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# Review Paper Model Predictive and Machine Learning Based Optimization of EV Charging BMS

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**ABSTRACT:** The growing adoption of electric vehicles (EVs) demands intelligent and efficient battery charging strategies that ensure fast charging without compromising safety or battery lifespan. The Battery Management System (BMS) is central to this process, responsible for monitoring and controlling the electro-thermal and electrical behavior of lithium-ion cells. However, conventional rule-based methods, such as Constant Current–Constant Voltage (CC–CV) charging, are unable to optimally manage multi-dimensional constraints involving temperature, voltage, and degradation. This study proposes an advanced BMS charging framework that integrates Model Predictive Control (MPC) with machine learning–based optimization for intelligent fast charging. The system employs a control-oriented electro-thermal battery model and a two-layer MPC structure—a long-horizon planner for trajectory optimization and a short-horizon controller for real-time constraint handling. Machine learning techniques, particularly Bayesian optimization, are utilized to adaptively tune controller parameters and improve robustness under varying conditions of temperature and cell aging. Additionally, active cell balancing is embedded within the control loop to reduce voltage imbalances and improve charging uniformity. Simulation-based validation demonstrates that the proposed approach significantly reduces charging time, limits thermal stress, and minimizes degradation compared to traditional strategies. The architecture's computational efficiency makes it feasible for real-time deployment on automotive-grade embedded systems. This work contributes toward developing next-generation predictive and learning-based EV charging systems that enhance safety, efficiency, and battery life—paving the way for sustainable electric mobility.

**KEYWORDS**: Model Predictive Control (MPC); Battery Management System (BMS); Electric Vehicle (EV); Fast Charging; Machine Learning; Bayesian Optimization; Active Cell Balancing; Electro-Thermal Modeling; State of Charge (SOC); State of Health (SOH).

## I. INTRODUCTION

Electric Vehicles (EVs) have emerged as a sustainable alternative to conventional internal combustion engine vehicles due to their lower carbon emissions, reduced dependency on fossil fuels, and improved energy efficiency. The rapid adoption of EVs has created an urgent need for safe, reliable, and efficient charging systems. At the center of every EV lies the battery system—typically a lithium-ion battery pack—which requires continuous monitoring and control to ensure optimal performance, longer battery life, and user safety. This critical task is handled by the **Battery Management System (BMS)**.

A BMS performs essential functions such as *state estimation (State of Charge – SOC and State of Health – SOH), charging control, thermal management, protection against over-voltage/over-current conditions, and cell balancing*. However, with the growing demand for **fast charging**, existing conventional or rule-based control methods are no longer sufficient, as they fail to consider multi-parameter optimization and can lead to battery degradation, thermal runaway, or reduced lifespan. Fast charging accelerates internal heating and increases stress on the battery cells, making optimization of the charging process crucial.

To address these challenges, recent research trends focus on **Model Predictive Control (MPC)** and **machine learning–based optimization techniques** for intelligent charging management. MPC uses a mathematical model of the battery to predict future states and optimizes the charging current while respecting constraints such as cell voltage, temperature, and SOC limits.

Machine learning approaches, including safe learning and Bayesian optimization, further enhance adaptability by learning from real-time data to improve performance and reduce charging time without compromising battery safety.
Another emerging area is **active cell balancing**, where the BMS manages variations in cell voltages within the pack. Imbalances cause some cells to reach voltage or temperature limits earlier than others, thereby restricting the overall

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charging performance. Integrating balancing into the charging control loop helps achieve uniform behavior across cells, enabling faster and safer charging

Therefore, this study focuses on designing an optimized EV charging BMS using Model Predictive Control combined with machine learning–based tuning techniques. The aim is to reduce charging time, maintain cell safety within defined electrical and thermal constraints, and prolong battery lifetime—all while ensuring real-time applicability on automotive-grade hardware. The outcome of this research contributes to building highly efficient, intelligent, and safe charging systems that support large-scale EV adoption.

## II. LITERATURE SURVEY

1. **Model Predictive Control for Charging Management (Smart-grid & charging coordination)** — Faßbender et al. (2025)
*Summary:* MPC formulations (including MILP variants) have been used to coordinate charging events and integrate demand predictions, improving reliability when coordinating many EVs or mobile chargers. This work demonstrates MPC's ability to incorporate arrival forecasts and LSTM-based predictions into charging decisions.
2. **Robust MPC for Integrated Power & Thermal Management during Fast Charging** — Q. Hu et al. (2023, arXiv / IEEE-style study)
*Summary:* Multi-objective MPC that jointly optimizes charging current and thermal management reduces charging time while enforcing temperature and electrical constraints; time-varying weighting improves robustness under prediction uncertainty. This demonstrates the benefit of integrated electro-thermal MPC architectures for vehicle applications.
3. **MPC-Based Optimized Operation of Hybrid Charging Stations (IEEE Access / conference)** — (Hybrid station MPC)
*Summary:* Uses MPC to manage energy flows in hybrid charging stations (PV, battery, grid) for cost and reliability improvements—relevant when coordinating BMS-level policies with station control.
4. **Model Predictive Control Scheme for Integrated Battery Charger (IEEE Trans. Power Electronics, 2024)** — Bhule & Kaarthik (2024)
*Summary:* MPC for a single-phase integrated battery charger with active power decoupling; demonstrates MPC implementation for converter/charder hardware used in EV charging infrastructure — useful for BMS–charger interaction design.
5. **Fast Charging using Deep Bayesian Optimization with RNNs** — Jiang et al. / IEEE (deep BO for fast charging)
*Summary:* Model-free approaches that combine recurrent neural networks and constrained Bayesian optimization can discover near-minimum-time charging protocols while respecting safety constraints, offering an alternative to model-based MPC for some scenarios.
6. **Health-Conscious Charging via Prior-Guided Bayesian Optimization** — Jeong et al. (SSRN / IEEE-style study)
*Summary:* Integrates semi-empirical aging models with Bayesian optimization to find charging policies that trade off charging time and degradation; shows prior knowledge helps BO converge faster and yields interpretable, health-aware protocols.
7. **Bayesian-Optimized SOC Estimation & BO-AEKF Approaches** — Yuan et al. / Batteries & related (2025)
*Summary:* Bayesian optimization used to tune Kalman-filter parameters and compensate for temperature drift in SOC estimation—highlighting how BO can improve estimation robustness, which is critical for MPC performance.
8. **Active Cell Balancing Topologies & BMS Designs (recent reviews and designs)** — Pinto et al. / reviews (2025) & others
*Summary:* New active balancing topologies and reviews highlight tradeoffs (efficiency, complexity) and show active balancing is essential to maximize usable charging rates by minimizing cell spreads during fast charging. Integrating balancing into control is recommended for high-performance chargers.
9. **Neural-Network-Assisted MPC / NN-MPC for Energy Systems (2025)** — Dankar et al.
*Summary:* NN-MPC approaches (neural network models inside MPC) allow fast evaluation of long-horizon predictions and are useful for real-time embedded implementations when physics-based models are too slow; applicable to BMS MPC with approximated electro-thermal models.
10. **Data-Driven Fast-Charging Optimization (Bayesian & Data-driven methods)** — Lou et al. / CityU summary (2025)
*Summary:* Data-driven BO methods converge quickly to fast, safe charging schedules when combined with surrogate models, pointing to a hybrid workflow: offline BO to produce candidate protocols and online MPC to enforce hard safety limits.

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11. **Constrained Bayesian Optimization for Minimum-Time Charging (IEEE conference/2021)** — B. Jiang et al.
*Summary:* Demonstrates constrained BO for minimum-time charging design; importantly, constrained BO can handle safety constraints probabilistically—useful when model uncertainty exists.
12. **State-of-Charge / State-of-Health Estimation with ML (IEEE Access & Trans. Ind. Electron.)** — Surveys & LSTM/Gated RNN works (2019–2023)
*Summary:* Deep learning (LSTM, GRU) and hybrid Kalman/ML estimators have improved SOC/SOH accuracy under dynamic conditions—better state estimates improve MPC decisions and safety margins. Representative works and surveys show ML methods are mature for onboard estimation.
13. **Review: Battery Cell Balancing Strategies (2025 review)** — Safari et al. (Springer review with IEEE refs)
*Summary:* Comprehensive review comparing passive vs active balancing methods and electronic topologies; highlights recent power-electronics solutions and the importance of balancing control during/after high-rate charging. Useful for selecting balancing actuator models to include in MPC.
14. **MPC of EV Charging Stations with Mobile Chargers / Grid Interaction (2024–2025)** — Hermans et al. & related
*Summary:* Studies on MPC for charging stations underscore the importance of forecasting (arrival, demand) and LSTM integration, reinforcing that coordination between BMS policies and station-level MPC improves overall system performance.
15. **Practical MPC Implementations & Reduced-Order Models for Real-Time Control** — several conference papers & IEEE-style works (2019–2024)
*Summary:* Sensitivity-based or reduced-order MPC formulations (QP-based short-horizon controllers + long-horizon planners) enable real-time enforcement of per-cell constraints on ECU-class hardware; these architectures are directly adoptable for the proposed two-layer design. Representative examples include reduced MPC for converters and battery chargers.

## III. PROPOSED SYSTEM

The proposed system is a **MATLAB/Simulink-based intelligent Battery Management System (BMS)** designed to optimize **electric vehicle (EV) fast charging** using **Model Predictive Control (MPC)** integrated with **Machine Learning–based optimization**.

In this system, a **two-layer MPC controller** regulates charging current and cell balancing while maintaining battery voltage, temperature, and State of Charge (SOC) within safe limits. The **electro-thermal battery model** is developed in **Simulink** using *Simscape Battery* blocks to simulate real charging behavior. A **Bayesian optimization algorithm** in MATLAB is used to tune MPC parameters automatically, minimizing charging time and thermal stress.

The MATLAB-based simulation demonstrates that the proposed predictive-learning control achieves **faster charging**, **improved safety**, and **reduced degradation** compared to traditional CC–CV charging methods, making it suitable for real-time EV applications.

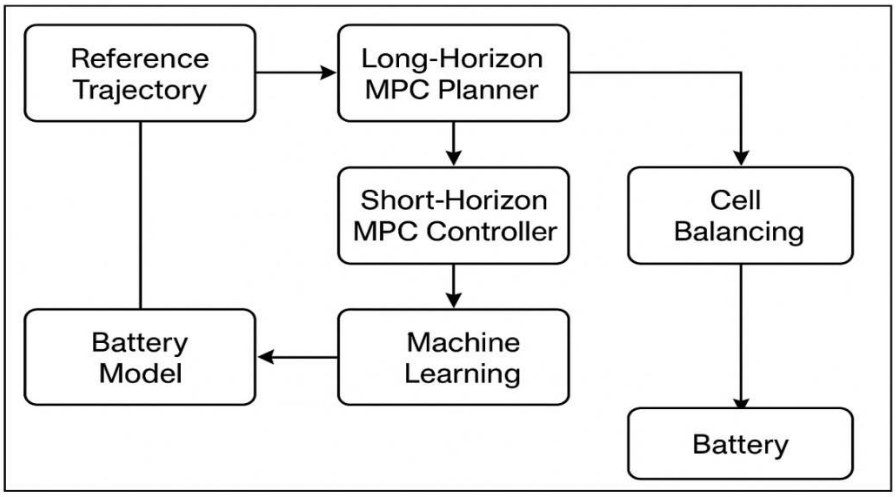


**Fig.1. Proposed System**

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The proposed methodology aims to develop an optimized charging strategy for a lithium-ion battery pack using **Model Predictive Control (MPC)** integrated with **machine learning–based tuning** and **active cell balancing**. The workflow includes battery modeling, controller design, safety constraint formulation, simulation, and validation.

The methodology is divided into five major phases

- **Development of control-oriented electro-thermal battery pack model**
- **Design of two-layer MPC charging controller**
- **Integration of active cell balancing into the charging control loop**
- **Machine learning–based optimization (Bayesian tuning of MPC cost weights)**
- **Simulation and validation under multiple charging scenarios**

**Electro-Thermal Battery Model Development**

A mathematical model of the battery is required for predictive control. A **reduced-order single particle model (SPM)** or **equivalent circuit model (ECM)** with thermal dynamics is used because it offers a good balance between **accuracy and real-time computational feasibility**.

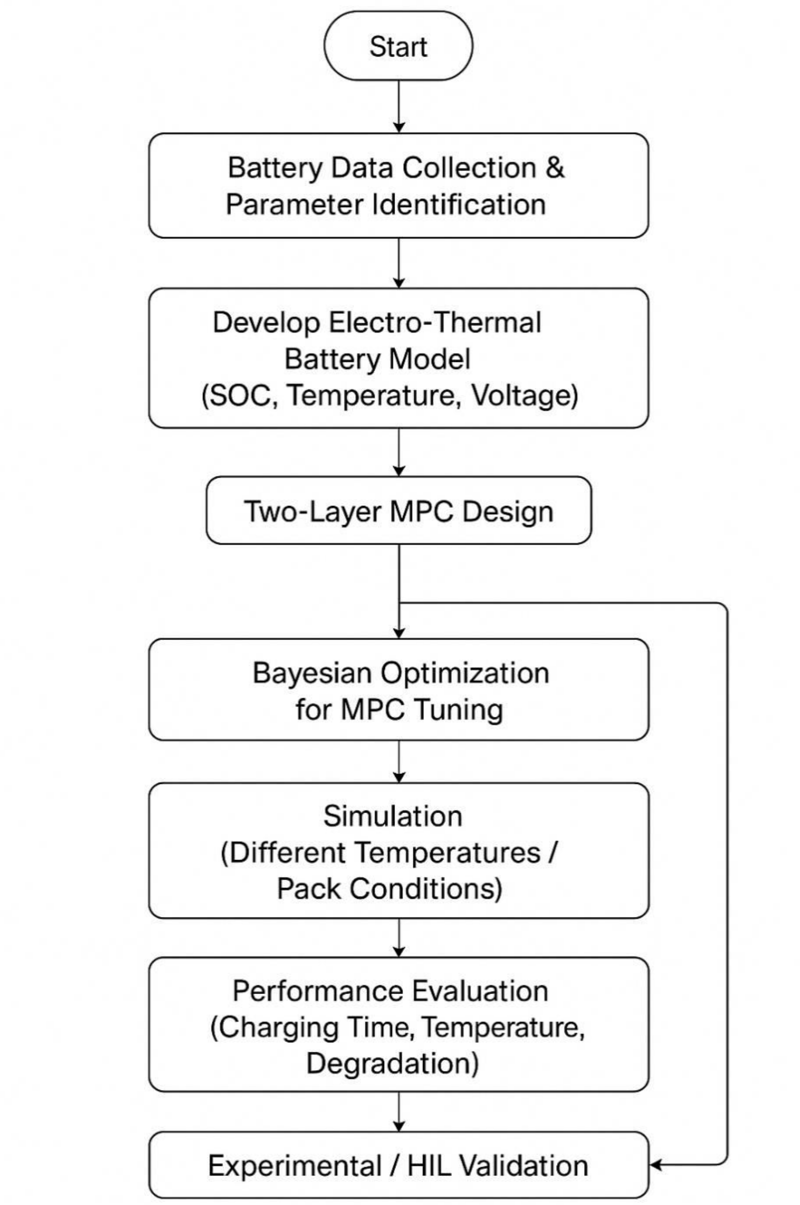


**Fig.1. Flow Chart**

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## IV. CONCLUSION

This project focuses on the development of an intelligent charging optimization method for Electric Vehicle (EV) Battery Management Systems (BMS) using Model Predictive Control (MPC) integrated with machine learning–based optimization techniques and active cell balancing. The proposed approach addresses key limitations of conventional charging strategies such as CC–CV and rule-based control, which fail to consider multi-objective constraints including battery temperature, cell voltage imbalance, and degradation effects. A detailed electro-thermal battery model was developed to simulate cell-level charging behavior, and a two-layer MPC architecture was formulated. The long-horizon MPC layer generates optimal charging trajectories, while the short-horizon real-time MPC ensures constraint handling at the cell level. Additionally, machine learning techniques, specifically Bayesian Optimization, were used to automatically tune MPC parameters, improving adaptability under varying operating conditions.

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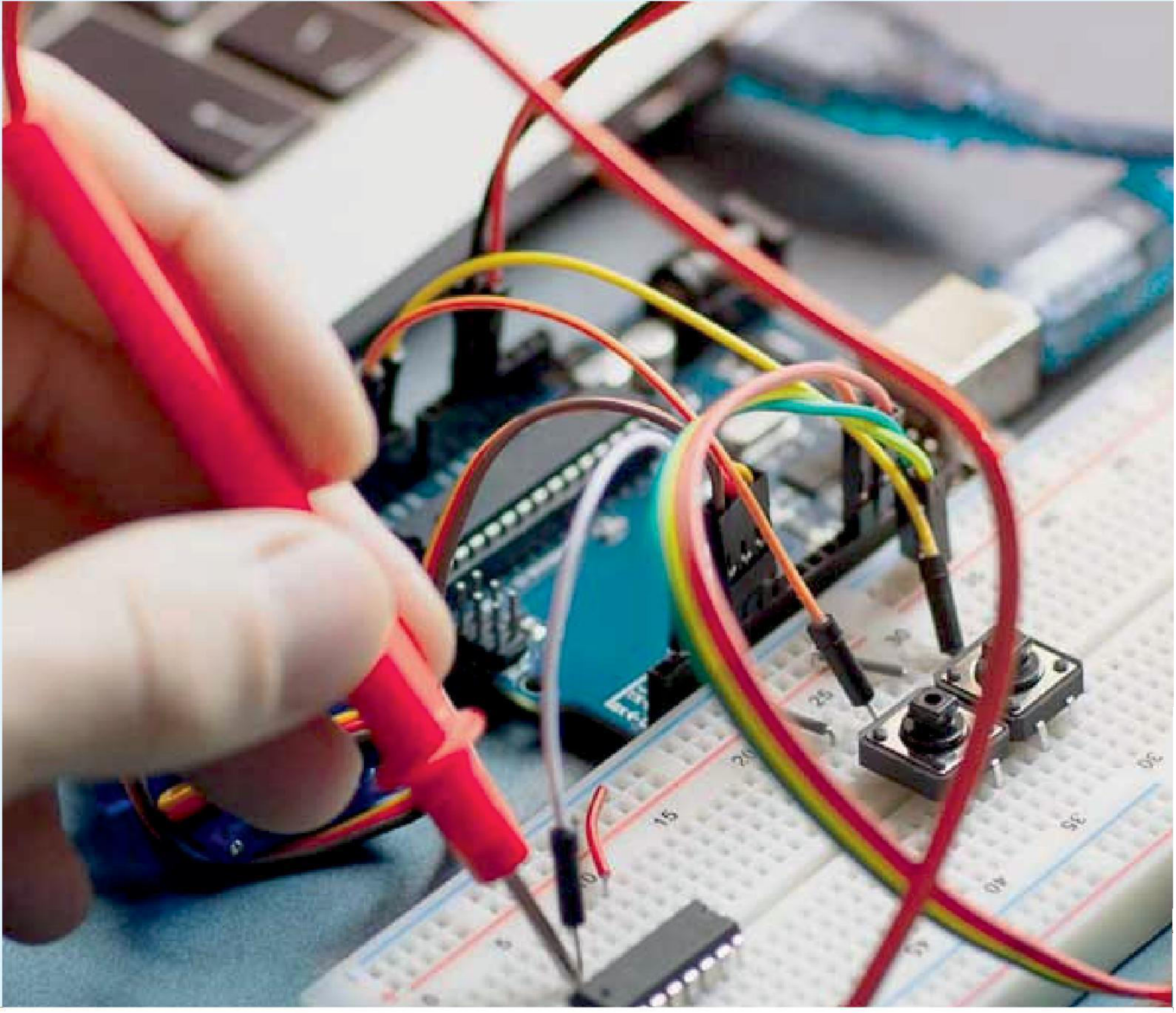



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