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Efficient Charging Strategy in Megawatt Charging Station Using Model Predictive Control: Balancing Cooling Energy and Charging Current for Heavy-Duty Battery Electric Vehicles

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Executive Summary

This paper presents a novel charging strategy for megawatt-scale charging stations, primarily focusing on managing the battery temperature. Thus, most battery packages used in EVs are equipped with an effective cooling system to avoid overheating. The proposed Model Predictive Control (MPC)-based strategy ensures that the battery temperature stays within optimal thermal limits with the minimum possible charging duration extension for the user. The control algorithms discussed in this study will be implemented using both equation-based thermal and charging models of the battery in a Mega Charging Station (MCS) within MATLAB. For the sake of comparison, two other approaches are also discussed: the passive cooling approach and unlimited cooling. Finally, this paper presents a multi-mode charging strategy based on each approach's potential in different charging scenarios, offering flexibility and efficient management in high-power charging stations.

1 Introduction

Although Medium- and Heavy-Duty Vehicles (MDVs and HDVs) comprise only a small fraction of the total vehicles on main routes, they are responsible for approximately one-third of greenhouse gas emissions in road transportation [1]. Therefore, various regions and communities have established strict regulations to achieve zero-emission transportation, with Battery Electric Vehicles (BEVs) being a promising solution. However, challenges such as range anxiety, charging time, and battery degradation, especially in MDVs and HDVs, present significant barriers. Due to the large battery packs required for electric trucks [2], studies suggest the development of MCS as a rapid charging solution for HDVs. Implementing these MCSs helps alleviate range anxiety and makes electric trucks more viable for widespread use. Nowadays, most BEVs use lithium-ion batteries, which are valued for their higher energy density and lower environmental impact compared to other alternatives.

One critical concern for MDV and HDV BEV owners is battery degradation, as high-power charging at MCS can reduce battery lifetime and reliability over time. Various factors, such as temperature, State of Charge (SoC), battery voltage, and battery resistance, can influence battery capacity and lifetime [3]. Among these, temperature plays a vital role, especially under the high charging currents typically found at MCS. Therefore, an effective cooling system is essential to achieve fast charging safely within a short time.

Solid electrolyte interphase and lithium deposition may accelerate battery degradation caused by high and low operational temperatures. In contrast, near room-temperature operation leads to a prolonged lifetime of batteries [3]. Temperature effects are more critical during charging than discharging, which makes a narrow operational temperature threshold necessary during high-power charging [4]. Research by Mokashi et al. suggests that keeping battery temperature below 40°C can mitigate thermal degradation [5]. Another study recommends a maximum temperature of 56.8°C for natural convection cooling conditions [6], while fast-charging cycles lasting up to 10 minutes may cause battery temperatures to rise to 60°C [7]. To prevent critical degradation, a safe maximum temperature of 55°C has been suggested as a threshold for charge durations in MCSs [8].

Optimizing the charging strategy in an MPC system can be beneficial by balancing multiple objectives, such as efficiency and charging time. MPC also facilitates advanced thermal management by predicting battery temperature and adjusting operations accordingly. Using predictive modeling, MPC forecasts battery temperature based on charging conditions, allowing for cooling adjustments or modifications to the charging current to prevent overheating. Authors in [9] employed generalized predictive control to enable the controller to adjust the charging current of a 10Ah Li-ion battery cell, preventing overheating and maintaining the cell's temperature within defined limits. Although the authors in [10] utilized MPC to optimize battery thermal management and enable real-time cooling adjustments, they did not consider optimizing the charging current to reduce energy consumption in the cooling system and enhance the overall efficiency of the charging process. The authors in [11] propose an MPC-based algorithm to enhance modular converters' efficiency by generating optimal power references for each module. However, overall efficiency in charging events depends on various factors beyond converter performance.

This publication aims to enhance the overall efficiency of charging events in an MCS by optimizing the charging current and minimizing the cooling energy required to keep the battery temperature below a specific threshold. The proposed approach is applied to battery packs used in electric trucks. The results of this paper can be utilized in a charging reservation system to offer optimal charging times to EV owners, ultimately prolonging battery life and improving efficiency.

2 System Modeling

The following sections are organized as follows: first, a low-fidelity model of high-capacity battery packs based on prismatic cells is developed. Next, the architecture is briefly introduced. A simplified representation of the converter efficiency map follows this. Finally, the charging model for the battery packs is presented.

2.1 Battery Thermal modeling

Several major heavy-duty electric vehicle (HD EV) manufacturers utilize different battery chemistries and formats tailored to their performance and safety goals. Volvo Trucks adopts high-energy-density NCA (Nickel Cobalt Aluminum Oxide) chemistry integrated into cylindrical cells, while Tesla uses high-nickel NMC 811 chemistry in large-format 4680 cylindrical cells to achieve greater energy density and reduce pack complexity. In contrast, BYD and Daimler have opted for LFP (Lithium Iron Phosphate) prismatic cells due to their superior thermal stability, longer cycle life, and lower cost, particularly beneficial for commercial applications requiring frequent charge-discharge cycles.

Volvo's electric trucks utilize 90 kWh battery modules built from 21700-format cylindrical cells. Each module contains approximately 4,500 cells arranged in a configuration of 98 cells in series and 46 in parallel. These modules serve as the fundamental building blocks of the complete battery system, enabling flexible scaling based on vehicle range requirements. The 21700 lithium-ion cell has a diameter of 21 mm and a height of 70 mm, offering an energy capacity of approximately 18-21 Wh per cell. The average weight of a single cell is around 70 grams. This format provides an optimal balance between energy density, thermal management capability, and mechanical robustness, making it a popular choice for high-performance EV battery systems.

Each 90 kWh battery module, composed of approximately 4,500 cylindrical 21700 cells, has physical dimensions of approximately 768 mm $\times$ 684 mm $\times$ 668 mm, resulting in a total volume of about 0.351 m^3. While the active cell material takes up a large portion of the total volume, the remaining space plays a critical role in accommodating essential support systems such as liquid cooling channels, structural reinforcements, electrical insulation, and the battery management system. These components ensure effective thermal regulation, electrical protection, and mechanical stability, all of which are critical for safe and reliable operation in heavy-duty electric vehicle applications. By connecting two 90 kWh, 400 V modules in series, an 800 V, 180 kWh battery pack can be formed. This series configuration not only achieves the desired voltage level but also enables modular scalability. These 800 V units can be paralleled to reach various total energy capacities, depending on vehicle range and powertrain requirements.

In this study, three configurations are considered: a 360 kWh battery pack consisting of two 180 kWh units in parallel, a 540 kWh configuration with three units, and a 720 kWh pack composed of four units. These configurations represent typical energy demands for short-, medium-, and long-haul HD electric trucks, respectively, and form the basis for evaluating thermal behavior, electrical performance, and integration constraints in future sections. The weight, dimensions, equivalent resistance, and convection area for each pack are reported in Table 1.

Resistive power losses determine heat generation during charging and discharging, while heat dissipation occurs through natural convection (with a heat transfer coefficient, h, of 5 W/m²-K) and the cooling system [12]. The equivalent resistor represents the package's heat losses, and the cooling system adjusts heat flow based on specific coefficients when the cell temperature deviates from set thresholds. The average specific heat capacity ($C_{p,ess}$) is 600 J/kg-K, encompassing the cell's casing, electrolytes, and electrodes [12].

Table 1: Combined Battery Pack Specifications

Configuration	No. of Packs	Total Weight (kg)	Effective Area (m^2)	Req (mΩ)
360 kWh	4	1000	5.5	42
540 kWh	6	1500	9	31.5
720 kWh	8	2000	12.5	21

The coefficient of performance and efficiency of the cooling system are not considered in this study, due to the fact that this efficiency may have the same impression in all different approaches. The model for the calculation of battery temperature and required energy that should be removed from the battery package are discussed in (1) to (4) [12], where $P_{cooling}$, P_{conv}, and P_{Loss} are the rate of energy removed by cooling and natural convection from packs and generated by the losses in the battery pack, respectively. $\theta_{batt}, \theta_{amb}$,and θ_{init} represent the current battery, ambient, and initial battery temperatures (θ^0_{Batt}), respectively. The ambient and initial battery temperatures are considered to be equal.

$$\Delta P = P_{Loss} - P_{conv} - P_{cooling} \tag{1}$$

$$P_{conv} = h * A_{conv} * (\theta_{batt} - \theta_{amb}) \tag{2}$$

$$P_{Loss} = R_{eq} * I^2_{charge} \tag{3}$$

$$\theta^{k+1}_{batt} = \Delta\theta + \theta^k_{Batt} = (\Delta P * T_{step}/(m * C_P)) + \theta^k_{Batt} \tag{4}$$

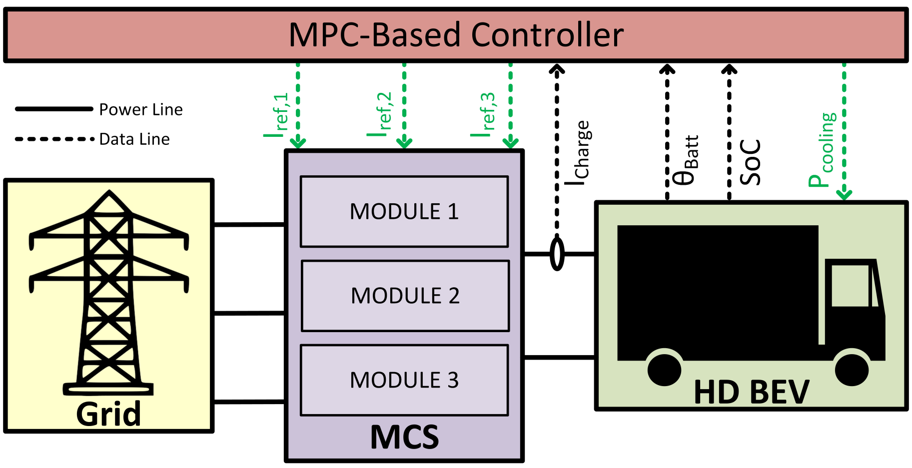

Figure 1: MPC-based controlled MCS Architecture

2.2 MCS architecture

This study adopts a modular design approach to address challenges associated with dedicated converter designs, offering benefits such as enhanced reliability, easier maintenance, and improved efficiency. Given the high power requirements of MCSs, most research suggests a direct connection to the medium-voltage (MV) grid. This study uses three similar charging converters with the ability to deliver a maximum power of 450 kW for each converter. The MCS architecture with MPC controller is shown in Figure1. Regardless of the low-level controller used in the modules, it is understandable to consider the I_{charge} to be the summation of all reference currents, as shown in (5).

$$I_{charge} = \sum_{k=1}^{3} (I_{ref,k}) \tag{5}$$

2.3 Converter Efficiency Model

To enhance the overall efficiency of a charging event, the loss that occurs in power electronics modules must also be included. Data on variations of efficiency in each module must be collected to determine the optimal working point of each module. So the efficiency map of the power electronics component can be considered as a quadratic equation as shown in (6), where the α, β, and γ are the coefficients calculated by interpolation of a quadratic equation with the efficiency map, and P_{DC} is the output DC power of each module. The relationship between the P_{DC} and I_{ref} is shown in (8), by considering that low-level control is working ideally, results in $I_{ref} = I_{out}$. Th

$$\eta(P_{DC}) = \alpha * P_{DC}^2 + \beta * P_{DC} + \gamma \tag{6}$$

$$P_{Loss,PE} = \sum_{i=1}^{3} (1 - \eta_i(P_{i,DC})) * P_{i,DC} \tag{7}$$

$$P_{DC} = V_{DC} * I_{ref} \tag{8}$$

The Figure 2 illustrates the efficiency versus power curves for three converter modules, each with a distinct peak efficiency point, at 320 kW, 350 kW, and 380 kW, highlighting their optimized performance regions within the 0–450 kW range.

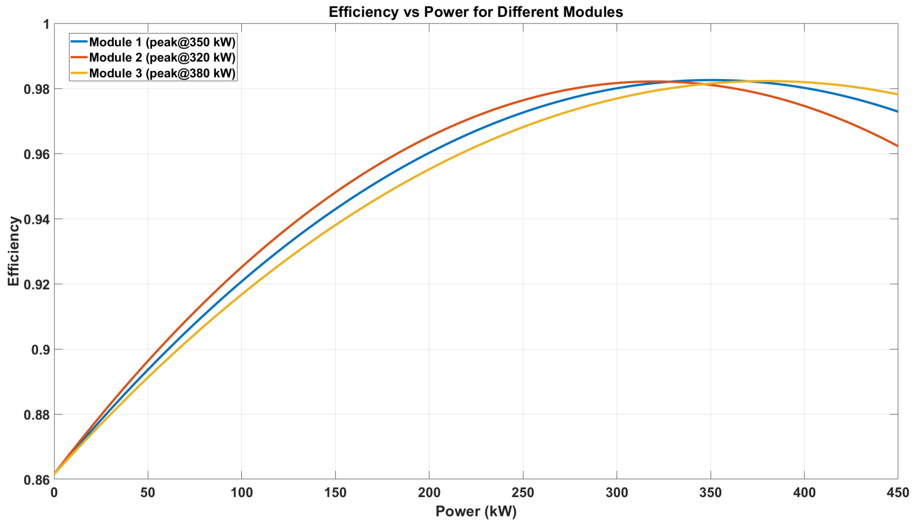

Figure 2: Efficiency Map of Modules

2.4 Battery Charging Model

The equation to calculate the next step SoC (SoC^{k+1}) of BEVs equipped with battery with a capacity of $C_{batt}(kWh)$ if charged with the power equals to $P^k_{charge}(A)$ for the duration of $T_{step}(h)$, based on current SoC (SoC^k) is shown in (9).

$$SoC^{k+1} = SoC^k + \frac{T_{step} * (P^k_{charge} - (P^k_{Loss} + P^k_{cooling}))}{C_{batt}} \tag{9}$$

3 MPC-based approach and other approaches

Charging event efficiency refers to the proportion of energy effectively stored in the battery compared to the total energy consumed during the charging process, as shown in Equation (10). This metric is essential for evaluating the performance and sustainability of megawatt charging systems. One of the primary objectives of this study is to minimize the cooling power consumption (P_{cooling}) during high-power charging events, which directly affects both energy efficiency and battery thermal safety. To address this, an MPC strategy is employed to dynamically manage the power distribution between charging and cooling, while respecting system constraints and ensuring optimal performance. The desired objective function and the equation-based model of the MCS are defined in Equations (11) and (12), respectively, and serve as the foundation for the MPC formulation. The Modular Converter System (MCS) considered in this study includes three 450 kW power modules, resulting in a total maximum charging power of 1.35 MW. This modular architecture enables high scalability and flexibility for heavy-duty charging applications. The MPC algorithm is implemented in MATLAB using the CASADI [13] toolbox, a symbolic framework that supports automatic differentiation and numerical optimization. In this implementation, the MPC problem is solved at each sampling instant, providing real-time control decisions to minimize charging losses while ensuring safe and efficient battery charging. In our simulation, we consider a charging rate of up to 3C, and only one electric truck is connected and charged at a time. All battery packs are assumed to begin charging at 20% SoC and are disconnected upon reaching 80% SoC. This reflects a common practice in fast-charging protocols to preserve battery health and reduce thermal stress, while also allowing for standardized comparisons across different charging strategies.

$$\eta_{Charging} = \frac{P_{AC} - (P_{Loss,PE} + P_{Loss,Batt} + P_{cooling})}{P_{AC}} \tag{10}$$

$$\min_{I^k_{ref,1}, I^k_{ref,2}, I^k_{ref,3}} \sum_{k=1}^{N} J(SoC^k, \eta^k_{Charging}) \tag{11}$$

$$J(SoC^k, \eta^k_{Charging}) = W_{SoC} * (SoC^k - SoC_{des})^2 + W_\eta * (1 - \eta^k_{Charging})^2 \tag{12}$$

For the sake of comparison, two other approaches are also considered: the simulation. Regarding the passive cooling approach, there are no limitations on the charging current except for the C_{rate}, as long as the battery temperature does not exceed a specified threshold. Once the battery temperature reaches this threshold, $P_{cooling}$ becomes zero in order to prevent surpassing the temperature limit, leading to a condition where $P_{conv} \geq P_{Loss}$. During charging under the unlimited power charging strategy, the only limitation on the charging current is the C_{rate}. This approach generally results in shorter charging durations and lower efficiency compared to the strategies examined in this study.

4 Simulation Results

To evaluate the impact of different thermal and control strategies on system losses and charging performance, three approaches were assessed: a fast charging scenario with unlimited cooling power, a passive cooling scenario, and an MPC-based coordinated charging strategy. These approaches were applied across three battery pack configurations representing short-, medium-, and long-haul applications: 360 kWh, 540 kWh, and 720 kWh. The metrics considered include power electronic (PE) loss, battery loss, cooling energy, charging time, and overall charging efficiency.

4.1 360 kWh Battery Pack

In the unlimited cooling scenario, the battery loss was 14.41 kWh, while the PE loss was measured at 5.75 kWh. The cooling energy required for this scenario was 10.15 kWh, resulting in a total charging time of 10 minutes and a charging efficiency of 86.03%. Under passive cooling conditions, the PE loss increased to 16.83 kWh, while the battery loss decreased to 4.99 kWh. Cooling energy was negligible in this scenario, and the charging process required approximately 74.33 minutes, yielding an efficiency of 89.91%. In the MPC-based case, battery loss was 9.04 kWh, and PE loss was 6.27 kWh. The system consumed 4.7 kWh for cooling, resulting in a total charging duration of 18 minutes and a charging efficiency of 90.70%.

4.2 540 kWh Battery Pack

In the unlimited cooling case, battery loss reached 14.70 kWh, with a corresponding PE loss of 8.76 kWh. The required cooling energy amounted to 9.81 kWh. The charging time was 14.66 minutes, and the system achieved a charging efficiency of 89.6%. For the passive cooling scenario, battery loss was reported at 5.77 kWh, and the PE loss rose to 24.03 kWh. Cooling energy was approximately 0 kWh due to the absence of forced cooling. Charging time was recorded at 69.33 minutes, and the efficiency was 90.78%. Under MPC control, battery loss was 9.98 kWh, and PE loss totaled 11.05 kWh. Cooling energy demand was 3.21 kWh, resulting in a 25.67 minute charging time and a charging efficiency of 92.48%.

4.3 720 kWh Battery Pack

In the unlimited cooling case, battery loss was recorded at 18.99 kWh, with a PE loss of 11.72 kWh. Cooling energy consumption reached 10.28 kWh. The charging time was 19.67 minutes, and the charging efficiency was calculated at 90.5%. The passive cooling approach resulted in 10.14 kWh of battery loss and 27.33 kWh of PE loss. No cooling energy was recorded. The total charging time extended to 74 minutes, with an efficiency of 91.27%. The MPC-based charging strategy yielded a battery loss of 12.92 kWh and a PE loss of 15.74 kWh. Cooling energy consumption was 3.78 kWh, and the charging event lasted 36 minutes, with an efficiency of 92.53%.

The results across all battery sizes are shown in Table 2, showing that the MPC-based charging strategy demonstrated the most favorable trade-off between charging duration, energy efficiency, and thermal performance. While the unlimited cooling method achieved the shortest charging times, it incurred significantly higher auxiliary energy use. Passive cooling minimized cooling energy consumption but led to longer charging times and increased thermal-related losses. These results underscore the importance of intelligent thermal and current management, particularly for high-capacity batteries in electric trucks. The MPC approach proposed in this study not only enhances system efficiency but also contributes to battery longevity by maintaining operation within safe thermal limits.

Table 2: Results of Simulation of Charging Strategies Across Battery Configurations

Battery Pack	Strategy	Charging Time (min)	Batt. Loss (kWh)	PE Loss (kWh)	Cooling Energy (kWh)	Efficiency (%)
360 kWh	MPC	18.0	9.04	6.27	4.70	90.7
	Passive Cooling	74.3	4.99	16.83	0	89.9
	Unlimited Cooling	10.15	14.41	5.75	10.14	86.0
540 kWh	MPC	25.67	9.98	11.05	3.21	92.5
	Passive Cooling	69.3	5.77	24.03	0	90.8
	Unlimited Cooling	14.7	14.29	8.76	9.81	89.6
720 kWh	MPC	36.0	12.92	15.74	3.78	92.5
	Passive Cooling	74.0	10.14	27.33	0	91.3
	Unlimited Cooling	19.7	18.99	11.72	10.28	90.5

5 Conclusion

This study evaluated the thermal and efficiency performance of three different charging strategies, unlimited cooling, passive cooling, and the MPC-based method, across three representative battery pack configurations (360 kWh, 540 kWh, and 720 kWh). The results highlight that the unlimited cooling approach enables rapid charging within a significantly shorter time frame, making it suitable for high-demand, time-critical scenarios such as emergency logistics or scheduled rest stops. However, this approach comes at the cost of increased energy consumption, particularly from the cooling system, which can impact the overall charging efficiency. On the other hand, passive cooling requires no external energy for thermal management and yields reasonable efficiency, though at the expense of significantly longer charging times. As such, it is best suited for depot charging or during extended loading and unloading operations, where time constraints are less stringent. The MPC-based method offers a well-balanced solution by maintaining high efficiency while keeping battery temperature below critical thresholds through predictive adjustments to both charging current and cooling power. This approach supports battery longevity and energy optimization, making it particularly effective for routine operations where minimizing energy loss and maintaining battery health are priorities.

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Presenter Biography

Amin Dalir is a Ph.D. candidate in Electrical Engineering at Vrije Universiteit Brussel (VUB), specializing in EV charging station technology and methods at the EPOWERS-MOBI research group. He holds a Master's degree in Power Systems Engineering and a Bachelor's in Electrical and Electronics Engineering from Shiraz University, Iran. His current research focuses on optimizing charging efficiency, safety, and compatibility for medium- and heavy-duty electric vehicles. Amin is dedicated to advancing sustainable transportation solutions through innovative EV charging technologies.