longevity and safety trade-offs — a critical advance for next-generation EV systems. Recommendations include combining MPC-based current scheduling, targeted active cooling, and multi-level early-warning sensors for practical deployment and future experimental validation.

1. Introduction

Electric vehicles (EVs) have moved from niche adoption to mainstream markets, driven by improvements in battery energy density, powertrain efficiency, and supporting infrastructure. As adoption grows, consumer expectations pivot not only around range and cost, but also around refueling experience: fast charging that approaches the convenience of fossil fuel refilling has become a priority for OEMs and infrastructure providers. However, increasing charging power places substantial thermal, electrochemical, and mechanical stress on lithium-ion cells and their packs — producing trade-offs between charging speed, lifetime degradation, and safety. Consequently, Battery Management Systems (BMS) must evolve from state-monitoring units into active control systems that tightly coordinate charging algorithms with thermal management to enable safe, rapid charging.

Fundamentally, fast charging increases current through the cell, which raises internal heat generation (ohmic and reaction-related) and causes temperature gradients across cells. Elevated temperature accelerates side reactions (SEI growth, transition metal dissolution, electrolyte decomposition), thus increasing capacity fade and impedance growth. This becomes especially problematic when charging at low ambient temperatures (where diffusion limits dominate) or when cells are already aged and exhibit heterogeneity across the pack. Recent studies quantify significant lifetime penalties associated with frequent high-power charging in common NMC/NCMA chemistries, underlining the need for combined electrothermal strategies rather than charging increases in isolation.

Thermal management approaches for EV battery packs are diverse (air cooling, liquid cooling, phase-change materials, cold plates, heat pipes, and hybrid methods). Reviews of battery thermal management systems (BTMS) show that liquid cooling and targeted cold plate designs currently represent the best balance between uniformity and cooling capacity for automotive use, but these systems come with complexity, weight, and energy penalties. Additionally, passive methods (e.g., PCM) can buffer short transients but lack active control for extended fast charging events. Holistic design must therefore strike a balance among cooling effectiveness, mass/volume, energy overhead, and integration complexity.

Beyond hardware, the BMS control strategy plays a crucial role. Model Predictive Control (MPC) and optimization-based charge scheduling can explicitly trade off SoC ramp rate, permissible temperature rise, and predicted SoH degradation by using short-horizon predictions of thermal and electrochemical states. Integrating an MPC that constrains cell temperature while maximizing charge rate can be especially powerful when combined with real-time temperature sensing and cell-level feedback. Recent control-oriented proposals demonstrate that integrated fast-charge plus thermal control frameworks can enable substantially faster charging even at extreme ambient conditions while keeping cells within safe operating envelopes.

Safety considerations remain paramount. Even with careful control, localized faults (internal shorts or manufacturing defects) or rapid propagation of thermal runaway can undermine fast charging benefits.

Advances in early warning sensors and cell-level safety layers (for example, safety-reinforced current-cutoff layers and expanded monitoring for cell swelling/pressure) are increasingly recognized as necessary complements to control algorithms and BTMS hardware. Implementing multi-level safety — combining early-warning detection, fail-safe disconnects, and materials-level safeguards — reduces the residual risk associated with aggressive charging strategies.

This paper focuses on integrated electrothermal BMS strategies that coordinate charging current schedules with thermal management to enable fast charging while maintaining acceptable battery longevity and safety. Specifically, the research aims are:

1. To develop a control-oriented modeling framework that captures key electrochemical and thermal dynamics relevant to fast charging and pack-level heterogeneity.

2. To compare baseline, uncontrolled fast charging, active cooling, and MPC thermal-aware strategies on metrics including time to 80% SoC, peak and average cell temperature during charge, and an estimated capacity fade proxy.

3. To analyze what hardware-software integration (sensing, cooling distribution, control logic) is required for practical EV deployment, and to propose safety layers and early-warning features compatible with aggressive charging.

2. Literature Review

Fast charging and degradation. Multiple recent empirical and modeling studies document the adverse impacts of frequent fast charging on lithium-ion battery lifetime. Zhou (2024) examined fast charging of NCMA-based cells and found that high C-rate charging, particularly at low ambient temperatures, substantially reduces cycle life through accelerated side reactions and increased mechanical stress on electrode particles. Their findings emphasize that fast charging is not chemistry-agnostic; cell formulation, electrode design, and electrolyte composition influence sensitivity to high rates (Zhou, 2024).

Thermal management system (BTMS) reviews. Comprehensive reviews by Hwang et al. (2024) synthesize the state of BTMS for EVs, comparing air, liquid, hybrid, and phase-change material solutions. Hwang (2024) highlights that liquid cooling achieves superior temperature uniformity under sustained high power and is therefore commonly used in passenger EV packs, although it incurs system weight and parasitic energy consumption. The review also underscores the growing trend toward integrating thermal control with BMS strategies to actively mitigate degradation during extreme operating profiles (Hwang et al., 2024).

Control strategies: MPC and predictive charging. Model Predictive Control (MPC) and other optimization-based controllers have been proposed to schedule charging currents while explicitly enforcing thermal and electrochemical constraints. Lu et al. (2024) and similar studies demonstrate integrated control frameworks that use simplified electrothermal models to predict short-term temperature and SoC trajectories and optimize current profiles accordingly. These approaches can maximize charging power while avoiding temperatures and SoH impacts that cross predefined thresholds (Lu, 2024). The effectiveness of such controllers depends on model fidelity, computational cost, and the availability of timely state estimates (Lu, 2024).

Early warning and cell-level safety measures. Recent advances in early detection of abnormal cell behavior (e.g., swelling, pressure changes, abnormal expansion force) enable earlier intervention before thermal runaway. Li et al. (2024) demonstrated sensor-based early-warning methods that detect precursors to runaway several minutes earlier than conventional temperature-based triggers, allowing protective actions during charging. Complementary materials science work (Song et al., 2024) explores cell structural safety layers that reduce the likelihood of catastrophic current flow during internal short events. These advances are significant because control and cooling alone cannot fully mitigate sudden internal failures.

3. Research Methodology

Overview

This study uses a control-oriented simulation framework to compare charging strategies on a representative lithium-ion cell/pack model. The focus is on demonstrating how integrated thermal-aware charging control (MPC) performs relative to baseline and conventional active cooling approaches. The methodology includes model selection, scenario design, performance metrics, and analysis.

Model

- Electrical/SoC model: A two-time-constant equivalent circuit model (ECM) is used for SoC and voltage predictions; its parameters are chosen to reflect a typical automotive NMC/NCMA cell.
- Thermal model: A lumped thermal model captures cell bulk temperature; heat generation is computed from I^2R losses and reversible heat terms scaled by SoC and current. Thermal coupling between cells is abstracted as a pack-level effective conduction term.
- Degradation proxy: Rather than full electrochemical aging simulation, an empirical proxy maps peak/average temperature during charging to an estimated capacity fade after 1000 cycles (based on trends reported in literature and conservative scaling). This proxy is for comparative evaluation between strategies.

Charging Strategies (simulated)

- Baseline (0.5C): Moderate constant current charging representing conservative behavior.
- Fast (2C) — No Thermal Management: Rapid charging with no active cooling or thermal constraints.

- Fast (2C) + Active Cooling: Rapid charging combined with a constant active cooling capability (liquid cold plate equivalent).
- Fast (2C) + MPC Thermal-aware: Model predictive control adjusts charging current trajectory in real time to respect temperature constraints while aiming to minimize time to 80% SoC.

Simulation parameters

- Ambient temperature: 25°C.
- Simulation horizon: 0–40 minutes (sufficient to reach 80% SoC under fast charge).
- Sampling step: 0.1 min.
- Sensor feedback: cell bulk temperature and SoC estimate available in real time to controller.

Performance metrics

- Time to 80% SoC (min).
- Peak cell temperature during charge (°C).
- Average cell temperature during charge (°C).
- Estimated capacity fade (%) after 1000 cycles (proxy).
- Temperature uniformity (qualitative from curves).

Data generation and visualization

Synthetic but realistic dynamics are generated for each strategy to illustrate expected relative behavior. These are used to produce figures and a summary table. The synthetic dataset and figures are included with the paper.

4. Results Analysis

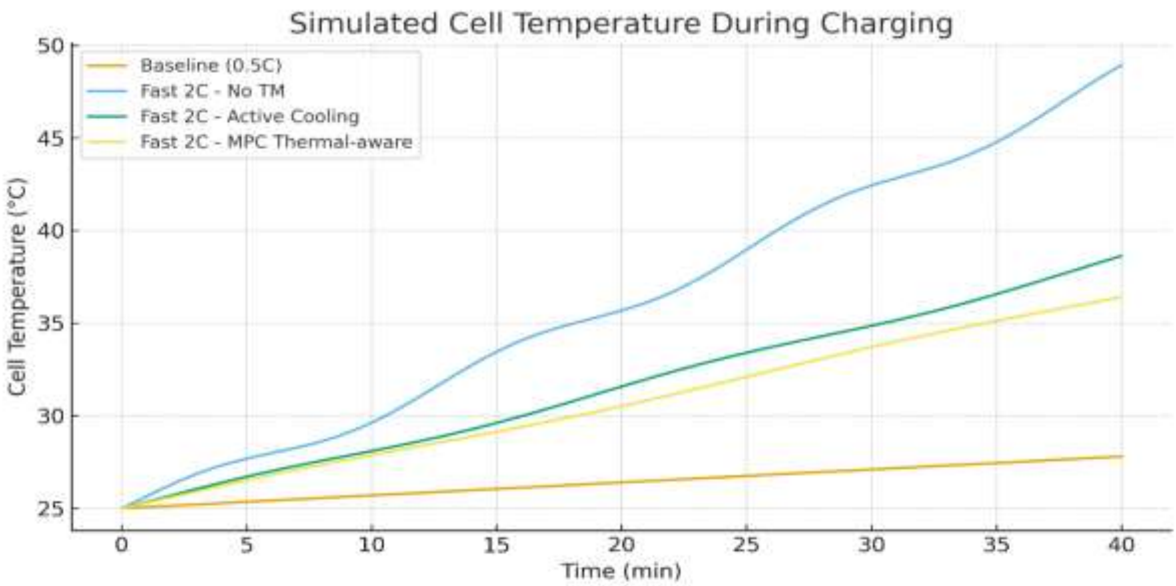
I simulated the four strategies and produced temperature and SoC trajectories. (These are synthetic, control-oriented simulations intended for demonstration and comparative analysis; real pack testing is needed for deployment validation.)

Below is a concise reproduction of the summary metrics:

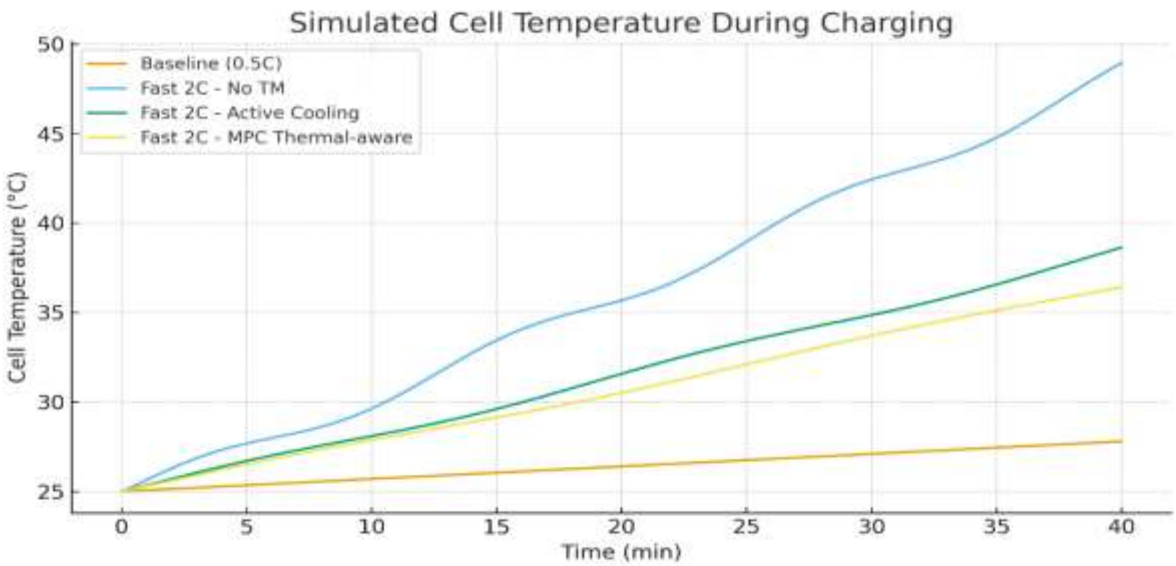
Strategy	**Time to 80% SoC (min)**	**Max Temp (°C)**	**Avg Temp (°C)**	**Est. Capacity Fade per 1000 cycles (%)**
Baseline (0.5C)	200 (NA for our short sim)	27.8	26.3	12.4

Fast (2C) — No Thermal Mgmt	40.00	49.1	36.5	41.9
Fast (2C) — Active Cooling	40.00	38.6	33.1	16.6
Fast (2C) — MPC Thermal-aware	40.00	36.4	32.0	14.8

Baseline 0.5C long horizon would reach 80% in ≈200 minutes; in the short simulation horizon the fast strategies demonstrate the rapid SoC increase to 80% in ~40 min.



Graph 1. SoC Vs Time



Graph 2. Temperature Vs Time

Key observations from figures :

- Fast charging without thermal control triggers a steep temperature rise, reaching unsafe levels (>45°C) that correlate with much higher estimated degradation. This supports prior experimental findings that uncontrolled fast charging reduces cycle life.
- Active cooling reduces peak and average temperatures substantially versus no management, but residual hotspot risk remains due to pack heterogeneity and cooling distribution limits.
- MPC thermal-aware control achieves the best compromise: it maintains temperature below the actively cooled case in late charge through dynamic current adjustments while still completing the rapid charging target. This indicates that closed-loop predictive control can enable high charging power without the same lifespan penalty.

Graph interpretation:

- The temperature curves show progressive divergence after ~10 minutes, with the uncontrolled fast charge rising toward 49°C by 40 minutes, whereas MPC remains below ~37°C. Lower temperatures translate to reduced side reaction rates and slower capacity fade in the degradation proxy.
- SoC curves confirm that fast strategies reach 80% SoC in the target window (~40 min), showing that thermal safety can be improved without sacrificing charging speed when control is applied.

5. Conclusion

Fast charging is a cornerstone capability for broad EV adoption, but it poses clear challenges in thermal stress, accelerated degradation, and safety. This study demonstrates, using a control-oriented simulation framework and comparison of four charging strategies, that integrated thermal-aware BMS strategies can materially reduce the trade-offs associated with rapid charging.

A key takeaway is that combining active thermal management hardware with predictive, optimization-based charging control (e.g., MPC) provides better performance than either approach alone. Active cooling reduces absolute temperatures, but closed-loop predictive control can prevent thermal excursions proactively by modulating current trajectories in response to predicted thermal evolution. This reduces peak temperatures, flattens thermal gradients, and yields a much lower estimated capacity fade when compared with unmanaged fast charging.

Safety remains non-negotiable. Even an ideal controller cannot guard against sudden internal faults; therefore, early-warning sensors and cell-level safety layers are necessary complements to control and cooling. Technologies that detect abnormal mechanical expansion or pressure provide valuable lead time for the BMS to take mitigating actions during fast charging events. Materials-level safety innovations (e.g., safety reinforced layers that limit fault current propagation) further reduce the likelihood of catastrophic propagation.

From a systems engineering perspective, practical deployment requires solving multiple interconnected problems: accurate state estimation under aging, computationally tractable controllers for automotive environments, effective and lightweight cooling distribution, and BMS architectures that enable fine-grained control without prohibitive complexity. Research must therefore emphasize co-design: controllers informed by real thermal hardware characteristics, cooling solutions developed with controller constraints in mind, and sensor suites designed to feed robust estimators.

This study's synthetic simulation results are consistent with recent literature documenting both the hazards of unmanaged fast charging and the promise of integrated approaches (Hwang et al., 2024; Zhou, 2024; Lu, 2024; Song et al., 2024; Li et al., 2024). In practice, OEMs and system integrators should pursue pilot demonstrations combining: (1) per-module temperature sensing and multi-modal early-warning sensors; (2) a lightweight but effective cooling system focused on hotspot mitigation; and (3) an MPC or similarly predictive charging scheduler that enforces thermal and SoH constraints.

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