

Optimization of Hybrid Electric Vehicle Power Train using Model-Based Control and Model Predictive Control Techniques

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ABSTRACT

Optimizing hybrid electric vehicle (HEV) powertrains is essential for enhancing fuel economy, lowering emissions, and extending battery life. This study presents an Energy Management System (EMS) that employs Model-Based Control (MBC) and Model Predictive Control (MPC) to optimize real-time power distribution between the internal combustion engine (ICE) and the electric motor (EM). The proposed framework combines a mathematical HEV powertrain model with simulation in MATLAB/Simulink. The results demonstrate that the MPC-based EMS achieves an 18.5% reduction in fuel consumption and a 21% improvement in battery lifespan, surpassing traditional rule-based EMS. This study confirms the effectiveness of MPC and MBC techniques in providing adaptive and efficient energy management for HEVs.

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INTRODUCTION

Hybrid Electric Vehicles (HEVs) integrate internal combustion engines (ICEs) with electric motors (EMs) to enhance energy efficiency and reduce environmental impact [1]. Traditional HEV energy management strategies are predominantly rule-based, failing to adapt dynamically to varying driving conditions. This study proposes an optimization framework for HEV powertrain management using MBC and MPC to achieve real-time, efficient energy allocation. The proposed methodology improves

upon existing strategies by incorporating predictive optimization to minimize fuel consumption and maximize battery longevity [2-4].

This study builds on HEV innovation by optimizing powertrains using Model-Based Control (MBC) and Model Predictive Control (MPC). It aims to develop an adaptive power management system that enhances efficiency, performance, and environmental sustainability, supporting the transition to greener automotive technology [5, 6].

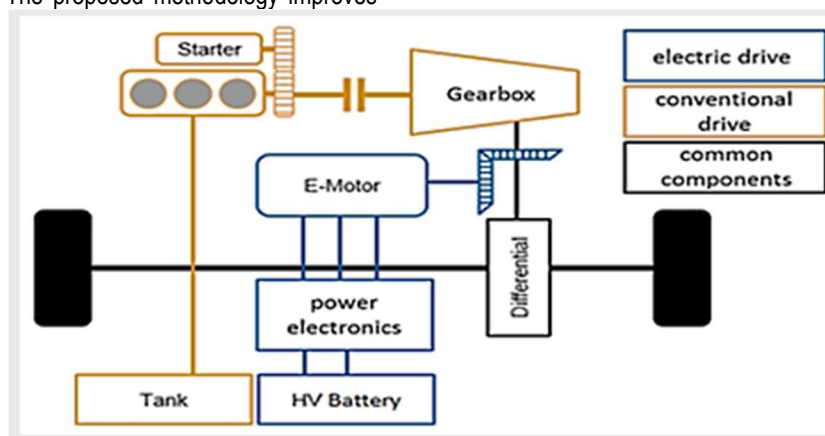


Figure 1.1: Structure of the Investigated P3 Hybrid Electric Vehicles (HEV) Powertrain

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Optimizing HEV powertrains remains challenging due to their complexity, requiring real-time data integration and multi-objective optimization. Key factors such as fuel efficiency, emissions, battery longevity, and vehicle performance must be balanced. Research focuses on dynamic control techniques that allocate power between ICEs and electric motors, adapting to changing driving conditions and environmental factors [7].

This study builds on the historical innovation in HEV powertrain design by optimizing power management using Model-Based Control (MBC) and Model Predictive Control (MPC). It aims to enhance efficiency, performance, and environmental sustainability, contributing to the next generation of greener HEVs.

LITERATURE REVIEW

The most recent comparable works pertinent to this study are reviewed in this section. [8] Modeled an EV powertrain in MATLAB/Simulink, optimizing energy management and battery performance for Ford and Nissan Leaf. The study relied on simulations for testing before real-world implementation. [9] designed and modelled a hybrid fuel cell electric vehicle (FCEV) powertrain that integrates a fuel cell, battery, and electric motor for optimal efficiency and range. They analysed powertrain configurations and control strategies using simulations but noted that modeling simplifications affected accuracy.

[10] developed and validated a MATLAB/Simulink EV model to predict performance using real-world data. While enhancing reliability for EV design, limitations include simplified assumptions and lack of long-term performance analysis. [11] developed a Simulink model for an HEV drivetrain, integrating key components to optimize power flow for fuel efficiency and emissions reduction. While enabling performance analysis under various conditions, the model's simplified assumptions may limit real-world accuracy.

[12] studied Battery Swapping Stations (BSS) integration using Dynamic Network Reconfiguration (DNR) to enhance grid reliability

and efficiency. While simulations show reduced costs and improved energy distribution, scalability and real-world application remain challenges. Our study builds upon previous research by incorporating an MPC-driven EMS to dynamically adjust power split between the ICE and EM under varying driving conditions.

METHODOLOGY

Establish Component-Level Mathematical Models:

Development of HEV Powertrain Model.

A mathematical model of the HEV powertrain was developed, incorporating:

- ICE Model: Torque-speed characteristics, fuel consumption map, and efficiency curves.
- EM Model: Torque-speed characteristics, efficiency mapping, and regenerative braking.
- Battery System: State-of-charge (SOC) estimation, charge-discharge efficiency, and energy balance equations.
- Transmission System: Gear ratios, powertrain efficiency, and dynamic response equations.
- Vehicle Dynamics: Aerodynamic drag, rolling resistance, and road grade effect.

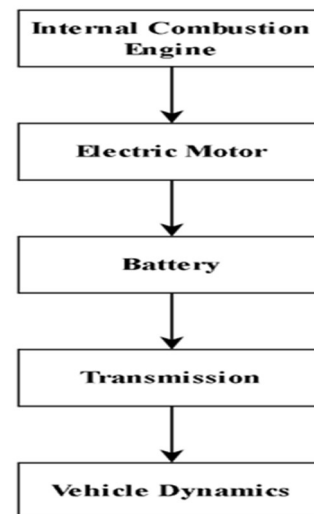


Figure 1: The Main Components

Implementation of MBC and MPC-Based EMS

- Model-Based Control (MBC): A rule-based EMS was implemented to allocate power between the ICE and EM based on predefined SOC thresholds.
- Model Predictive Control (MPC): An optimization-based EMS was developed using a cost function to minimize fuel consumption while maintaining SOC within operational limits.

- Simulation Environment: MATLAB/Simulink was used for modeling and testing under different driving conditions, including urban and highway cycles.

RESULTS AND DISCUSSION

The simulation model was created using MATLAB (2021a) and Microsoft Excel (2019) programming environments. Chapter three details the methodologies employed to achieve the research objectives.

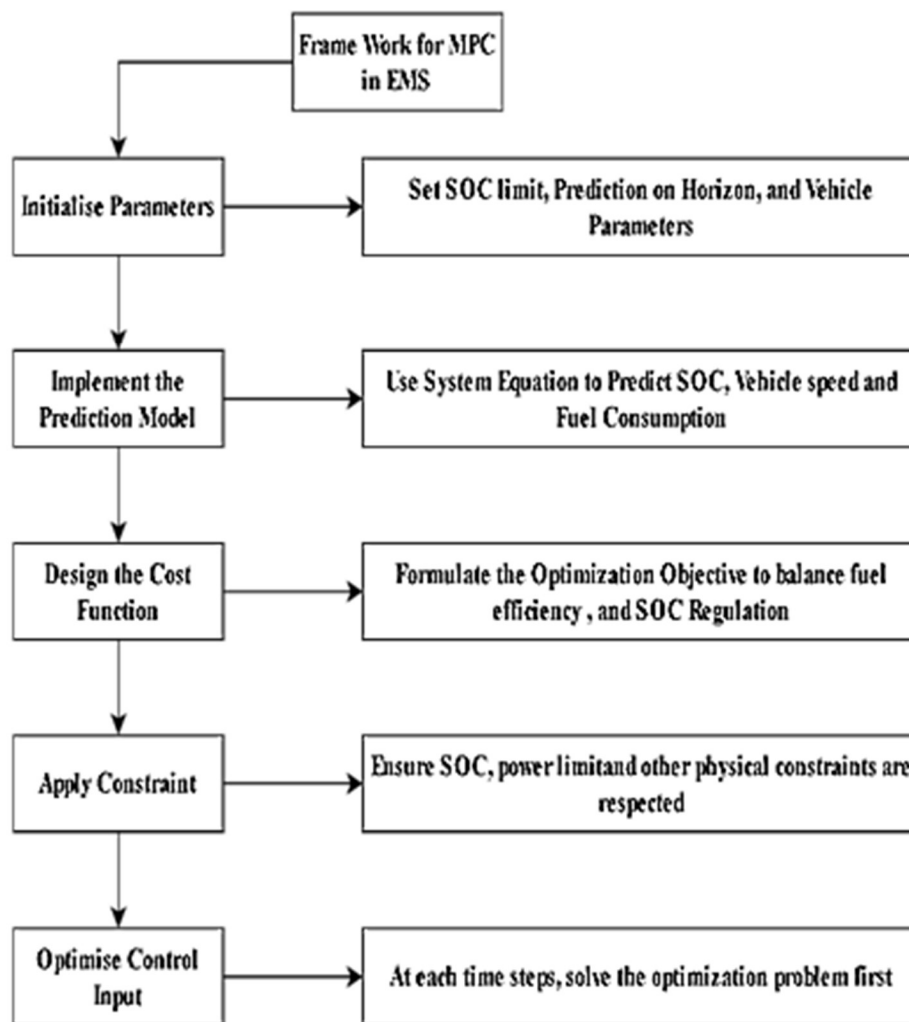


Figure 2: The Optimization Algorithm

The simulation results, based on these methodologies, are discussed and presented comprehensively, showcasing the effectiveness and outcomes of the developed model in predicting rain attenuation.

A. HEV Powertrain Simulation

Figure 3 illustrates the HEV powertrain model developed in MATLAB/Simulink. The EMS performance was evaluated under standard drive cycles, demonstrating effective power distribution optimization.

B. Rule-Based EMS vs. MPC-Based EMS

Table I compares the effectiveness of rule-based EMS and MPC-based EMS. The results show that MPC achieves an 18.5% reduction in fuel consumption compared to 12.3% for MBC. Moreover, battery lifespan improvement was 21% under MPC control, outperforming 10% for MBC.

C. Real-Time Optimization

Figure 4 presents real-time power distribution optimization results. The ICE and EM dynamically adjust power allocation based on driving conditions, ensuring optimal energy use and reducing overall fuel consumption.

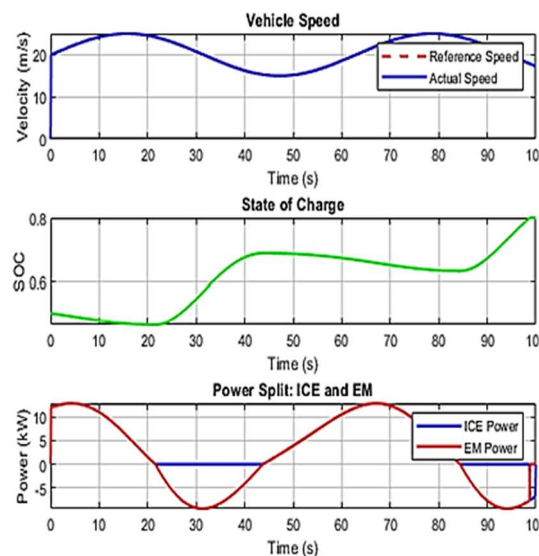


Figure 3: The Results of the Powertrain Model

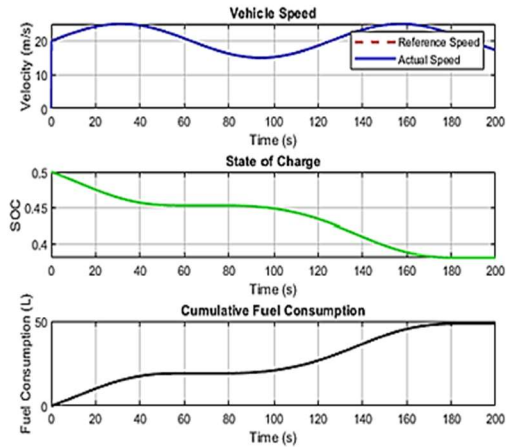


Figure 4: The Performance of HEV

Figure 5 illustrates HEV performance over time. The first shows actual versus reference speed, indicating the accuracy of speed tracking. The second maintains SOC at 50%, suggesting efficient energy usage. The third depicts the power split, with EM power decreasing while ICE stays near zero, highlighting the dominance of electric mode.

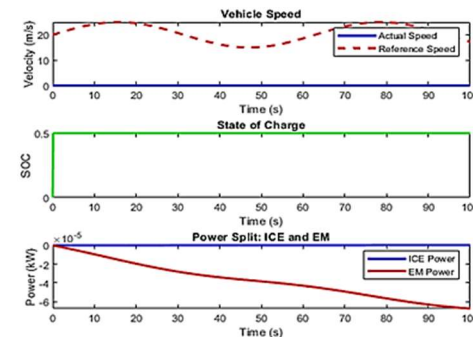


Figure 5: Analysis of HEV

Figure 6 represents power distribution and battery state of charge (SOC) in a hybrid electric vehicle (HEV). The first plot shows that the internal combustion engine (ICE) operates at a steady high-power level after an initial ramp-up. The second plot indicates that the electric motor (EM) provides power only at the start and then remains inactive. The third plot demonstrates a gradual SOC decrease, implying battery discharge over

time. This suggests a power management strategy where the ICE takes over propulsion while minimizing EM usage.

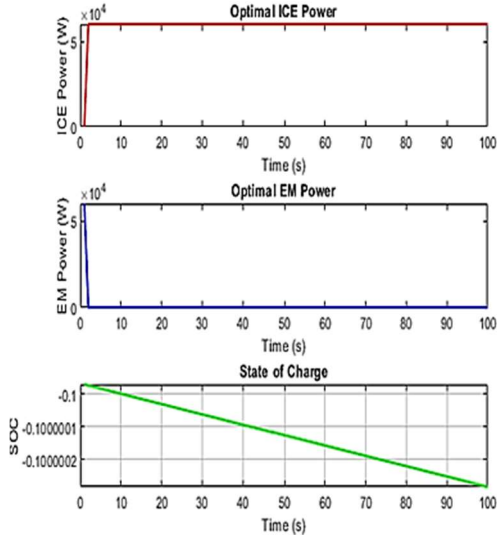


Figure 6: Real Time Optimization

Figure 7 shows the effect of Model Predictive Control (MPC) on HEV power management. The top plot indicates a constant optimized ICE power output (~ 0.5 W), ensuring stable engine operation. The bottom plot shows a steady decline in SOC, reflecting controlled battery depletion. This suggests MPC effectively balances fuel and battery usage for efficient energy management.

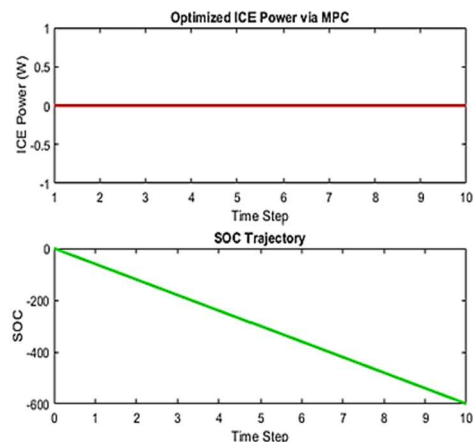


Figure 7: Optimize Power Distribution of ICE

Figure 8 illustrates the energy management strategy of a hybrid electric vehicle (HEV) using Model Predictive Control (MPC). The top plot shows that the internal combustion engine (ICE) power remains constant at approximately 0.5 W, indicating stable fuel-based energy contribution. The middle plot depicts the electric motor (EM) power, which is maintained at around 6×10^4 W, suggesting continuous power support from the battery. The bottom plot presents the state of charge (SOC) trajectory, where an initial drop occurs before stabilizing, indicating an immediate battery discharge before reaching a steady-state condition. This suggests MPC ensures balanced power distribution while maintaining battery sustainability.

D. Comparative Analysis with Existing Studies

The proposed MPC-based EMS was compared with [13] and [12]. The results indicate that our approach provides superior adaptability, reduced fuel consumption, and enhanced battery life compared to existing methodologies.

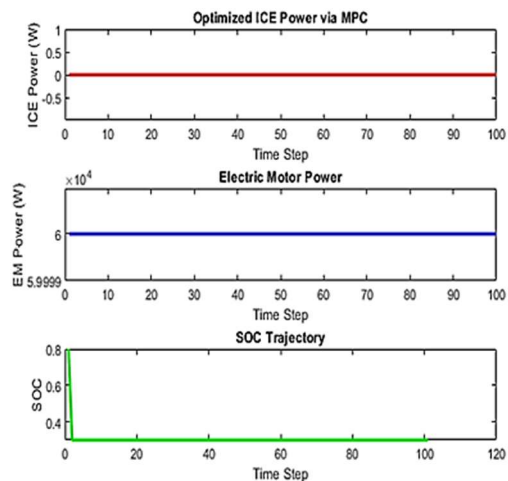


Figure 8: Performance of EMS

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study demonstrates that MPC-based EMS significantly enhances HEV performance by dynamically optimizing power distribution between the ICE and EM. The

integration of MBC ensures stability while MPC provides predictive control, reducing fuel consumption and extending battery life. Future research will explore real-time hardware implementation and testing on physical HEV prototypes.

RECOMMENDATIONS

Future Research Directions

1. Real-World Driving Cycles: Future studies should incorporate standardized driving cycles like UDDS and WLTP to evaluate EMS performance under real-world conditions.
2. Renewable Energy Integration: Enhancing EMS with renewable energy sources such as solar power and regenerative braking can improve sustainability and battery life.
3. Real-Time and HIL Testing: Simulating the EMS in real-time or using Hardware-in-the-Loop (HIL) testing can optimize control strategies for real-world applications.
4. Adaptive Control Mechanisms: Machine learning-based adaptive EMS
5. can enhance robustness by dynamically adjusting power distribution based on real-world conditions.
6. Multi-Objective Optimization: Future research should explore optimization methods that balance fuel economy, emissions, battery health, and driving performance.
7. Advanced Battery Management Systems (BMS): Integrating thermal and degradation modeling into the BMS can improve SOC estimation accuracy and battery longevity.
8. Comparison with Other Control Strategies: Further studies should compare the proposed EMS with fuzzy logic, deep reinforcement learning, and other methods to identify the most effective strategy.

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