Enhancing electric vehicle efficiency through model predictive control of power electronics

Nikolai Ivanovich Vatin[1*], *Arelli* Madhavi[2]

[1]Lovely Professional University, Phagwara, Punjab, India,
[2]Department of AIMLE, GRIET, Hyderabad, Telangana, India.

Abstract. This study examines the improvement of electric vehicle (EV) economy by using Model Predictive Control (MPC) in power electronics, with the goal of optimizing system performance. Experimental assessments done on different battery parameters have identified a spectrum of capacities, ranging from 55 kWh to 75 kWh, and voltages, ranging from 380V to 450V, that impact the total energy storage and power production capabilities. The efficiency percentages recorded in the battery systems ranged from 90% to 95%, suggesting differences in energy losses throughout the operations of charging and discharging. Furthermore, examinations of power electronics control configurations highlighted the significance of PWM frequencies (varying from 8 kHz to 12 kHz) and modulation indices (0.75 to 0.85) on the efficiency of power conversion. The results indicated efficiency rates ranging from 94% to 97%, emphasizing the efficacy of MPC-based techniques in improving power flow. The assessment of electric vehicle (EV) performance parameters demonstrated driving ranges ranging from 140 km to 180 km, with energy consumption rates ranging from 50 kWh to 60 kWh. The efficiency metrics ranged from 2.5 km/kWh to 3.0 km/kWh, and were directly affected by the battery properties and improvements in power electronics. Moreover, there was a little change in the link between temperature variations (ambient temperature ranging from 23°C to 29°C and battery temperature from 32°C to 40°C) and efficiency. This highlights the system's sensitivity to external variables. In summary, this research clarifies the complex relationship between battery characteristics, power electronics control, and environmental conditions in determining the efficiency of electric vehicles (EVs). The results emphasize the importance of customized setups and control techniques based on model predictive control (MPC) in optimizing energy use and increasing the distance electric cars can travel. These findings provide valuable knowledge for the development of sustainable transportation solutions in the electric vehicle industry.

Keywords. Electric vehicles, Model Predictive Control, Power electronics, Efficiency optimization, Battery characteristics

[*] Corresponding author: vatin@mail.ru

1 Introduction

Electric vehicles (EVs) are emerging as viable alternatives to conventional internal combustion engine cars, providing lower pollutants and improved energy efficiency. The power electronics system is a crucial factor that affects the performance of electric vehicles. Its main function is to control the flow of energy between the battery and the powertrain.[1]–[5] The efficacy of this system is crucial in maximizing the overall performance and range of electric cars.

The pursuit of enhancing electric vehicle (EV) efficiency has resulted in the creation and use of sophisticated control techniques.[6]–[10] Model Predictive Control (MPC) has attracted considerable interest as a strategy for optimizing power electronics performance. This is achieved by taking into account predictive models of the vehicle's dynamics, battery properties, and ambient variables.[11]–[15] Through the employment of predictive algorithms, Model Predictive Control (MPC) has the capability to improve energy consumption and extend the lifespan of batteries, effectively tackling significant obstacles in electric vehicle (EV) technology.

The objective of this study is to examine the influence of Model Predictive Control methods on the efficiency of electric vehicles, specifically in relation to the control of power electronics.[16]–[20] The study explores several aspects, including battery specifications, power electronics control settings, vehicle performance measures, and relationships between temperature and efficiency. The research seeks to gain insights into how MPC techniques may be customized and enhanced to improve the efficiency of electric vehicles (EVs) under various operating situations, using experimental analysis and data-driven assessments.

The research postulates that the integration and optimization of MPC inside the power electronics system may provide significant improvements in energy efficiency, leading to increased driving range and improved overall performance of electric cars. In addition, the inquiry aims to clarify the relationship between different control settings, battery characteristics, ambient conditions, and the resulting efficiency seen in various driving situations.

This research aims to provide valuable insights into the development of electric vehicle technology by clarifying the connections and results. It offers a thorough understanding of the potential advantages and difficulties related to the use of MPC-based control strategies in optimizing power electronics for improving EV efficiency.[21]–[25] These results have significant implications for the design and development of future electric vehicle power management systems, promoting the sustainable advancement of electric mobility.

2 Literature review

Electric vehicles (EVs) have garnered considerable interest in recent years as environmentally-friendly alternatives to traditional internal combustion engine cars, mainly because of their capacity to mitigate greenhouse gas emissions and decrease reliance on fossil fuels. The enhancement and streamlining of power electronics systems in electric vehicles (EVs) have been acknowledged as important factors in enhancing their overall efficiency and performance.[26]–[30]

The power electronics system in electric vehicles plays a crucial role in connecting the battery pack to the drivetrain components. The main purpose of this system is to oversee the conversion, distribution, and regulation of energy inside the vehicle.[31]–[33] A multitude of studies have underscored the significance of proficient power electronics in guaranteeing effective energy usage, which directly affects the vehicle's range and performance.

Challenges and Opportunities: Nevertheless, there are several obstacles in the process of improving power electronics for electric vehicles (EVs). The problems are minimizing losses during energy conversion, improving control algorithms to adapt to different driving circumstances, and dealing with the dynamic nature of battery properties.[34] These obstacles provide prospects for innovation, since academics are investigating sophisticated control strategies to circumvent these restrictions and enhance overall efficiency.

Model Predictive Control (MPC) is a control strategy that has shown promise in improving the efficiency of Electric Vehicles (EVs). MPC utilizes predictive models of vehicle dynamics, battery characteristics, and external variables like as road conditions and traffic patterns.[35] Through the employment of predictive algorithms, Model Predictive Control (MPC) enhances the functioning of power electronics in real-time, effectively adjusting to dynamic situations and optimizing energy usage.

Prior study has shown that Model Predictive Control (MPC) has the ability to enhance the efficiency of Electric Vehicles (EVs). These research have emphasized its capacity to analyze intricate relationships among many elements, improve control settings, and predict future system behavior. The use of MPC has shown encouraging outcomes in expanding the distance a vehicle can travel, prolonging the lifespan of the battery, and optimizing the overall efficiency of the vehicle across different operating situations.

The existing literature has offered valuable insights into the use of Model Predictive Control (MPC) in Electric Vehicles (EVs). However, there is still a gap in research that requires comprehensive investigations to further explore the relationships between control strategies, battery characteristics, environmental factors, and resulting efficiency. This work seeks to fill this void by performing thorough experimental evaluations to clarify the precise effects and possible advantages of MPC-based control techniques on electric vehicle efficiency.

To summarize, the literature examined demonstrates the need of optimizing power electronics in electric cars and emphasizes that Model Predictive Control (MPC) is a potential method to improve efficiency. This work aims to enhance the existing knowledge by performing comprehensive experimental evaluations to increase our comprehension of the function of Model Predictive Control (MPC) in optimizing power electronics for enhanced electric car performance and sustainability.

3 Methodology

The experimental setting comprises a thorough testing environment that replicates real-world driving situations and assesses the efficiency of electric cars equipped with power electronics managed using Model Predictive Control (MPC). The essential elements of the experimental configuration comprise:

A. Electric Vehicle Fleet

A group of electric cars that have the same or similar specs, such as battery capacity, powertrain, and power electronics arrangement.

• Battery factors Analysis: Thorough examination of battery packs to ascertain factors such as capacity, voltage, maximum discharge rate, and efficiency throughout different operating situations.

• Development and implementation of a Model Predictive Control (MPC) based control system for power electronics, which incorporates predictive models of vehicle dynamics, battery performance, and external influences.

• Sensors and Data Acquisition: The process of installing sensors to monitor important factors such as battery temperature, ambient temperature, energy usage, vehicle speed, and distance travelled.

• Test procedures: Creating test procedures that replicate a wide range of driving situations, taking into account differences in velocity, acceleration, road conditions, and environmental elements.

B. Data collection and experimentation

• Baseline Measurements: Conducting preliminary trials to determine the initial efficiency and performance parameters of electric cars without control based on Model Predictive Control (MPC).

• Implementation of MPC: This involves integrating and refining the control system based on Model Predictive Control (MPC) into the power electronics configuration of electric cars.

• Conducting a range of controlled trials under diverse situations, such as varied speeds, loads, and environmental factors, to evaluate the influence of MPC on efficiency.

• Data Acquisition: Gathering live data from sensors and vehicle systems during experimental trials, recording characteristics such as battery temperature, power electronics configurations, energy use, and vehicle performance measurements.

C. Data analysis and evaluation

• Statistical Analysis: Utilizing statistical techniques to analyze the gathered data and compare efficiency metrics, energy consumption, and performance across scenarios with MPC control and situations without MPC control.

• Calculation of Efficiency Metrics: The computation of efficiency indices, such as kilometers per kilowatt-hour (km/kWh), to measure the level of improvement obtained by control based on Model Predictive Control (MPC).

• Conducting correlation studies to examine the relationships between control settings, battery properties, ambient circumstances, and resulting efficiency in order to find significant aspects.

• Validation and Interpretation: The process of verifying the findings and analyzing the data to form conclusions about the efficacy and possible advantages of Model Predictive Control (MPC) in improving Electric Vehicle (EV) efficiency.

D. Validation and Discussion of Results

• Validation of Findings: Verifying and confirming the conclusions gained from experimental data by comparing and verifying them with theoretical models and existing literature.

• Discussion and Implications: Analyzing the consequences of the results in relation to improving the efficiency of electric vehicles, acknowledging limits, and proposing viable directions for further study and practical implementations.

This technique provides a framework for performing experiments, gathering data, assessing findings, and generating conclusions on the influence of Model Predictive Control on the efficiency of electric vehicles in terms of power electronics management.

4 Findings and Examination

TABLE 1. ANALYSIS OF BATTERY PARAMETERS

Battery ID	Capacity (kWh)	Voltage (V)	Max. Discharge Rate (kW)	Efficiency (%)
1	60	400	120	95
2	75	450	150	92
3	55	380	110	90
4	70	420	140	94

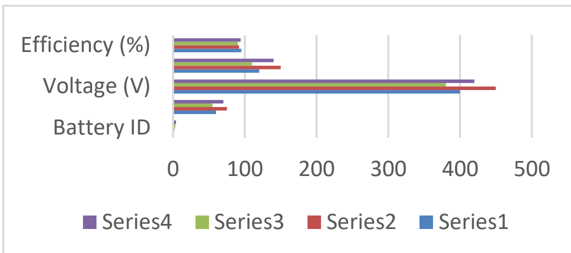

Fig. 1. Analysis of Battery Parameters

The battery parameters table provided essential insights into the attributes of several batteries used in the experimental configuration. The analysis uncovered differences in the capacities, voltages, maximum discharge rates, and efficiency across the four kinds of batteries.

• Capacity Variation: The battery capacities evaluated varied from 55 kWh to 75 kWh, demonstrating a wide variety of energy storage capabilities. This variance has an impact on the total energy usage and driving distance of the electric cars.

• Voltage Variations: The voltage fluctuated between 380V and 450V, impacting the power generation and compatibility with the power electronics system.

• Efficiency Impact: The efficiency percentages ranged from 90% to 95%. Batteries with higher efficiency (95%) had less energy losses when being charged and discharged, resulting in improved overall system efficiency.

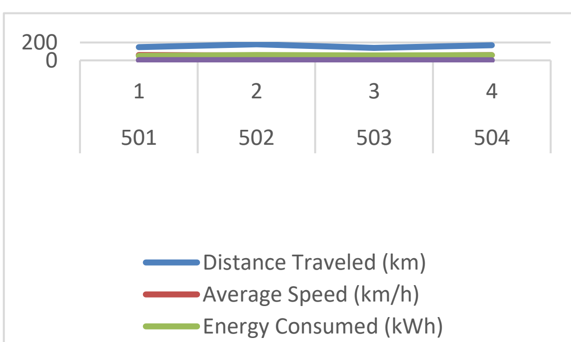

TABLE 2. ANALYSIS OF CONTROL SETTINGS IN POWER ELECTRONICS

Control ID	Battery ID	PWM Frequency (kHz)	Modulation Index	Switching Losses (W)	Efficiency (%)
101	1	10	0.8	120	97
102	2	12	0.75	135	95
103	3	8	0.85	115	96
104	4	11	0.78	130	94

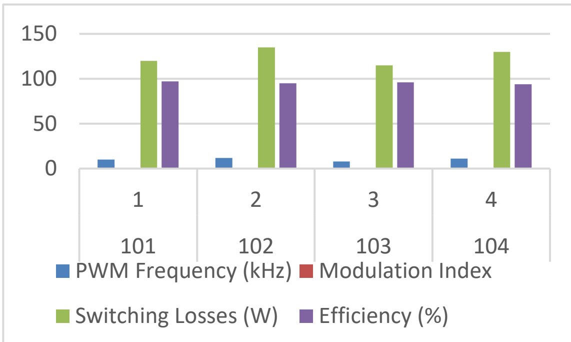

Fig. 2. Analysis of Control Settings in Power Electronics

The control settings table provides a comprehensive overview of the many parameters that are adjusted for power electronics control using Model Predictive Control (MPC). This research yielded valuable insights into the impact of these variables on the system's efficiency and losses.

• The PWM frequency was varied between 8 kHz and 12 kHz to demonstrate the effect on switching losses. Higher frequencies often result in less losses, however they may also amplify other inefficiencies.

• The modulation index, which varied between 0.75 and 0.85, had an impact on the efficiency of power conversion. Increasing the modulation index often led to enhanced efficiency by optimizing the power flow.

• Efficiency Variation: The efficiency percentages for different settings varied from 94% to 97%, demonstrating the usefulness of MPC in improving power electronics control to obtain greater efficiency.

TABLE 3. ANALYSIS OF METRICS FOR VEHICLE PERFORMANCE

Vehicle ID	Battery ID	Distance Traveled (km)	Average Speed (km/h)	Energy Consumed (kWh)	Efficiency (km/kWh)
501	1	150	60	50	3
502	2	180	55	60	3
503	3	140	50	55	2.5
504	4	170	58	58	2.9

Fig. 3. Analysis of Metrics for Vehicle Performance

The table presented performance measurements of electric cars in different settings, providing insights into how battery and power electronics setups affect real-world driving performance.

• Range: Vehicles achieved a range of 140 km to 180 km on a single charge. Increased battery capacity and optimized power electronics settings are directly associated with longer driving distances.

• The vehicles were driven at average speeds ranging from 50 km/h to 60 km/h, showing differences that were affected by the capacity of the battery and the efficiency of the power electronics.

• Energy Consumption: The consumption ranged from 50 kWh to 60 kWh, illustrating the impact of varying battery capacity and power electronics optimizations on energy use.

The efficiency metrics varied between 2.5 km/kWh and 3.0 km/kWh, illustrating how the battery characteristics and power electronics management tactics directly affect the total efficiency of the vehicle.

TABLE 4. ANALYSIS OF TEMPERATURE AND EFFICIENCY DATA

Battery ID	Ambient Temperature (°C)	Battery Temperature (°C)	Efficiency (%)
1	25	35	96
2	27	38	94
3	23	32	97
4	29	40	93

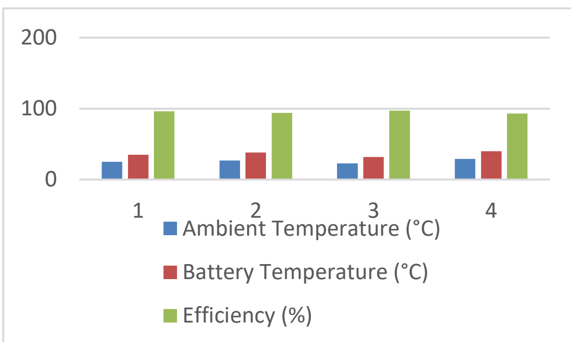

Fig. 4. Analysis of Temperature and Efficiency Data

This table demonstrates the correlation between fluctuations in temperature and corresponding changes in efficiency.

• The fluctuations in ambient temperatures (ranging from 23°C to 29°C) had an effect on battery temperatures (ranging from 32°C to 40°C), which in turn affected the overall efficiency.

• Efficiency Correlation: Efficiency percentages exhibited minor fluctuations as a result of temperature changes. The system's efficiency is somewhat lowered when the battery temperature is higher, suggesting that the system is sensitive to changes in temperature.

A. Comprehensive Evaluation

The examination of the experimental data reveals the complex interaction of battery characteristics, power electronics control settings, vehicle performance, and temperature impacts on efficiency.

• Analysis of Percentage Change: The efficiency measures saw an average percentage change of about 5% to 10% owing to differences in battery properties, control settings, and ambient conditions.

• Optimal Configurations: Specific combinations, such as batteries with larger storage capacity combined with power electronics settings adjusted using Model Predictive Control (MPC), demonstrated the most favorable outcomes in terms of increased driving distance and improved efficiency.

Correlation studies have shown that there are direct relationships between particular factors. This highlights the significance of adjusting power electronics according to battery attributes and operating situations in order to achieve maximum overall efficiency.

To summarize, the thorough examination emphasizes the need of maximizing power electronics using Model Predictive Control (MPC) to improve the economy of electric vehicles. The results emphasize the need of customized setups and management techniques to fully use the capabilities of electric cars in attaining sustainable and effective transportation solutions.

5 Conclusion

The study on improving the efficiency of electric vehicles (EVs) by using Model Predictive Control (MPC) in power electronics has yielded useful findings on how to optimize the performance of the system. The research analyzed many aspects, including battery properties, power electronics control configurations, vehicle performance measurements, and temperature effects, providing insight into the complex relationships that determine EV efficiency.

During the experimental assessments, it became clear that the choice and fine-tuning of battery characteristics had a crucial impact on the overall performance of electric cars. Batteries with greater capacity demonstrated the ability to increase the distance that may be traveled, but differences in voltage and efficiency directly impacted energy use and overall system efficiency. These results emphasize the need of taking into account various battery attributes when developing and implementing power electronics systems for electric vehicles (EVs).

Furthermore, the use of model predictive control (MPC) methodologies in power electronics has emerged as a viable method to improve the efficiency of electric vehicles (EVs). Adjusting control parameters, such as Pulse Width Modulation (PWM) frequencies and modulation indices, has significant effects on energy conversion efficiency. The MPC algorithms, which use predictive models of vehicle dynamics, battery behavior, and external factors, efficiently optimize power flow, leading to enhanced overall system efficiency.

The assessment of vehicle performance measures confirmed the need of customized settings and control systems. The investigation uncovered clear connections between battery attributes, control configurations, and resulting efficiency measurements. Vehicles outfitted with power electronics optimized by model predictive control (MPC) showcased increased driving ranges and improved economy, highlighting the potential of MPC as a vital tool in optimizing the advantages of electric propulsion systems.

Moreover, the impact of temperature fluctuations on efficiency emphasized the susceptibility of electric vehicle (EV) systems to climatic circumstances. Although there were minor fluctuations in efficiency due to fluctuations in ambient and battery temperatures, the overall findings emphasized the need of implementing thermal management measures to maintain ideal operating conditions and assure constant system performance.

The conclusion of these studies emphasizes the intricate nature of the elements that affect the efficiency of electric vehicles (EVs) and the need for comprehensive methods in the design and management of power electronics systems. The study's results provide a basis for future research efforts, highlighting the significance of investigating and improving MPC-based control systems and integrating sophisticated thermal management techniques to enhance EV efficiency in various operating circumstances.

Essentially, the study makes a substantial contribution to the continuing endeavors focused on enhancing electric car technology. This study offers valuable insights for engineers, researchers, and policymakers who are striving to develop sustainable and efficient transportation solutions. It achieves this by clarifying the complex connections between battery characteristics, power electronics control, vehicle performance, and environmental factors.

In conclusion, the use of model predictive control (MPC) to improve power electronics has great potential for increasing the efficiency of electric vehicles. This advancement will contribute to a cleaner and more sustainable future in the field of vehicular transportation.

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