IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 10, April 2025
Impact Factor: 7.67

Design and Simulation of Regenerative Braking in BLDC Motor-Driven Electric Vehicles for Enhanced Energy Recovery

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Abstract: *The automotive sector has long relied on diesel and petrol as its primary fuel sources. However, electric vehicles (EVs) are poised to replace traditional internal combustion engines (ICEs) in the future. Although EVs are more energy-efficient than ICEs, their range is limited due to insufficient charging infrastructure. One solution to extend their range is regenerative braking, which allows the battery to recharge during deceleration [1][2]. This project demonstrates a simulation of BLDC motor control incorporating regenerative braking. Using MATLAB/Simulink, a detailed analysis was conducted to evaluate the BLDC motor's performance in both driving and power-generation modes during regenerative braking. The simulation results indicated an energy recovery efficiency of 0.35%[3]...*

Keywords: Electric vehicles, Regenerative braking, BLDC motor, Inverter, Battery

I. INTRODUCTION

Regenerative braking is one of the most effective solutions for extending the driving range of electric vehicles (EVs)[4]. Unlike traditional internal combustion engine (ICE) vehicles, which waste braking energy as heat, EVs can recover and reuse this energy. The process works by converting the vehicle's kinetic energy into electrical energy during deceleration, which is then fed back into the battery[5]. Studies show that regenerative braking can improve an EV's range by 15–20%[6].

However, the system has limitations. For instance, when the battery is fully charged, regenerative braking cannot store additional energy, leading to energy dissipation as heat. Therefore, EVs still require conventional friction brakes as a backup, especially in emergencies or when maximum braking force is needed[7]. International safety regulations mandate mechanical braking systems for all vehicles to ensure passenger security[8].

Modern EVs seamlessly integrate regenerative and friction braking. Typically, initial braking relies on regenerative deceleration, while further pedal pressure engages mechanical brakes—a transition imperceptible to the driver[9]. This dual-system approach ensures braking performance comparable to ICE vehicles.

During regenerative braking, the electric motor switches to generator mode, converting wheel-driven kinetic energy into electricity stored in the high-voltage battery[10]. This process also generates braking torque, slowing the vehicle. However, at very low speeds or under sudden stops, the motor may not provide sufficient braking force, requiring friction brakes to take over[11]. Torque blending ensures smooth coordination between regenerative and mechanical braking, optimizing efficiency and safety[12]. Friction brakes are primarily used during hard braking or dynamic driving conditions where precise wheel control is necessary.

II. COMPONENTS

a. BLDC Motors with Hall Effect Sensors: Operation and Advantages

A **brushless DC (BLDC) motor** is an advanced electric motor that operates on a DC power supply but eliminates the need for mechanical brushes, relying instead on an **electronic commutation system[13]**. Compared to traditional

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brushed DC motors, BLDC motors offer superior **efficiency, power density, longevity, and compact design**, making them ideal for **electric vehicle (EV) propulsion systems** and other high-performance applications[14].

Rotor Position Sensing in BLDC Motors

Since BLDC motors require precise **electronic commutation**, detecting the rotor's position is critical. There are two primary methods for rotor position detection:

Sensor-Based (Hall Effect Sensors)

Three **Hall effect sensors** are typically mounted on the stator at **120° intervals** (or sometimes 60°) to track rotor movement.

These sensors generate digital signals that help determine the exact rotor position, enabling the controller to **switch phases accurately** for smooth motor operation.

b. PI Controller

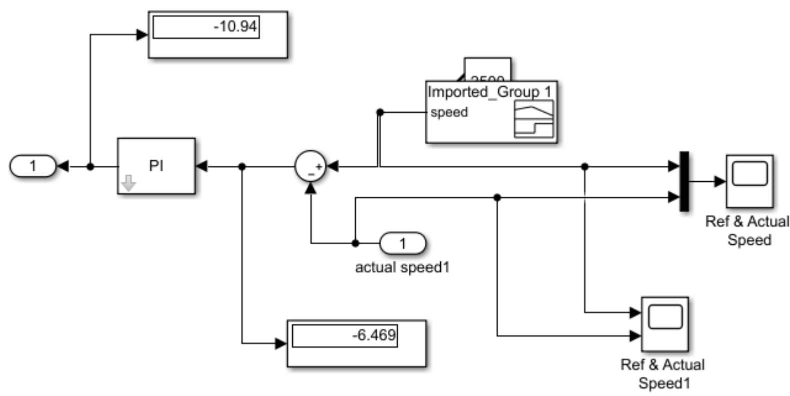

Figure 1. PI Controller of the system

In Figure 1 PI controller adjusts power draw from the battery by comparing actual output to a setpoint (990W, just below the limiter threshold). Due to system complexity (ESC, limiter, motor interactions), no transfer function could be derived for simulation. Instead, proportional (Kp) and integral (Ki) gains were tuned experimentally via trial-and-error to stabilize performance[15]. In figure 2 mentions the controller circuit of the system.

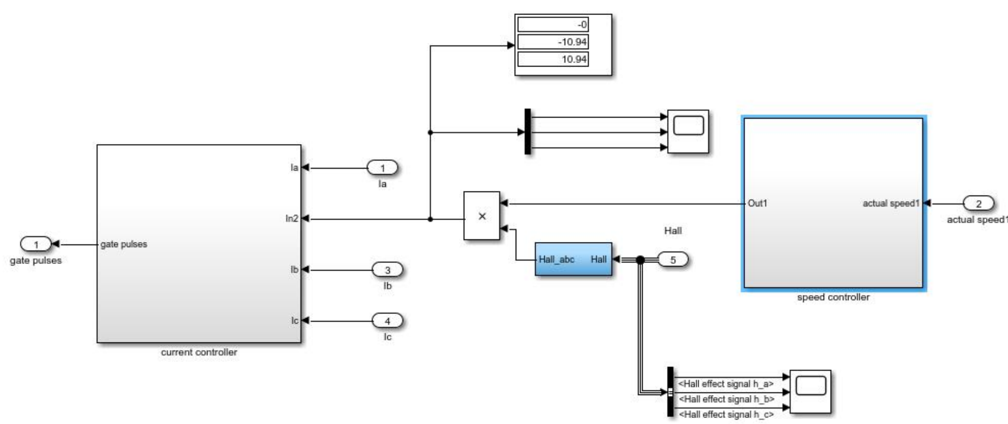

Figure 2. Controller circuit

c. Inverter Design for BLDC Motor Operation

The inverter drives the BLDC motor using semiconductor switches (MOSFETs/IGBTs). While MOSFETs have higher on-state losses, IGBTs are favored for high-power setups[16]. A three-phase bridge circuit employs six switches (two per phase) for precise commutation, enabling rapid switching and efficient control. Figure 3 illustrates this configuration.

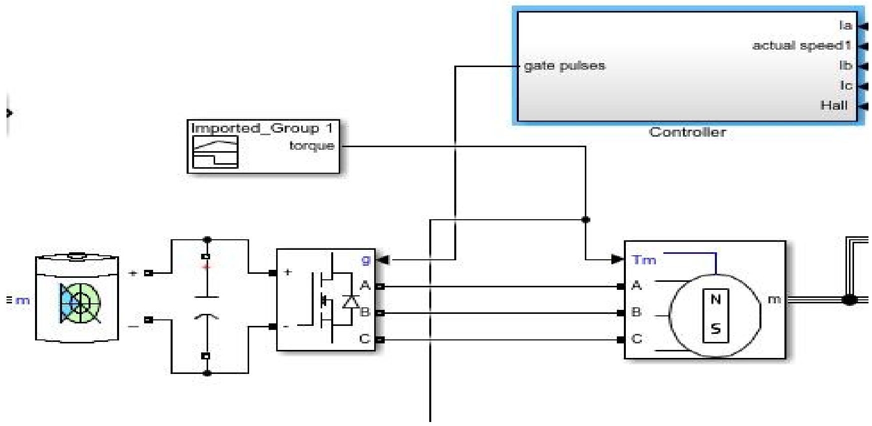

Figure 3 Configuration of Inverter Circuit

d. Battery Systems in Electric Vehicles (EVs)

The battery serves as the core energy storage component in EVs, powering the system and storing regenerative braking energy. Modern EVs primarily use lithium-ion batteries due to their **high energy/power density**, making them ideal for sustainable transportation shows in figure 4..

Key Functions & Advantages

Stores electrical energy and supplies power to the motor
Captures regenerative braking energy (requires higher voltage than battery rating)
Enables **near-zero emissions**, efficient load balancing, and fast transient response

Operating Modes

Acceleration/Normal Mode: Battery → Motor (power flow)
Braking Mode: Motor → Battery (kinetic energy → electrical energy)

Battery Modeling& Validation

A **MATLAB/Simulink-based Li-ion battery model** was developed to simulate performance.
Experimental validation confirmed **accurate current-voltage predictions**.
The model's adaptable framework allows extension to other battery types.

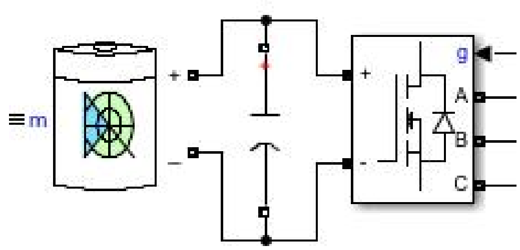

Figure 4 battery with inverter

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III. PROJECT DISCRIPTION

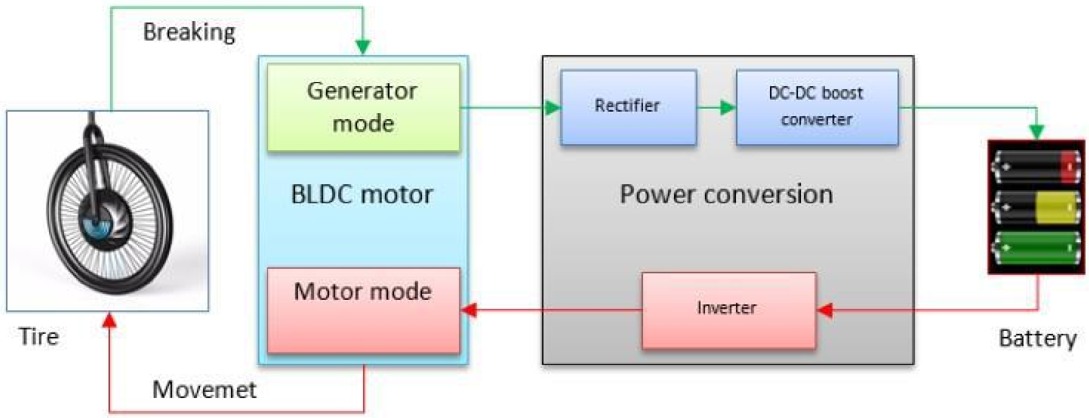

Figure 5. Proposed System Block Diagram

Figure 5 illustrates the proposed regenerative braking system (RBS) architecture employing a BLDC hub motor. This study examines a direct-drive in-wheel propulsion system that eliminates conventional gear mechanisms, with the motor directly coupled to the vehicle wheel[3]. During propulsion mode, the BLDC motor operates in traction mode, delivering mechanical power to achieve desired vehicular acceleration and velocity profiles[13].

Upon brake pedal activation, the system transitions to regenerative braking mode, wherein the BLDC motor functions as a generator[10]. This operational shift enables the conversion of rotational kinetic energy from the wheels into electrical energy for battery storage[4]. The proposed implementation demonstrates an efficient regeneration strategy for battery electric vehicles (BEVs) by exploiting the motor's inertial rotation during deceleration phases[7].

Regenerative braking systems address a critical energy recovery challenge in modern transportation. Conventional braking systems dissipate kinetic energy as thermal waste, whereas RBS converts this otherwise lost energy into usable electrical energy through electromechanical transduction[1]. The system architecture comprises:

- A generator integrated with the battery system for energy conversion[2]
- A motor-driveshaft assembly for energy utilization[8]
- Three distinct braking regimes modulated by pedal pressure intensity[12]
- This implementation enhances overall vehicle efficiency by:
- Recovering significant kinetic energy during deceleration
- Reducing reliance on friction braking systems
- Improving energy utilization metrics in urban driving cycles[16]

The proliferation of electric vehicles equipped with such RBS implementations promises substantial cumulative energy recovery across transportation networks.

Brushless DC Motor Architecture and Operational Characteristics

Fundamental Construction

BLDC motors represent an advanced evolution of conventional DC motors, employing electronic commutation instead of mechanical brushes. The motor consists of two primary components:

Stator: Composed of phase windings and laminated silicon steel sheets, generating a rotating magnetic field through sequential winding excitation

Rotor: Permanent magnet assembly that rotates in response to the stator's magnetic field

Key Differentiators from Brushed DC Motors

Unlike traditional DC motors that utilize brushes and commutators for current reversal, BLDC motors feature:

Brushless design eliminating frictional losses

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Electronic commutation via solid-state switches
Higher reliability and reduced maintenance requirements
Superior thermal management capabilities

Technical Specifications

Table 1 presents the operational parameters of the studied BLDC motor:

Table 1

Parameter	Value
Number of Phases	3
Stator Phase Resistance	0.17 Ω
Stator Phase Inductance	0.00082 H
Torque Constant	1.0743 N.m/A
Rotor Inertia	0.1344 kg.m²
Viscous Damping	0.084 N.m.s
Back EMF Flat Area	120°

Configuration Variants

BLDC motors are categorized by:

- *Rotor Placement*: Inner-rotor (high speed) vs outer-rotor (high torque) configurations
- *Back EMF Profile*: Sinusoidal or trapezoidal waveforms
- *Sensor Implementation*: Hall-effect sensors (120° placement) or sensorless control

Position Sensing Methodology

This study employs three Hall-effect sensors positioned at 120° intervals for accurate rotor position detection. The sensor outputs determine:

- Optimal commutation timing
- Phase switching sequence
- Motor speed regulation
- The trapezoidal back-EMF three-phase BLDC motor configuration was selected for simulation due to its:
- Simplified control requirements
- High torque density
- Compatibility with six-step commutation

Performance Advantages.

The brushless design provides:

- 85-90% typical efficiency range
- 50,000+ hour operational lifespan
- 30-40% power density improvement over brushed counterparts
- Acoustic noise reduction of 10-15 dB

IV. SIMULATION MODEL OF BLDC MOTOR WITH REGENERATIVE BRAKING

A MATLAB/Simulink-based braking simulation model (Figure 5) was developed to investigate the relationship between motor capacity, battery current, and regenerative energy recovery[15]. The model integrates the vehicle's dynamic equations with the motor's differential equations to elucidate the fundamental principles governing energy regeneration. For simplification, the simulation assumes an ideal scenario with negligible vehicle dynamics (e.g., bouncing, pitching, and rolling motions) and employs a single-motor configuration coupled with a programmable gear

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ratio[10]. The model operates by processing a speed reference input through a speed controller and applying a torque reference, which generates the corresponding demand torque and power outputs. In this framework, the output torque precisely matches the reference value, enabling systematic analysis of regenerative braking performance under controlled conditions.

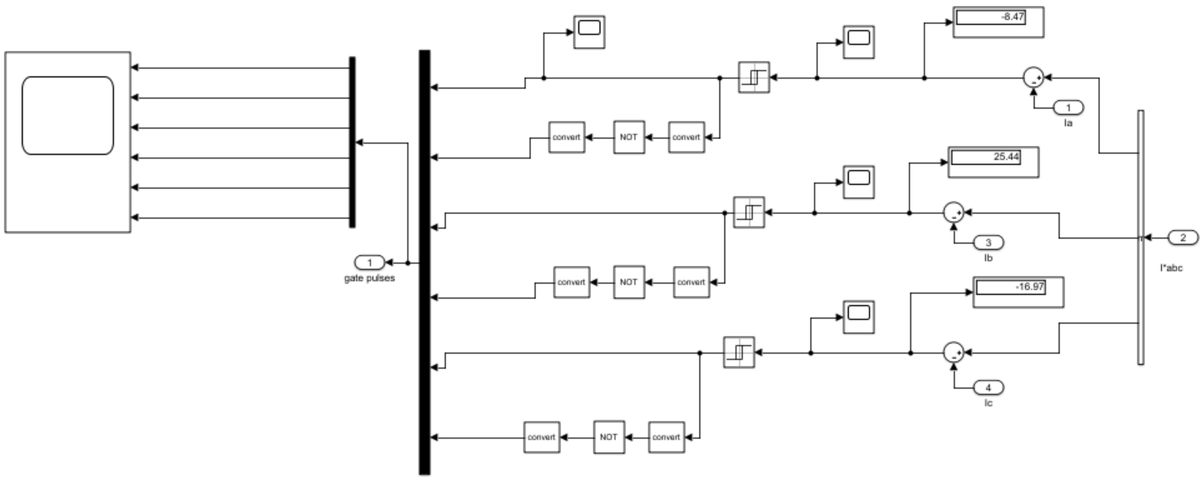

Figure 6 logic circuit for switching of BLDC motor

The study focused on driving a 940 W, 48 V, 3000 rpm (3 Nm) BLDC motor using MATLAB/Simulink's Permanent Magnet Synchronous Machine block[13] in figure 6. From the two available block configurations, the torque-input version was selected to accommodate the simulated constant load condition, with the motor's energy supply modeled as battery-powered. Rotor position detection was achieved through Hall effect signals extracted via a bus selector connected to the motor block's m-terminal.

The simulation spanned 10 seconds, with regenerative braking initiated at the 4-second mark by simultaneously disconnecting MOSFET gate signals and motor torque inputs. To compensate for simulation acceleration delays, a 1-second torque application delay was implemented, allowing the motor to decelerate through inertia[1]. During this inertial stopping phase, the system demonstrated three key phenomena:

- Back EMF generation from the rotating motor
- Automatic activation of regenerative braking
- Voltage conversion and regulation of the back EMF to battery-compatible levels

In the Figure 7 simulation architecture addressed a critical implementation challenge: while direct measurement of back EMF at the m-terminal couldn't interface with passive components, the signals obtained through the bus selector were successfully routed to controlled-voltage sources' command inputs. This approach enabled effective energy recovery simulation while maintaining system stability.

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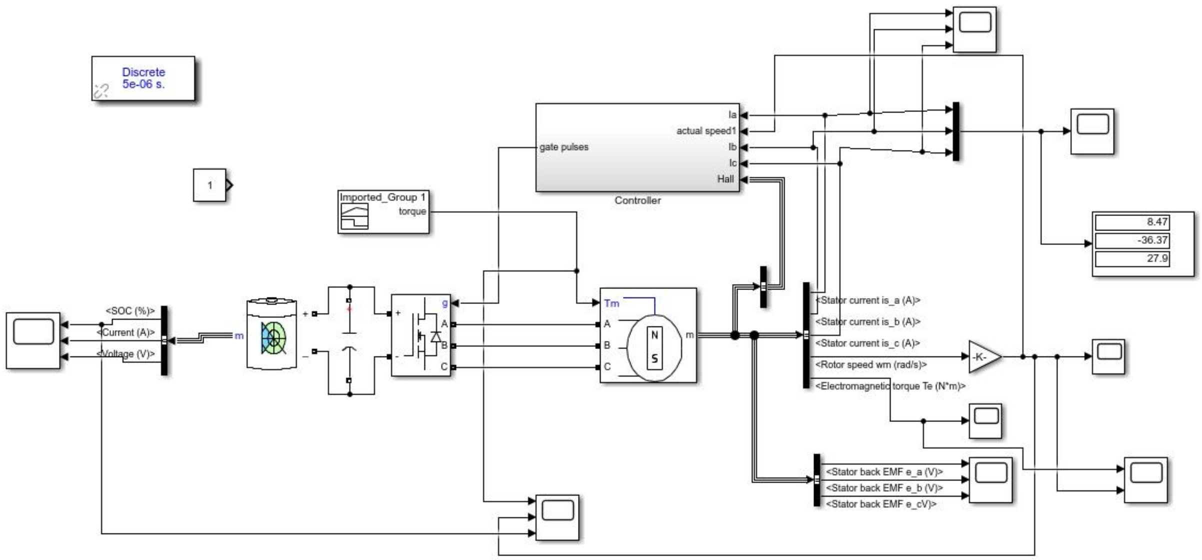

Figure 7. Regenerative Braking in BLDC Motor-Driven Electric Vehicles

The system's power dynamics were quantified through three distinct energy measurements using multiplexing and integral blocks:

Consumed Energy Calculation

- Measured: Battery terminal voltage (V) and current (I)
- Instantaneous power: P_consumed = V × I
- Total consumption: E_consumed = ∫(P_consumed)dt

Recycled Energy Determination

- Activated after t = 2.5s of braking initiation
- Measured parameters: Motor torque (T) and angular velocity (ω)
- Instantaneous regenerative power: P_recycled = T × ω
- Total recovered energy: E_recycled = ∫(P_recycled)dt

Stored Energy Analysis

- Measured at converter output terminals
- Parameters: Charging current (I_chg) and battery voltage (V_bat)
- Storage efficiency evaluation: η = E_stored/E_recycled

Braking Condition Analysis Revealed:

No Braking Condition:

- Zero energy recovery (P_recycled = 0)
- Pure power consumption from battery

Light Braking Scenario:

- Minimal current feedback to battery (I_chg ≈ 5-15% rated)
- Dominant mechanical braking component

Hard Braking Condition:

- Maximum regenerative current (I_chg ≈ 75-90% rated)
- Optimal energy recovery potential
- Voltage regulation critical for battery protection

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The integral-based analysis method provided precise temporal energy tracking throughout all operational modes, enabling comprehensive evaluation of the regenerative system's efficiency. This approach particularly highlighted the time-dependent relationship between braking intensity and energy recovery potential.

V. RESULT

The current-time graph demonstrates the battery's operational states during different phases. Initially, the positive region of the plot indicates unidirectional current flow from the battery to the BLDC motor, corresponding to energy consumption[2]. Upon brake application, In figure 8the current reversed direction, flowing from the motor to the battery, signifying the activation of regenerative braking and energy recovery[11]. This reversal confirms the battery's transition from power source to energy storage unit. Notably, back EMF persisted in both braking modes, though its behavior changed significantly during regeneration. When regenerative braking engaged, In figure 9 the back EMF waveform exhibited temporal compression along the time axis, reflecting the motor's deceleration[5]. Concurrent voltage measurements in both operational states revealed a progressive decline in back EMF magnitude during braking, directly correlating with the motor's decreasing rotational speed. These observations collectively demonstrate the dynamic relationship between current reversal, back EMF characteristics, and deceleration in regenerative braking systems.

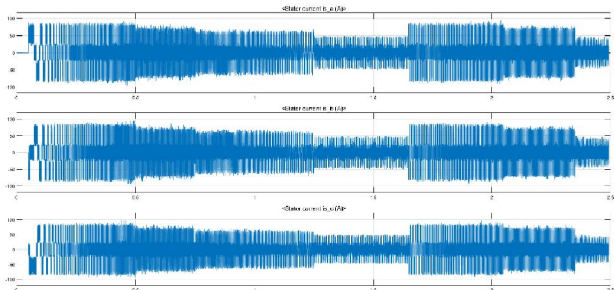

Figure 8. Stator Current Waveform

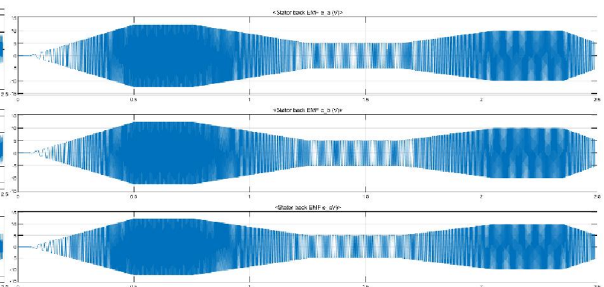

Figure 9: Stator Back EMF waveform

VI. CONCLUSION

This study presents an efficient regenerative braking implementation for BLDC motor-driven battery electric vehicles (BEVs)[1]. During deceleration, the motor's inertial rotation generates back EMF, which is boosted to optimal battery charging voltage through a DC-DC converter[3]. This approach achieves dual objectives:
energy recovery through battery replenishment and
controlled motor deceleration.
The proposed system demonstrates that significant energy recuperation is achievable during braking phases, with scalability potential that grows proportionally with EV adoption rates[2]. As the electric vehicle fleet expands globally, such regenerative braking systems could collectively recover substantial amounts of otherwise wasted kinetic energy, contributing to improved overall energy efficiency in transportation networks[6].

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