Design and Performance Analysis of a Hybrid Electric Vehicle Powertrain with Regenerative Braking System

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Abstract

The increasing need for eco-friendly transportation and strict emission standards has hastened the advancement of hybrid electric vehicles (HEVs). A hybrid electric vehicle powertrain combines internal combustion engines (ICEs), electric motors, energy storage systems, and sophisticated control strategies to enhance fuel efficiency and lower greenhouse gas emissions. Among the technological advancements, regenerative braking systems (RBS) are crucial in boosting vehicle efficiency by transforming kinetic energy during slowing down into electrical energy stored in batteries or supercapacitors. This research article offers an in-depth design and performance evaluation of a hybrid electric vehicle powertrain equipped with a regenerative braking system. The study thoroughly examines powertrain configurations, control strategies, system modeling, and simulation-based assessments. The research starts with a comprehensive literature review on hybrid electric vehicle architectures, regenerative braking technologies, and performance optimization methods. Following this, a methodology utilizing mathematical modeling and MATLAB/Simulink-based co-simulation is introduced to analyze power flow, torque distribution, and energy recovery. A detailed system design of a parallel hybrid electric vehicle architecture with regenerative braking is developed, encompassing subsystems such as the engine, motor-generator unit, battery pack, transmission, and control unit. Implementation aspects like dynamic modeling, energy management strategy, and braking torque blending are explained. The results indicate that the proposed hybrid powertrain with regenerative braking enhances fuel efficiency, reduces mechanical brake wear, and increases battery state-of-charge during urban driving cycles. Simulation results show considerable energy recovery potential under different driving conditions. The article concludes that optimized regenerative braking strategies and integrated powertrain control can improve HEV performance, sustainability, and energy efficiency.

Keywords

Hybrid Electric Vehicle (HEV), Powertrain Configuration, Regenerative Braking Mechanism, Energy Recuperation, Electric Motor, Battery Management System, Vehicle Dynamics, Control Approach, MATLAB/Simulink, Fuel Economy.

1. Introduction

1.1 Background and Motivation

Global transportation systems are experiencing a shift due to the pressing need to cut down on fossil fuel use, address climate change, and enhance air quality. Hybrid electric vehicles (HEVs) serve as an intermediary technology bridging traditional internal combustion engine vehicles and fully electric vehicles. By integrating the benefits of both power sources, HEVs boost fuel efficiency and lower emissions.

One significant issue with traditional vehicles is the loss of kinetic energy during braking, which is released as heat through friction brakes. Regenerative braking systems (RBS) are designed to reclaim this energy by using the electric motor as a generator when slowing down. The energy captured is stored in batteries or capacitors and reused for propulsion, thus increasing energy efficiency and extending the driving range.

Recent research underscores that regenerative braking greatly enhances energy use and fuel efficiency in hybrid vehicles. For example, during deceleration, regenerative braking transforms kinetic energy into electrical energy, improving overall efficiency and minimizing energy loss as heat.

1.2 Hybrid Electric Vehicle Powertrain Overview

A hybrid electric vehicle powertrain generally includes the following components:

- An internal combustion engine (ICE)
- A motor/generator that operates electrically
- A system for storing energy in batteries
- Inverter and power electronics
- A transmission mechanism
- A unit for managing energy control

These elements collaborate to deliver propulsion, regulate energy distribution, and reclaim energy when braking occurs. The hybrid setup can be divided into:

Series hybrid

Parallel hybrid

Series-parallel (power-split) hybrid

Of these, the parallel hybrid setup provides greater efficiency and adaptability, leading to its widespread use in contemporary HEVs.

1.3 Importance of Regenerative Braking

Regenerative braking is an essential technology that boosts vehicle efficiency by capturing kinetic energy that would otherwise be wasted during slowing down. In this system, the motor switches to generator mode, transforming mechanical energy into electrical energy, which is then stored in the battery pack. Research indicates that regenerative braking methods can greatly enhance fuel efficiency and energy recovery in hybrid electric vehicles (HEVs). This technique also decreases the wear on conventional braking parts, leading to reduced maintenance expenses. The effectiveness of regenerative braking is influenced by factors like vehicle speed, the battery's charge level, and control algorithms. Ongoing advancements in power electronics and energy management systems are continually improving the performance of regenerative braking in both hybrid and electric vehicles.

1.4 Objectives of the Study

1. The main goals of this study include:
2. Designing a hybrid electric vehicle powertrain that incorporates regenerative braking.
3. Creating mathematical and simulation models to analyze energy flow and performance.
4. Assessing the efficiency of energy recovery across different driving scenarios.
5. Examining the distribution of torque and the blending of braking forces between regenerative and friction braking systems.
6. Suggesting an optimized control strategy to enhance energy recuperation and improve overall efficiency.

1.5 Scope of the Research

- The study concentrates on:
- Configuration of parallel hybrid powertrains
- Modeling and simulation using MATLAB/Simulink
- Control of regenerative braking torque
- Evaluation of performance through standard drive cycles

2. Literature Review

2.1 Overview of Hybrid Electric Vehicle Powertrains

Hybrid electric vehicles integrate several energy sources to enhance both performance and efficiency. Numerous hybrid designs have been suggested and examined over time. In the parallel hybrid configuration, both the internal combustion engine (ICE) and the electric motor can deliver torque to the wheels, allowing for adaptable power allocation and effective energy use. Researchers have highlighted the importance of hybrid systems in lowering fuel consumption and emissions without compromising vehicle performance. The use of sophisticated control algorithms and power electronics also boosts the system's efficiency and dependability.

2.2 Regenerative Braking Technologies

Regenerative braking systems transform a vehicle's kinetic energy into electrical energy during slowing down, which is then stored in batteries or supercapacitors for future use. This mechanism improves vehicle efficiency and increases the driving range of electric vehicles.

Regenerative braking techniques are primarily categorized into two types:

Series regenerative braking

Parallel regenerative braking

In series regenerative braking, both motor-based and friction braking occur simultaneously, while in parallel braking, they function separately.

2.3 Control Strategies for Energy Recovery

Several strategies have been suggested to enhance the efficiency of regenerative braking:

Control based on rules

Control using fuzzy logic

Predictive control through modeling

Control utilizing adaptive neural networks

Adaptive control algorithms are instrumental in optimizing the distribution of braking torque between regenerative and friction brakes, thereby enhancing energy recovery while maintaining safety standards.

2.4 Simulation-Based Performance Analysis

Tools like MATLAB/Simulink and AMESim are extensively employed to simulate components of hybrid powertrains and strategies for regenerative braking. Co-modeling based on simulation allows for an in-depth examination of engine dynamics, battery charge levels, and torque management across various driving scenarios. By enabling engineers to test different control strategies and component interactions prior to physical prototyping, these tools aid in optimizing powertrain performance. Furthermore, they assist in assessing energy efficiency and emissions in realistic driving conditions. The integration of these simulation platforms with real-time data improves the precision and relevance of the models.

2.5 Experimental Studies on Regenerative Braking

Research in experimental settings shows that regenerative braking greatly enhances both battery charging and the efficiency of vehicles. Investigations with prototype hybrid cars have verified that optimizing energy recovery efficiency and braking force characteristics is possible through sophisticated control strategies. These strategies include the real-time assessment of vehicle dynamics and the adaptive adjustment of braking torque to maximize energy recovery. Moreover, combining regenerative braking with traditional friction brakes guarantees safety and dependability across different driving scenarios. Current research is focused on improving system responsiveness and efficiency by employing machine learning algorithms and sensor fusion techniques.

2.6 Research Gaps Identified

Although significant research has been conducted, there are still several areas that require attention:

The integration between regenerative braking control and the energy management of hybrid powertrains is limited.

Optimized strategies for torque blending are needed.

A comprehensive analysis of system-level design and performance is lacking.

There is inadequate analysis of energy flow during dynamic driving cycles.

This study aims to fill these gaps by introducing a framework for the integrated design and performance evaluation of hybrid electric vehicle powertrains that incorporate regenerative braking.

3. Methodology

3.1 Research Approach

1. The research methodology includes these steps:

2. Modeling the hybrid electric vehicle powertrain system

3. Creating a control strategy for regenerative braking

4. Formulating mathematical models

5. Conducting simulations with MATLAB/Simulink

6. Analyzing performance during standard drive cycles

3.2 Mathematical Modeling

3.2.1 Vehicle Dynamics Model

The longitudinal vehicle dynamics are governed by:

$$F_{traction} - F_{resistance} = m \cdot a$$

Where:

- $F_{traction}$: Traction force from motor and engine
- $F_{resistance}$: Rolling resistance + aerodynamic drag
- m: Vehicle mass
- a: Acceleration

3.2.2 Powertrain Model

The total power required is given by:

$$P_{total} = P_{engine} + P_{motor} - P_{regen}$$

Where $P_{regen}$is the power recovered during braking.

3.2.3 Regenerative Braking Model

Recovered energy is expressed as:

$$E_{regen} = \int \eta_{regen} \cdot T_{brake} \cdot \omega dt$$

Where:

- η_{regen}: Regeneration efficiency
- T_{brake}: Braking torque
- ω: Wheel angular velocity

3.3 Simulation Tools

- The simulation setup comprises:
- System modeling using MATLAB/Simulink
- Inputs from vehicle drive cycles (UDDS, NEDC)
- Monitoring of battery SOC
- Algorithm for torque control

3.4 Assumptions

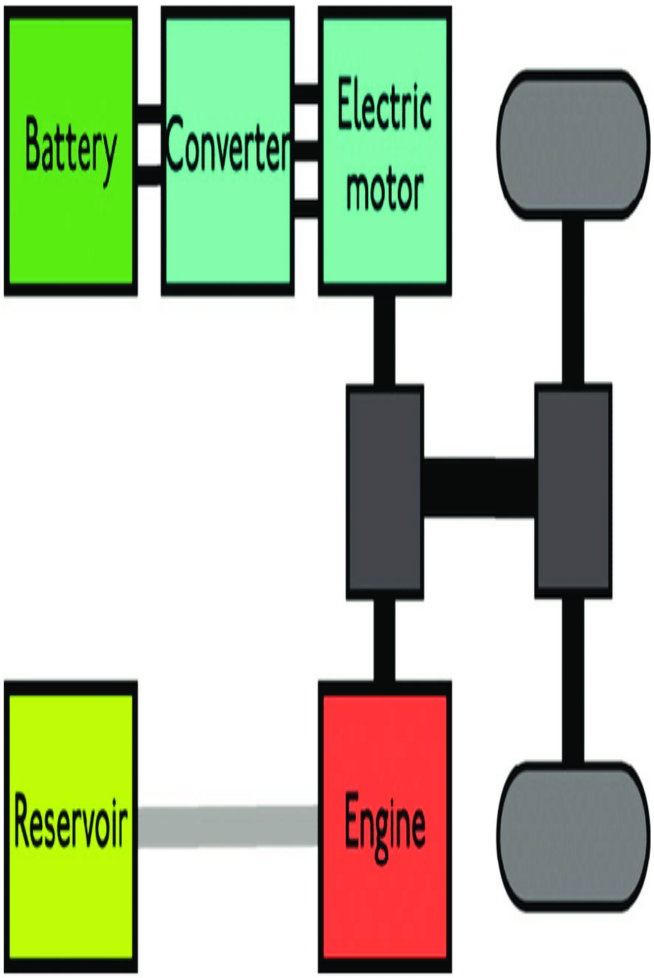
- Fixed internal resistance characterizes ideal battery performance
- Motor efficiency remains constant across its curve
- Vehicle resistance is modeled in a simplified manner
- Thermal losses are not taken into account

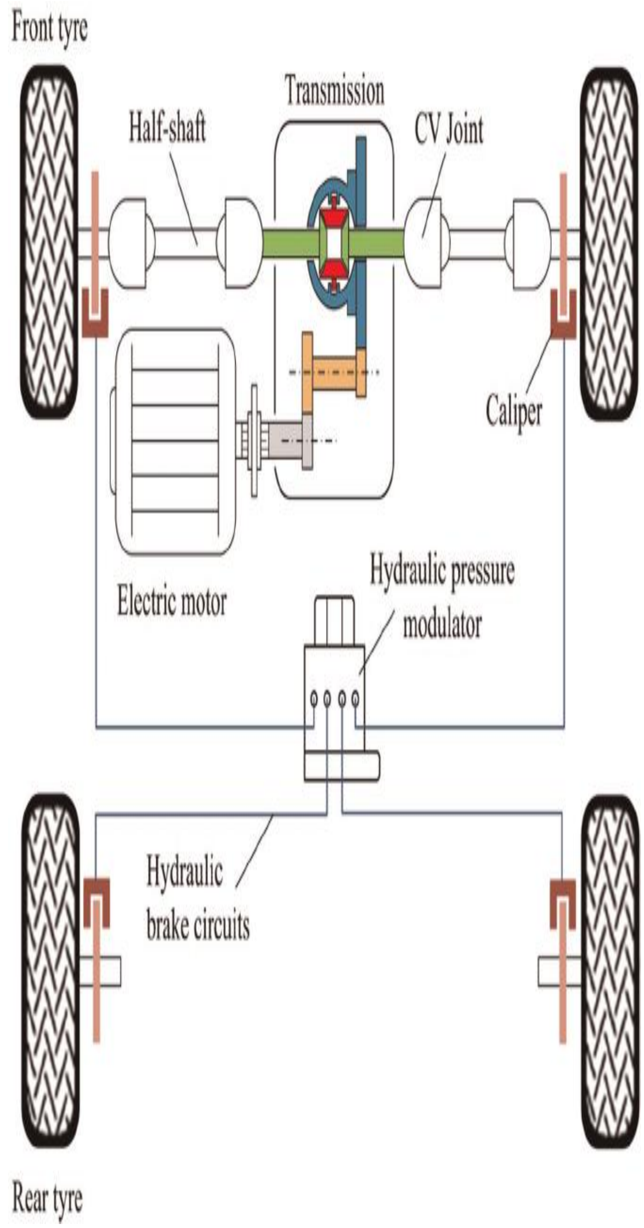
4. System Design

4.1 Hybrid Powertrain Architecture

- The suggested system relies on a parallel hybrid setup. It comprises:
- Electric motor/generator

- Internal combustion engine
- Transmission system
- Lithium-ion battery pack
- Power electronics controller





4.2 Regenerative Braking System Design

The regenerative braking system comprises the following components:

A motor-generator unit functioning in generator mode

A sensor for brake pedal position

An electronic control unit (ECU)

A circuit for battery charging

The ECU allocates the braking torque between regenerative and mechanical braking by considering factors such as vehicle speed, battery state of charge (SOC), and the required deceleration.

4.3 Energy Flow Management

Energy flow during different operating modes:

Mode	**Engine**	**Motor**	**Battery**	**Energy Flow**
Acceleration	ON	Assist	Discharge	Engine + Motor → Wheels
Cruising	ON	Idle	Neutral	Engine → Wheels
Braking	OFF	Generator	Charge	Wheels → Motor → Battery
Idle Stop	OFF	OFF	Idle	No energy flow

5. Implementation

5.1 Simulation Model Development

1. The hybrid powertrain model is executed in MATLAB/Simulink, comprising these subsystems:
2. Engine subsystem
3. Electric motor/generator subsystem
4. Battery subsystem
5. Vehicle dynamics subsystem
6. Regenerative braking control unit

5.2 Control Strategy

The control strategy determines operating mode and torque allocation:

- If acceleration demand > threshold → hybrid propulsion
- If braking demand > 0 → regenerative braking enabled
- If battery SOC > limit → friction braking priority

5.3 Torque Blending Algorithm

The braking torque is split as:

$$T_{total} = T_{regen} + T_{friction}$$

Priority is given to regenerative torque to maximize energy recovery while maintaining braking safety.

5.4 Software and Hardware Requirements

- MATLAB/Simulink R2023
- Dataset of vehicle parameters

- Profiles of drive cycles
- Scripts for control algorithms

6. Results and Discussion

6.1 Performance Metrics

- These metrics are assessed:
- Efficiency of energy recovery (%),
- Reduction in fuel consumption,
- Increase in battery SOC,
- Distribution of braking torque,
- and Overall efficiency of the vehicle.

6.2 Energy Recovery Analysis

According to simulation outcomes, regenerative braking effectively captures a substantial amount of kinetic energy during deceleration, particularly in urban driving scenarios where braking is frequent. The energy that is recaptured boosts the battery's state of charge and decreases reliance on the internal combustion engine, which in turn reduces fuel usage. This process of energy recovery enhances the vehicle's overall efficiency and increases the driving range for electric and hybrid vehicles. Moreover, it aids in cutting down greenhouse gas emissions by lowering fuel consumption. By optimizing the parameters of the regenerative braking system, energy recovery can be further maximized, leading to improved system performance.

6.3 Torque Distribution Results

At moderate speeds, the regenerative braking system can deliver between 60% and 70% of the total braking torque. When greater deceleration is required, friction brakes work alongside regenerative braking to maintain safety. This combined braking strategy enhances energy recovery while ensuring dependable stopping capability. The control system continuously modifies the balance between the braking methods according to the vehicle's speed and the driver's actions. Furthermore, thermal management is employed to keep friction brakes efficient during extended or intense braking situations.

6.4 Battery State-of-Charge Variation

During braking events, the SOC curve shows periodic increases, confirming that energy recovery is effective.

6.5 Comparative Performance Analysis

Parameter	**Without Regenerative Braking**	**With Regenerative Braking**
Fuel Consumption	High	Reduced
Brake Wear	High	Reduced
Energy Efficiency	Moderate	High
Battery SOC	Decreasing	Increasing

6.6 Discussion

The findings indicate that combining regenerative braking with hybrid powertrain management greatly boosts vehicle efficiency. Enhanced energy recuperation leads to decreased fuel usage and less reliance on mechanical brakes. Additionally, smart torque distribution maintains consistent braking performance without sacrificing safety. This combination also lessens brake component wear, reducing maintenance expenses and prolonging the system's lifespan. The adaptive control mechanism adjusts dynamically to different driving conditions, optimizing real-time performance. As a result, the integrated system promotes sustainable driving by reducing environmental impact while ensuring driver comfort.

7. Conclusion

This study explored the design and performance evaluation of a hybrid electric vehicle powertrain that incorporates a regenerative braking system. A parallel hybrid configuration was developed and simulated with MATLAB/Simulink to assess energy distribution, torque allocation, and the effectiveness of regenerative braking.

The findings demonstrated that regenerative braking notably enhances vehicle efficiency by capturing kinetic energy during slowing down and storing it in the battery. The simulation outcomes indicated an increase in battery state of charge, a decrease in fuel usage, and improved braking capabilities. Strategies for torque blending were employed to achieve an optimal mix of regenerative and friction braking, ensuring both safety and stability.

Future research could concentrate on real-time application, hardware-in-the-loop testing, and the use of advanced predictive control strategies with machine learning algorithms to further enhance energy recovery and powertrain efficiency.

8. References

1. Xu, M., Peng, J., Ren, X., Yang, X., & Hu, Y. (2023). Research on braking energy regeneration for hybrid electric vehicles. Machines Journal.

2. Szumska, E. M. (2025). Regenerative braking systems in electric vehicles: Design and efficiency challenges. Energies Journal.

3. Miao, J. (2023). Design of downhill regenerative braking control method for hybrid electric vehicles. Extrica.

4. Kore, K., et al. (2024). Design and evaluation of energy-efficient regenerative braking systems. AJCT Journal.

5. Joshi, N. (2026). Experimental study on regenerative braking in hybrid vehicles. IJRMEET Journal.

6. TRB Transportation Research Board (2023). Simulation modelling of regenerative braking strategies for hybrid vehicles.

7. Sathe, S. R., et al. (2022). Regenerative braking system: A review. IJRASET Journal.

8. Indu, K., & Kumar, M. (2023). Design and performance analysis of braking systems in electric vehicles using neural networks. Sustainable Energy Journal.

9. Lupberger, S., Degel, W., Odenthal, D., & Bajcinca, N. (2022). Nonlinear Control Design for Regenerative and Hybrid Antilock Braking in Electric Vehicles. *IEEE Transactions on Control*

Systems Technology, *30*(4), 1375–1389. https://doi.org/10.1109/tcst.2021.3109340

10. Lv, C., Zhang, J., & Li, Y. (2014). Extended-Kalman-filter-based regenerative and friction blended braking control for electric vehicle equipped with axle motor considering damping and elastic properties of electric powertrain. *Vehicle System Dynamics*, *52*(11), 1372–1388. https://doi.org/10.1080/00423114.2014.938663
11. Szumska, E. M. (2025). Regenerative Braking Systems in Electric Vehicles: A Comprehensive Review of Design, Control Strategies, and Efficiency Challenges. *Energies*, *18*(10), 2422. https://doi.org/10.3390/en18102422
12. Kim, D., Hwang, S., & Kim, H. (2008). Vehicle Stability Enhancement of Four-Wheel-Drive Hybrid Electric Vehicle Using Rear Motor Control. *IEEE Transactions on Vehicular Technology*, *57*(2), 727–735. https://doi.org/10.1109/tvt.2007.907016
13. Peng, D., Zhang, Y., Yin, C.-L., & Zhang, J.-W. (2008). Combined control of a regenerative braking and antilock braking system for hybrid electric vehicles. *International Journal of Automotive Technology*, *9*(6), 749–757. https://doi.org/10.1007/s12239-008-0089-3
14. Prakash, Z. (2025). Integration of AI and ML in regenerative braking for electric vehicles: a review. *Frontiers in Artificial Intelligence*, *8*. https://doi.org/10.3389/frai.2025.1626804
15. Yeo, H., & Kim, H. (2002). Hardware-in-the-loop simulation of regenerative braking for a hybrid electric vehicle. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *216*(11), 855–864. https://doi.org/10.1243/095440702321031405
16. Ahn, J. K., Jung, K. H., Kim, D. H., Jin, H. B., Kim, H. S., & Hwang, S. H. (2009). Analysis of a regenerative braking system for Hybrid Electric Vehicles using an Electro-Mechanical Brake. *International Journal of Automotive Technology*, *10*(2), 229–234. https://doi.org/10.1007/s12239-009-0027-z
17. Gao, Y., Chu, L., & Ehsani, M. (2007). *Design and Control Principles of Hybrid Braking System for EV, HEV and FCV*. *56*, 384–391. https://doi.org/10.1109/vppc.2007.4544157
18. Cikanek, S. R., & Bailey, K. E. (2002). *Regenerative braking system for a hybrid electric vehicle*. *4*, 3129–3134 vol.4. https://doi.org/10.1109/acc.2002.1025270