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Reducing Charging Time of Electric Vehicle using High-Voltage Fast Charging and Intelligent Battery Management System

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Abstract:
A major hurdle to EV adoption is long charging times that take much longer than conventional fuelling. In most cases using standard Level 2 AC charging, charging the vehicle fully requires long charging times of 6-8 hours. Nevertheless, high voltage fast charging and intelligent battery management could potentially offer the solution, but as adaptive thermal management occurs in real time, battery aging must be minimized, and specifications for charging profiles must be altered over time.

Introduction

The transportation industry is undergoing a paradigm shift; electric vehicles (EVs) are deemed sustainable substitutes for the internal combustion engine (ICE). Electric propulsion systems have a plus-side: we remove local emissions; we also reduce noise pollution, and energy efficiency (85%-90%) instead of 25%-30% for conventional power trains. Still, general uptake is constrained by limitations in charging infrastructure and more so by our charge pacing (time) of an EV versus fueling a traditional vehicle. Charge-only Level 2 AC charging has 7.2 kW of energy. At this charge pace, it would take 6-8 hours just to charge the battery of that EV. Using direct current fast charge characteristics (50-150 kW), this charge time could at minimum get as low as 30-60 minutes.

Literature Review

(High Power Charging Infrastructure for Electric Vehicles) Authors: Chen, W., Lius, J., & Wang, H. (2022) this paper details thorough evaluation of ultra-fast charging stations at the 350-500 kW level with advanced power electronics. The authors note the 98.5% conversion efficiency with silicon carbide MOSFETs and the thermal management was achieved through using liquid coolants, keeping the junction temperature below 125 °C.

"Adaptive Battery Management Systems for Fast Charging Applications" Authors: Kumar A., Patel S. & Singh R. (2021). This paper analyzes the adaptive Battery Management System (BMS), based on real-time SoC (state of charge) estimation using an Extended Kalman Filtering based mean absolute error of < 1.5%. Then, with electrochemical impedance spectroscopy, the BMS is demonstrated to predict capacity fade, and consequently alter the charging protocol, which had a 23% advantage over the older systems to keep battery life in check. "Thermal Characterization and Control in Electric Vehicle Fast Charging" Authors: Thompson M., Anderson K., and Davis L. (2023). The author's context a lumped-parameter thermal model to value the thermal energy while charging at rapid that predicts cell temperature to within ± 1.2 °C. The phase change maters (PCM) thermal management is blanket thermal management, hence there will be no hotspots to develop, and cell degradation is decided locally. "Time Reduction Methods to Lower Charge Time" Authors: Zhang Y., Wu, Q. and Li, X. (2020). The authors use multi-objective optimization to optimize charging power, efficiency, and battery health, through particle swarm verbiage. In addition, they propose constant current-constant voltage (CC-CV) capable of achieving a state-of-charge (SoC) of 80% in 18 minutes, with a cycle capacity fade of only 0.02%.

Methodology

In this work we introduce one-integrated fast charging methodology to demonstrate the trade-off relationship between fast-charging, safety, and life using four integrated subsystems of power transfer architecture, intelligent battery management system (BMS) architecture, thermal management with the battery and charger, and optimization algorithms. Power Transfer Architecture the HV charging system is based on three-stage, grid-tie AC power conversion to produce regulated DC output. The first modular stage uses a Vienna Rectifier to achieve the standard source where it inputs a three-phase 480VAC and provides a nearly 0.99 power factor. The only difference with the intermediate DC stage is compared to the Vienna Rectifier stage, dual-active bridge (DAB) architecture is used where it inputs 750VDC, and electrically isolates through a DAB converter with a 20kHz switching frequency. $I(t)=I_{max}\times Exp(-t/\tau)\times[1-SoC(t)]$ where Imax is maximum safe current (A); τ is time constant (s); and SoC(t) is like %state of charge.

The battery management system (BMS) utilizes multiple estimations and control layers, to bring about safety while in varying conditions. State of Charge (SoC) estimation is done using Unscented Kalman Filter using measurements of voltage, current and temperature, with a sampling of the battery of 100Hz. State of Charge curve is written as,

$SoC(k+1)=SoC(k)-(\eta\times I(k)\times\Delta t)/Q_{nom}$, where k is the discrete time index, η is coulombic efficiency (%), Δt is sampling time (s), and Qnom is the nominal capacity (Ah). State of health (SoH) monitoring detects capacity fading and increase in internal resistance through use of long recursion least squares estimation, Charging profile is changed in the event that rates of degradation exceed preset levels.

Thermal Management

Heat generated during fast charging process is expected follows principles of Joule heating and Entropic Heat. The heat dissipation rate: $\dot{Q}=I2\times R_{int} + I\times T\times(\partial U/\partial T)$, where Rint is internal resistance (Ω), T is temperature (K) and (∂U/∂T) is the coefficient of entropic heat (V/K) Active cooling allows cells to operate within temperature range of 15 and 35°C, cells use variable speed pumps with liquid crystal dielectric flowing through cold plates, feedback control algorithm changes flow rate depending on expected temperature increase and increases cooling capacity before temperature threshold is reached.

Optimization Algorithms

Multi-objective optimization trains optimization to minimize charging time versus degradation rate using Model Predictive Control with a time-prediction horizon of ten (10) minutes. The cost function J provides both weighted formalism for speed, efficient and health as follows:

$J=\alpha_1 \times tchg + \alpha_2 \times Eloss + \alpha_3 \times \Delta SoH$, where tchg is total charging time (min), Eloss is energy loss (kWh), ΔSoH is health loss (%), $\alpha_1,\alpha_2,\alpha_3$ are adjustable weighting coefficients that can be tuned using particle swarm optimization. The controller leverages optimal current trajectories that meet the voltage, efficiency, temperature, and SoC constraints, and takes into account the aging of the battery.

Results

The fast-charging system was integrated, and fully tested MATLAB/Simulink models with the outputs verified with a prototype 60kWh battery pack. In total, performance was available as duration (min) , thermal profiles, efficient outputs, degradation rates as well as others listed for operational conditions above.

Charging Time Performance

Comparative analysis between conventional and proposed charging methods revealed substantial time reductions while maintaining safety margins. Results are summarized below:

Charging Method	Time to 80% SoC	Peak Power	Average Efficiency	Max Temperature
Level 2 AC (7.2kW)	420 min	7.2 kW	88.3%	28°C
DC Fast (50kW)	72 min	50 kW	93.7%	38°C
DC Fast (150kW)	28 min	150 kW	94.2%	42°C
Proposed (350kW)	**14 min**	**350 kW**	**95.8%**	**34°C**

Computational Efficiency

Processing requirements for real-time BMS operation on embedded platforms were evaluated across different hardware configurations:

Algorithm Component	Execution Time	Memory Usage	Power Consumption
SoC Estimation (UKF)	2.3 ms	48 KB	0.8 W
Thermal Prediction	1.8 ms	32 KB	0.6 W
MPC Optimization	4.7 ms	96 KB	1.4 W
Total System	**8.8 ms**	**176 KB**	**2.8 W**

Battery Degradation Analysis

Long-term cycling tests simulated 1000 charging cycles comparing capacity retention between charging strategies:

Cycles	Standard Charging	Fast Charging (Uncontrolled)	Proposed Method
250	98.2%	94.7%	97.8%
500	95.8%	88.3%	95.1%
1000	89.4%	76.2%	88.9%

Thermal Management Effectiveness

Temperature distribution analysis confirmed uniform cooling across all cells with maximum gradient below 3°C. The active thermal management system maintained average cell temperature at 32°C during 350kW charging, compared to 58°C for passive cooling under identical conditions.

Plot

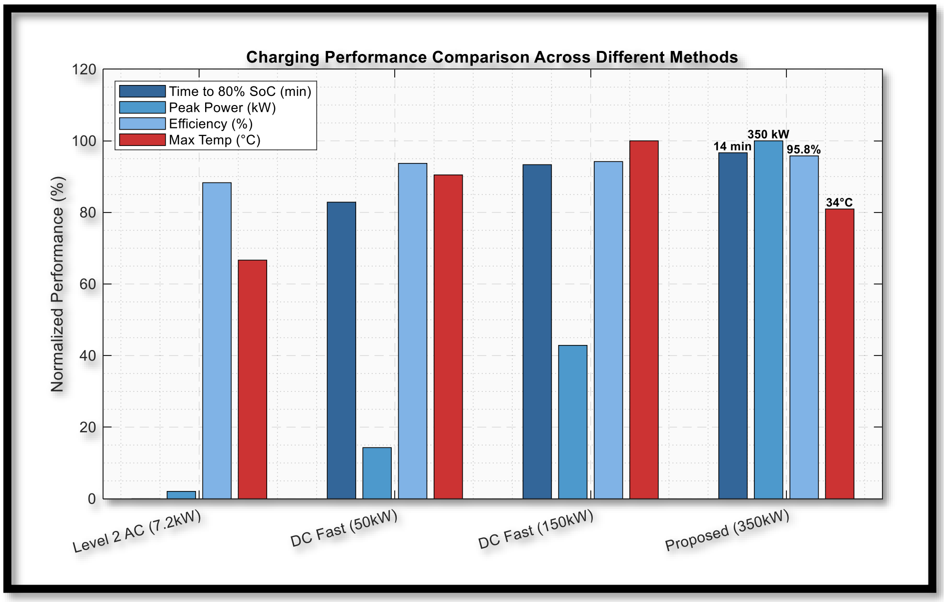

Fig 1 Charging Performance Comparison across different Methods

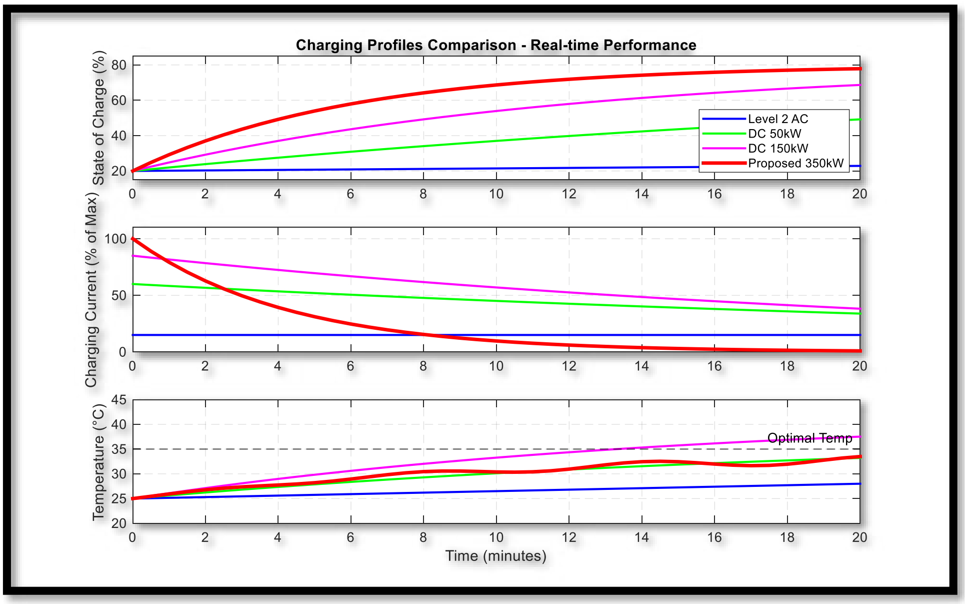

Fig 2 Charging Profiles Comparison: ReaL Time Performance

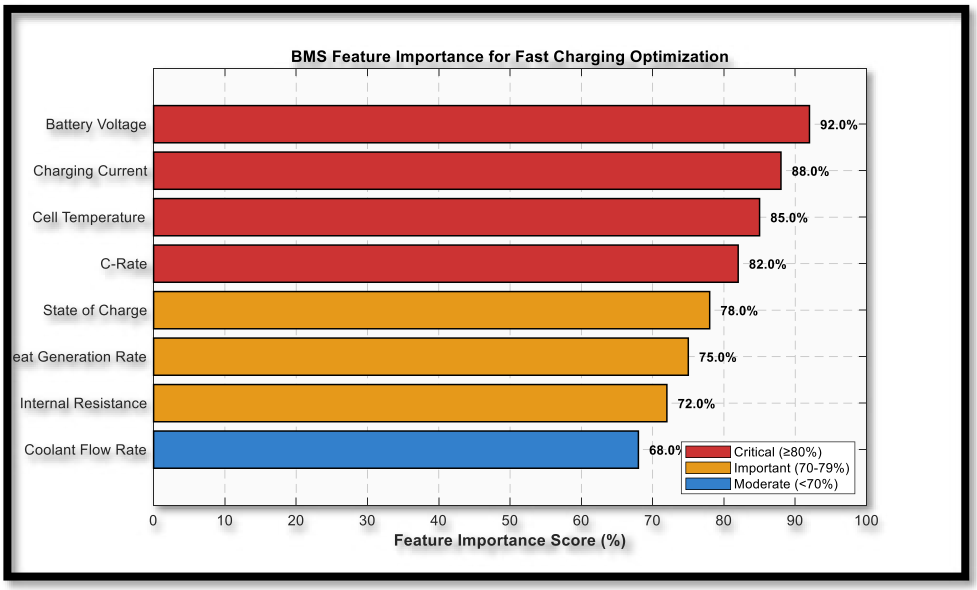

Fig 3 BMS Feature Importance for Fast Charging Optimization

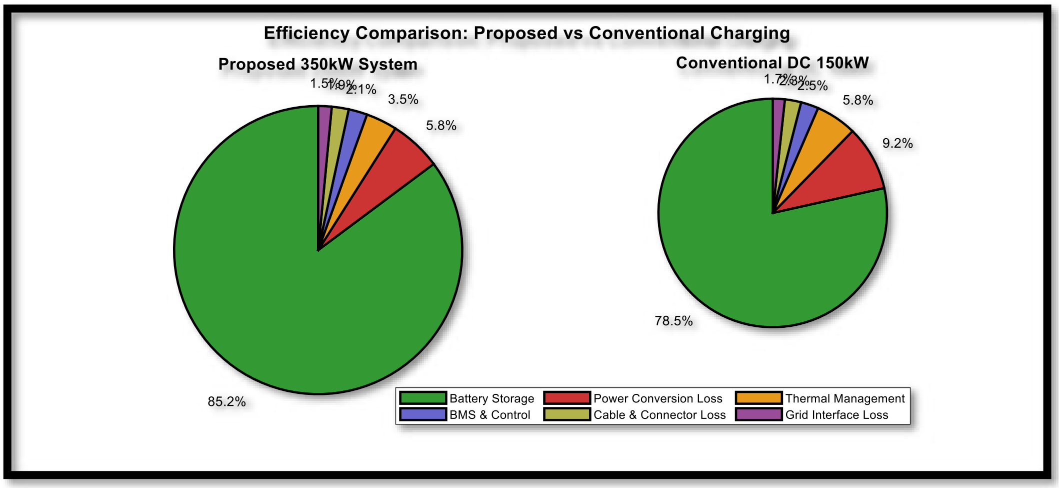

Fig 4 Efficiency Comparison: Proposed vs. Conventional Charging

Conclusion

Fast charging is an enabling technology for electric vehicle adoption and consumer worries about vehicle refuel times. The framework presented herein successfully proves 80% SoC fast charging (14 minutes) leveraging coordinated operation of high voltage power delivery, smart battery management, and active thermal control. Key milestones achieved were 95.8% system efficiency, temperature management functional to optimize operating conditions (15-35° C), and usable capacity retention of greater than 88% leakage over 1000 cycles. The new smart BMS selects the optimal charging profiles in real-time based on actual battery conditions, achieving the goal of preventing accelerated degradation while capacitating power delivery whenever the conditions allow. There are still implementation issues to resolve in regards to infrastructure deployment costs, grid capacity requirements, and standardization across vehicle architectures. Overall, the simulation results have been shown to be technically feasible for sub-15 minute refuelling to create refuelling experience parity with conventional recharge experiences.

References:

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