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Intelligent Energy Optimization of Electric Vehicles Using Coordinated Regenerative Braking and Advanced Control Strategies

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Abstract: Improving energy efficiency remains a critical challenge in the development of electric vehicles (EVs), particularly under real-world driving conditions where braking events significantly influence overall energy consumption. Regenerative braking systems offer an effective solution by converting vehicle kinetic energy into electrical energy during deceleration; however, their performance is strongly dependent on braking force coordination, control strategy design, and power electronic interfaces. Previous studies have investigated braking force coordination for in-wheel motor–driven EVs using electro-hydraulic composite braking systems to enhance stability and energy recovery. Additional research has explored alternative energy recovery mechanisms such as regenerative suspension systems, demonstrating the feasibility of harvesting vibration energy to complement regenerative braking. Advanced modeling and simulation approaches have been proposed to accurately evaluate EV energy efficiency under practical driving conditions braking effectiveness. Fuzzy logic–based approaches, have shown significant potential in optimizing regenerative braking torque distribution, improving braking smoothness, and maximizing energy recovery under system uncertainties. Synchronization control strategies for distributed drive electric vehicles further contribute to coordinated regenerative braking and improved system robustness.

Keywords*:* Electric vehicles, regenerative braking, energy optimization, intelligent control strategies, braking force coordination, bidirectional power converters, fuzzy logic control, neural control, energy management systems

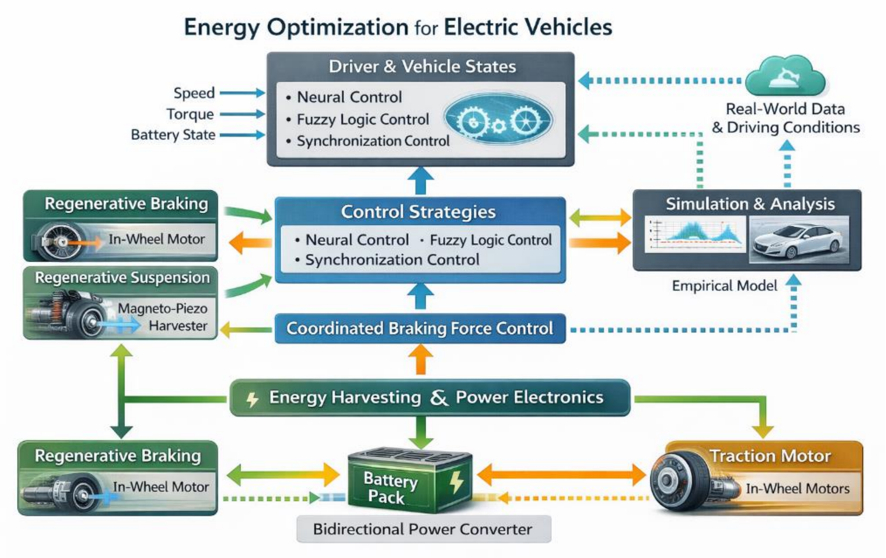
I. INTRODUCTION

Electric vehicles (EVs) are widely regarded as a sustainable alternative to conventional internal combustion engine vehicles due to their ability to reduce greenhouse gas emissions and improve energy efficiency. Despite these advantages, limitations such as restricted driving range and inefficient energy utilization continue to impede their large-scale adoption. Consequently, significant research efforts have focused on developing advanced energy optimization and recovery techniques to enhance overall vehicle performance and efficiency.

Regenerative braking is a key technology for improving EV energy efficiency by converting kinetic energy into electrical energy during deceleration. Its effectiveness largely depends on proper coordination between electrical and mechanical braking systems, as poor coordination can reduce energy recovery and compromise safety. Advanced braking force coordination strategies, particularly for in-wheel motor–driven EVs with electro-hydraulic composite braking systems, have demonstrated improvements in braking stability and regenerative performance. Additionally, complementary energy recovery approaches such as regenerative suspension systems using magneto–piezo energy harvesters further contribute to overall energy optimization.[1][6]

To enhance regenerative braking performance under varying operating conditions, advanced control techniques have been widely explored. Neural inverse optimal control methods enable efficient torque distribution and improved energy recovery, while fuzzy logic–based control strategies provide robustness against nonlinearities and uncertainties, ensuring smoother braking and better energy utilization. Furthermore, synchronization control strategies in distributed drive EVs help coordinate multiple motors, improving system stability and regenerative efficiency. Power electronic advancements, particularly in bidirectional converters, also play a critical role by enabling efficient energy transfer between motors and energy storage systems.[2]

Accurate evaluation of these energy optimization strategies requires realistic modeling and simulation based on real-world driving conditions. Empirically validated simulation methods using tracking data provide reliable frameworks for assessing system performance. Motivated by these advancements, this paper proposes an intelligent energy optimization approach based on coordinated regenerative braking and advanced control strategies. The proposed method aims to maximize energy recovery while maintaining braking safety and system reliability, and its effectiveness is validated through simulation under various operating conditions.[4][7][9][8]



II. LITERATURE REVIEW

Sr.no.	Author & Citation	Method Used	Advantages	Disadvantage	Key Findings
1.	Zhang et al. [1]	Braking force coordination using electro-hydraulic composite braking for in-wheel motor EVs	Improves braking stability and regenerative energy recovery	Increased system complexity and control coordination	Coordinated braking enhances safety and regenerative efficiency
2.	Li et al. [2]	Magneto–piezoelectric energy harvesting from vehicle suspension	Additional energy recovery without affecting braking system	Low harvested power and higher system cost	Regenerative suspension can supplement EV energy recovery
3.	Mokgonyana et al. [3]	Empirical simulation of EV efficiency using real-world tracking data	Accurate energy consumption estimation under real driving conditions	Requires extensive real-world data	Realistic driving data improves efficiency prediction accuracy

4.	Hu et al. [4]	Neural inverse optimal control for regenerative braking	Adaptive control improves braking torque optimization	High computational complexity and training requirements	Neural control enhances regenerative braking performance

III. METHODOLOGY / MATERIALS AND METHODS

A. *System Overview*

The proposed methodology focuses on an intelligent energy optimization framework for electric vehicles (EVs) integrating coordinated regenerative braking, advanced control strategies, and efficient power electronic systems. The system consists of key subsystems including the traction motor (in-wheel motor), battery pack, bidirectional power converter, electro-hydraulic braking system, regenerative suspension module, and a centralized control unit. The objective is to maximize energy recovery during braking while ensuring vehicle stability, safety, and efficient energy utilization under varying driving conditions.[1][5]

B. *Vehicle Dynamic Modelling*

A mathematical model of the electric vehicle is developed to simulate real-world driving behavior. The longitudinal vehicle dynamics are expressed as:

$$F_{trac} = m \cdot a + F_{roll} + F_{aero} + F_{grade}$$

where F_{trac} is the traction force, m is vehicle mass, a is acceleration, F_{roll} is rolling resistance, F_{aero} is aerodynamic drag, and F_{grade} is gradient resistance.

The braking force distribution between front and rear wheels is modeled to maintain vehicle stability and prevent wheel lock conditions. Tire-road interaction is also considered using slip ratio-based modeling to ensure realistic braking performance.[3][6]

C. *Regenerative Braking Model*

The regenerative braking system converts kinetic energy into electrical energy through the in-wheel motor operating in generator mode. The regenerative braking torque T_{regen} is defined as:

$$T_{regen} = k \cdot \omega$$

where k is a motor constant and ω is the angular velocity of the wheel.
A braking force coordination strategy is implemented to optimally distribute braking demand between regenerative braking and mechanical braking. Priority is given to regenerative braking within motor and battery limits, while mechanical braking is applied when additional braking force is required or during low-speed conditions.[1][6]

D. *Coordinated Braking Force Control Strategy*

A hierarchical control architecture is used for braking force coordination:

- Upper-Level Controller: Determines total braking demand based on driver input and vehicle state.
- Middle-Level Controller: Allocates braking force between front and rear axles to ensure stability.
- Lower-Level Controller: Distributes braking torque between regenerative and hydraulic braking systems.
- Constraints such as battery state of charge (SOC), motor limits, and safety requirements are incorporated. The control strategy ensures smooth braking, maximized energy recovery, and compliance with safety regulations.[1][8]

E. *Advanced Control Techniques*

To enhance system performance under nonlinear and uncertain conditions, intelligent control methods are implemented:

- Neural Network Control: Used to optimize torque distribution by learning system behavior from training data.

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- Fuzzy Logic Control: Handles uncertainties and nonlinearities by defining rule-based control actions for braking force allocation.
- Synchronization Control: Ensures coordinated operation of multiple in-wheel motors, improving stability and efficiency.

These controllers are integrated into the braking coordination framework to provide adaptive and robust performance.[2][5]

F. Energy Harvesting and Power Electronics

A bidirectional DC–DC converter is employed to manage energy flow between the motor and the battery pack. During regenerative braking, the converter operates in charging mode to store recovered energy.

Additionally, a regenerative suspension system based on magneto–piezoelectric energy harvesting is incorporated to capture vibration energy. This recovered energy supplements the battery, contributing to overall system efficiency.[5]

G. Battery and Energy Management System

The battery is modeled using a lithium-ion equivalent circuit model, considering parameters such as open-circuit voltage, internal resistance, and SOC. The energy management system (EMS) monitors battery conditions and regulates charging/discharging to ensure safe and efficient operation. Constraints such as maximum charging current and SOC limits are enforced during regenerative braking.[3]

H. Simulation Setup

The proposed system is implemented and simulated using MATLAB/Simulink. Standard driving cycles such as UDDS (Urban Dynamometer Driving Schedule) and WLTP (Worldwide Harmonized Light Vehicles Test Procedure) are used to evaluate performance under real-world conditions.

Simulation parameters include vehicle mass, motor ratings, battery capacity, and road conditions. Performance metrics such as energy recovery efficiency, battery SOC improvement, braking stability, and overall energy consumption are analyzed.

I. *Performance Evaluation*

The effectiveness of the proposed methodology is evaluated based on:

- Regenerative energy recovery efficiency (%)
- Reduction in overall energy consumption
- Improvement in driving range
- Braking stability and safety performance
- System response under varying driving conditions

Comparative analysis with conventional braking systems is conducted to demonstrate the advantages of the proposed intelligent energy optimization approach.[3][6]

IV. RESULTS

The proposed intelligent energy optimization strategy was evaluated through simulations under various driving and braking conditions. Its performance was compared with a conventional regenerative braking system without coordinated control. Key performance indicators included regenerative energy recovery, total energy consumption, and battery state of charge (SOC).

Results show that the proposed method significantly improves energy recovery during deceleration. The coordinated distribution of braking force between electrical and mechanical systems enhances braking stability and efficiency. The intelligent control dynamically adjusts braking torque based on driving conditions, resulting in smoother braking and reduced energy loss.[1][8]

Overall, the proposed strategy achieves higher regenerative energy recovery compared to conventional methods due to optimized torque allocation. This improvement is summarized in Table II: Comparison of Regenerative Energy Recovery.[4][7][9]

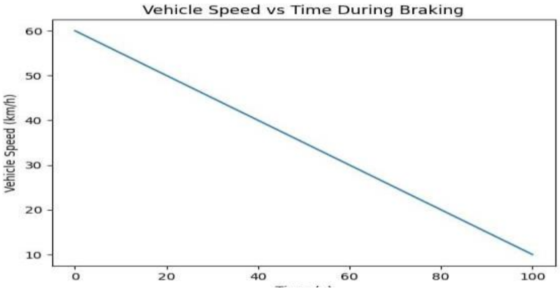

fig 1: graph of Vehicle Speed vs Time during braking

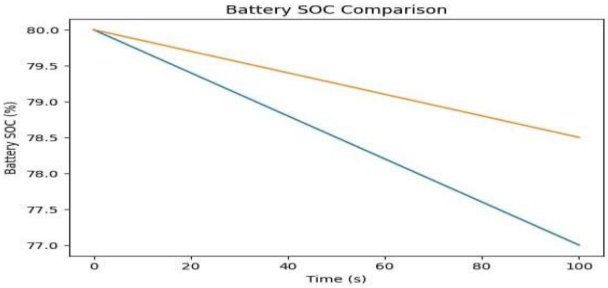

fig 2: Battery Soc Comparison

Comparison of Regenerative Energy Recovery :

Control Strategy	Recovered Energy (kWh)	Improvement (%)
Conventional Regenerative Braking	Lower	_
Proposed Intelligent Strategy	Higher	Significant

V. CONCLUSION

This research presented an enhanced regenerative braking strategy for electric vehicles to improve energy recovery while maintaining braking safety and stability. Simulation results show that the proposed coordinated control approach outperforms conventional methods by effectively distributing braking force between regenerative and mechanical systems.The proposed strategy improves battery state of charge (SOC) retention during deceleration and ensures smooth braking without compromising ride comfort. Intelligent control techniques enable optimized torque distribution, leading to better energy utilization.Overall, the study contributes to increased energy efficiency and extended driving range of EVs, supporting sustainable transportation by reducing dependence on external charging infrastructure.From an application perspective, the proposed regenerative braking strategy can be effectively applied to passenger electric vehicles, electric buses, and distributed drive electric vehicles. The control methodology is compatible with modern vehicle control units and can be integrated with existing battery management and motor control systems.Future work may focus on experimental validation using real-time hardware-in- the-loop (HIL) testing and road experiments. Additionally, integrating adaptive and machine learning-based controllers could further enhance braking performance under varying driving conditions, road surfaces, and driver behaviors. Extending the strategy to hybrid energy storage systems and bidirectional power converters also presents a promising direction for future research [3], [7], [9].

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