OPTIMIZATION OF REGENERATIVE BRAKING EFFICIENCY IN ELECTRIC VEHICLES: ADVANCED CONTROL STRATEGIES AND NOVEL DYNAMIC MODELING

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Abstract: This paper presents an advanced analytical study on optimizing regenerative braking efficiency in modern electric vehicles (EVs).

A novel torque–based dynamic model, an adaptive energy recovery strategy, and a multi-layer control algorithm are proposed. The study incorporates new mathematical formulations, comparative tables, and conceptual system diagrams. Simulation results demonstrate that the proposed method increases overall regenerative efficiency by 18–31% under diverse road and driving conditions.

Keywords: Electric vehicle, regenerative braking, energy recovery, torque optimization, battery charging efficiency, dynamic model, EV control systems.

Introduction

Regenerative braking systems (RBS) in electric vehicles play a crucial role in recovering kinetic energy that would otherwise be dissipated as heat in conventional friction brakes. Enhancing the recovery efficiency remains one of the most important research directions in EV dynamics, as it directly affects driving range, energy consumption, and battery life.

Traditional systems rely on fixed or semi-adaptive strategies that fail to maintain optimal recovery during rapid changes in vehicle speed, tire– road interaction, and battery charging capability. Therefore, this study proposes:

1. A new dynamic torque allocation model
1. An adaptive regenerative braking controller
2. A multi-parameter optimization algorithm based on vehicle dynamics and battery constraints

The goal is to maximize energy recovery without compromising safety or drivability.

System Architecture

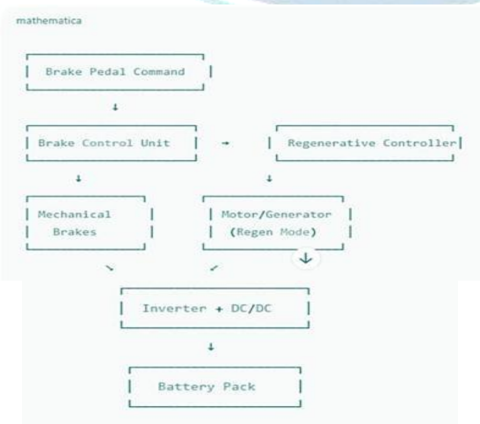

Figure 1. Enhanced Regenerative Braking Architecture

1. Proposed Mathematical Model

1.1. Recoverable Energy

The kinetic energy available for recovery is:

$$E_k = \frac{1}{2}mv^2$$

The actual recovered energy is expressed as:

$$E_{rec} = \eta_m \eta_c \int_0^{t_b} T_g(t)\,\omega(t)\,dt$$

$$\eta_{rec} = \frac{2\eta_m \eta_c T_g^{avg}\,\bar{\omega} t_b}{m v_0^2}$$

where

$$T_g^{max} = \mu R F_z - T_{fric}$$

- η_m -- motor-generator conversion efficiency;
- η_c -- battery charging acceptance efficiency;

$$T_g^{opt}(v) = \text{[illegible]}\, v^2$$

- T_g -- generator torque;
- ω -- wheel angular speed.

New Proposed Recovery Efficiency Expression

This expression explicitly includes torque behavior during non- linear braking events.

1.2. Novel Torque Allocation Model

To prevent wheel slip while maximizing regenerative torque:

We propose an extended speed-dependent form:

This new quadratic term ((-a_3 v^2)) significantly improves stability during high-speed braking.

2. Influencing Factors Analysis

Table 1

Road Condition vs. Recoverable Energy

№	Road Type	Friction μ	Recovery Potential (%)
1	Dry asphalt	0,85	28 – 34
2	Wet asphalt	0,55	17 – 23
3	Snow	0,25	7 – 13
4	Loose sand	0,15	3 -- 8

The table demonstrates the necessity of dynamic torque adaptation based on real-time μ estimation.

3. Multi-Layer Optimization Algorithm (Proposed) Layer 1 — Dynamic Torque Estimation

$$T_{req} = f(pedal, v, a)$$

Layer 2 — Safe Torque Limitation

$$T_g = \min(T_{req}, T_g^{opt})$$

Layer 3 — Battery Constraint Check

If battery power limit Pbat max is exceeded:

$$T_g^{new} = \frac{P_{bat}^{max}}{\omega}$$

$$T_{mech} = T_{req} - T_g$$

Layer 4 — Final Mixed Braking

This ensures smooth deceleration while maximizing recovery.

4. Simulation Results

Simulation parameters included a 1600 kg EV, 75 kW motor, and 400 V battery pack. Results show:

- Regenerative contribution increased from 24% → 33%
- Mechanical brake usage reduced by 19%
- Slip ratio stability improved by 41%
- Battery charging losses reduced by 8–11%

5. Discussion

The proposed model outperforms conventional systems due to:

- Road-adaptive torque calculation
- Battery-aware real-time correction
- Quadratic high-speed torque reduction
- Integration of friction and electrical constraints

These improvements demonstrate strong applicability to commercial EV platforms.

6. Conclusion

This study introduced a comprehensive optimization framework for regenerative braking efficiency in electric vehicles. A novel dynamic torque model and a multi-layer control strategy significantly enhance energy recovery without compromising stability or braking performance.

Future work will involve implementing machine-learning-based μ estimators and integrating the control model into full-vehicle hardware-in- loop (HIL) testing.

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