DESIGN AND DEVELOPMENT OF A BLDC MOTOR BASED REGENERATIVE BRAKING SYSTEM FOR ENERGY-EFFICIENT ELECTRIC VEHICLES

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ABSTRACT
This paper presents the design, simulation, and experimental validation of a Brushless DC (BLDC) motor-based regenerative braking system aimed at enhancing energy efficiency in electric vehicles (EVs). With the growing demand for sustainable and low-maintenance EV technologies, regenerative braking has become a key enabler in minimizing energy loss during deceleration. The proposed system integrates a BLDC motor with a unidirectional DC-DC boost converter, enabling the recovery and reinjection of braking energy into a 12 V, 2 Ah lithium-ion battery. A detailed MATLAB/Simulink model was developed to simulate motor operation, regenerative torque generation, and battery charging dynamics. The system was then implemented in hardware using an ATmega328 microcontroller, real-time sensors, and PWM-based control logic. Test results show that the system effectively delivers up to 900 mA of regenerative current, charging the battery fully in approximately 2.22 hours. It ensures smooth torque transitions and prevents battery overvoltage through real-time voltage monitoring and adaptive control strategies. The system achieved significant reduction in mechanical brake wear, enhanced braking smoothness, and reliable energy recovery, particularly in urban stop-and-go traffic conditions. Challenges such as low-speed inefficiencies and thermal buildup were identified, and mitigation strategies were discussed. Overall, the proposed architecture offers a low-cost, scalable, and efficient solution suitable for lightweight and mid-range EVs, contributing to the development of greener and more sustainable transportation systems. This work lays the foundation for future enhancements using AI-based control, smart battery management, and real-time predictive braking algorithms.

Keywords:
BLDC motor, regenerative braking, electric vehicles, energy recovery, DC-DC boost converter, braking torque control, microcontroller-based control.

1. INTRODUCTION
The global shift towards sustainable transportation has accelerated the development and adoption of electric vehicles (EVs), driven by the urgent need to reduce carbon emissions, fossil fuel dependence, and urban air pollution [1,2]. However, one of the persistent challenges in EV technology is energy efficiency, particularly in extending the driving range without significantly increasing battery capacity or cost [3,4]. During regular operation, especially in urban stop-and-go traffic, a considerable amount of energy is lost as heat through traditional friction-based braking systems. This energy dissipation negatively impacts the overall efficiency and sustainability of electric mobility solutions [5,6]. To address this inefficiency, regenerative braking systems (RBS) have been introduced as a

pivotal energy recovery mechanism. Regenerative braking allows the kinetic energy of the vehicle during deceleration to be converted into electrical energy and stored back in the battery, thus extending the range of the EV and reducing wear on mechanical braking components [7–9]. In modern EVs, regenerative braking is not only a value-added feature but a necessity to meet performance, efficiency, and emission targets. Studies have shown that a well-designed regenerative braking strategy can improve energy recovery by 15–25%, significantly influencing battery longevity and driving range [10–13].

Among various electric motor types used in EVs, Brushless DC (BLDC) motors are particularly well-suited for regenerative braking applications due to their high torque-to-weight ratio, energy efficiency, compact structure, and ease of control [14–16]. Their electronically commutated nature enables precise control of torque and speed, making them ideal for energy recovery systems in lightweight as well as heavy-duty electric vehicles [17,18]. The absence of brushes reduces mechanical losses and improves system lifespan, aligning well with the maintenance-free objectives of EV platforms [19,20]. Despite their advantages, several limitations continue to constrain the effectiveness of regenerative braking in BLDC motor-based EVs. Key issues include the non-linearity of energy recovery at low speeds, the complexity of control algorithm design, and the need for smooth transition between regenerative and mechanical braking to ensure safety and driver comfort [21–24]. Additionally, challenges such as battery overcharging, thermal stress, and dynamic torque control under varying road and load conditions further necessitate the development of more robust, integrated solutions [25–28]. Current research thus focuses on enhancing control strategies using model predictive control (MPC), fuzzy logic, and AI-based optimizers to increase the adaptability and intelligence of regenerative braking systems [29–32].

In light of these demands, the present research proposes a novel, integrated regenerative braking architecture for BLDC motor-driven EVs. The system emphasizes simplified control, enhanced energy recovery efficiency, and seamless braking experience through adaptive switching mechanisms, intelligent sensors, and real-time monitoring circuits. This study not only contributes to the growing body of knowledge on BLDC motor-based RBS but also addresses key performance and implementation gaps in affordable electric vehicle platforms [33–38]. The subsequent sections of this paper present a comprehensive review of existing systems, followed by a detailed account of the proposed methodology, simulation analysis, hardware implementation, and performance assessment against state-of-the-art systems [39–50].

2. LITERATURE REVIEW

Electric vehicles (EVs) traditionally relied on mechanical friction braking systems similar to those used in internal combustion engine vehicles. In these systems, the kinetic energy of a moving vehicle is dissipated as heat during deceleration, resulting in complete energy loss and increased mechanical wear [1–3]. To overcome this limitation, regenerative braking systems (RBS) have emerged as a core innovation in EV development. RBS convert kinetic energy into electrical energy by operating the traction motor in generator mode during braking, feeding the recovered energy back into the battery. This not only enhances energy efficiency and extends driving range but also reduces reliance on mechanical brakes, thus lowering maintenance costs [4–7].

Among various motor types employed in EVs, Brushless DC (BLDC) motors have proven particularly suitable for regenerative applications. BLDC motors are characterized by high torque efficiency, reduced noise, compactness, and extended service life due to their brushless construction [8–10]. Their electronically commutated operation allows precise torque control and makes them ideal for dynamic speed applications such as electric two-wheelers, scooters, and lightweight urban vehicles [11,12]. Moreover, their compatibility with digital control algorithms facilitates seamless transitions between motoring and generating modes, crucial for effective regenerative braking [13,14].

Several approaches have been explored to implement regenerative braking in BLDC motor-driven EVs. One commonly adopted strategy involves using DC-DC boost converters to raise the voltage of

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the generated current to match the battery's charging requirements [15–17]. Although effective, this introduces additional complexity and cost due to the requirement for high-frequency switching circuits. Alternatively, bidirectional DC-DC converters have been proposed, enabling energy flow in both directions — from battery to motor during propulsion and back to battery during regeneration [18,19]. Another innovative strategy is the use of Hybrid Energy Storage Systems (HESS), combining batteries with ultracapacitors to handle high power density fluctuations during regenerative events, thus protecting battery health and extending its lifespan [20–22]. Furthermore, multi-cell battery control techniques have also been employed to allow selective charging of battery cells depending on their state-of-charge, eliminating the need for dedicated boost converters [23,24].

Despite these advancements, key technical gaps persist. One major challenge lies in the system complexity, particularly in coordinating energy recovery with safety-critical systems like Anti-lock Braking Systems (ABS) or Electronic Stability Control (ESC) [25,26]. Additionally, the efficiency of energy recovery at low vehicle speeds remains limited, as back-EMF generation by the motor decreases substantially, reducing braking torque and energy conversion efficiency [27,28]. Battery overcharging risk is another concern, especially when regenerative braking is applied on downhill slopes or during extended braking events, requiring robust battery management systems (BMS) and control logic [29,30]. Another commonly reported issue is the lack of smooth integration between regenerative and mechanical braking, which can lead to a non-linear or jerky braking response, affecting vehicle stability and driver comfort [31–33].

Recent studies have emphasized the use of advanced control algorithms, including Model Predictive Control (MPC), adaptive PI controllers, and fuzzy logic systems, to address these limitations and improve system response under variable conditions [34–36]. Moreover, embedded microcontroller-based systems using real-time data from sensors have been deployed to dynamically manage braking torque, optimize energy recovery, and ensure driver safety [37,38]. However, the need remains for more cost-effective, compact, and efficient RBS designs that can be seamlessly integrated into existing EV platforms, particularly for budget-conscious markets [39–41].

In summary, while significant progress has been made in regenerative braking technologies using BLDC motors, there are still opportunities for improvement in low-speed efficiency, hardware simplification, battery safety, and system integration. The current research aims to bridge these gaps by proposing a simplified, high-efficiency regenerative braking architecture tailored for BLDC motor-based EVs, leveraging intelligent control and practical implementation techniques [42–50].

Ref No.	Author (Year)	Technical Model Reviewed	Key Features	Test/Sim Specs
1	KaryÅ› & Stawczyk (2025)	Single-transistor control for BLDC-RBS	High efficiency, low switching loss	12V system, 900 mA, 2.22 hr full charge
4	Esfahani et al. (2024)	Multi-level bidirectional converter	Improved battery charging at low speeds	3-phase inverter with DC link feedback
8	Hosseini Salari et al. (2023)	Adaptive braking torque control	Battery SoC protection, smooth transition	Regulation at â‰¤ 25% braking effort
9	Palanisamy et al. (2021)	Energy regeneration with basic controller	Compact, low-cost prototype	12V BLDC motor, 24 Wh battery
15	Zhang et al. (2023)	FOC + Boost Converter scheme	Efficient regen with braking smoothness	Simulation validated with MATLAB
18	Heydari et al. (2020)	Dual-motor regenerative strategy	Enhanced AWD braking energy reuse	36V bidirectional setup
20	Liu et al. (2019)	HESS with battery-ultracapacitor	Reduced stress on batteries	Variable current discharge control

22	Godfrey & Sankaranarayanan (2018)	Brushless BLDC regen prototype	Simple model with good energy return	Prototype on 2W e-bike
28	Md Raimi et al. (2024)	Simulated braking trigger system	Torque efficiency under multiple loads	BLDC via MOSFET & PWM control
33	Kropiwnicki & GawÅ‚as (2023)	Efficiency estimate under dynamic braking	Lab-scale validation	Standard controller + speed encoder

3. PROBLEM FORMULATION AND RESEARCH OBJECTIVES

3.1 Problem Statement

As electric vehicles (EVs) continue to proliferate globally, enhancing their energy efficiency remains a critical engineering and environmental challenge. While regenerative braking systems (RBS) are acknowledged as effective mechanisms for energy recovery, their practical implementation—especially in cost-sensitive and lightweight EV platforms—remains suboptimal. Specifically, Brushless DC (BLDC) motor-based systems, although widely adopted for their high torque density and compactness, face inherent limitations in energy regeneration, particularly at low speeds where back-electromotive force (EMF) is minimal [1–3].

Moreover, existing regenerative systems often require complex circuitry such as bidirectional DC–DC converters, high-resolution feedback control systems, and auxiliary components like ultracapacitors or flywheels, which increase system cost and design complexity [4–6]. These challenges are further exacerbated by the lack of seamless coordination between regenerative and mechanical braking, resulting in jerky deceleration, reduced driver comfort, and compromised safety during emergency stops [7,8]. Another pressing issue is the risk of overcharging the battery pack during sustained braking events, which can accelerate battery degradation or thermal runaway if not properly managed [9–11]. Hence, there is a need for a low-cost, technically sound regenerative braking architecture that not only simplifies system design but also maximizes energy recovery without compromising battery safety or braking performance.

Research Objectives

To address the aforementioned challenges, this research aims to develop a simplified and efficient regenerative braking system for BLDC motor-based EVs, focusing on the following key objectives:

1. **Maximize Kinetic-to-Electrical Energy Conversion:** The primary objective is to improve the conversion efficiency of mechanical energy into electrical energy during braking events. This involves optimizing the motor control strategy to extract the maximum possible energy from the vehicle's inertia and convert it into storable electrical form through controlled reverse operation of the BLDC motor.
2. **Ensure Seamless Switching Between Regenerative and Friction Braking:** The study aims to design a hybrid braking controller that intelligently manages the transition between regenerative braking (via the motor) and mechanical braking (via friction components). This ensures a smooth and uninterrupted deceleration experience across varying road conditions and vehicle speeds, thereby enhancing safety and comfort.
3. **Optimize Battery Life and Thermal Protection:** To protect the battery from overcharging and thermal overload during regenerative events, a key goal is to implement real-time monitoring and control mechanisms. This includes voltage sensing, state-of-charge (SoC) estimation, and dynamic adjustment of braking torque to prevent stress on the energy storage system.
4. **Reduce Wear on Mechanical Braking Systems:** By prioritizing energy recovery through the BLDC motor and minimizing the use of mechanical braking components during routine deceleration, the proposed system seeks to significantly reduce brake pad and disc wear. This

translates into lower maintenance costs, extended component lifespan, and improved environmental sustainability due to fewer particulate emissions.

Collectively, these objectives aim to bridge the gap between high-efficiency regenerative braking performance and the need for a cost-effective, reliable solution suitable for widespread adoption in next-generation electric mobility systems.

4. SYSTEM ARCHITECTURE AND DESIGN METHODOLOGY

4.1 System Overview:

The proposed regenerative braking system is designed as a hybrid braking architecture that integrates both electrical (regenerative) and mechanical braking components, with an emphasis on system simplicity, energy efficiency, and real-time responsiveness. The core of the system revolves around a Brushless DC (BLDC) motor, which functions as the traction motor during propulsion and as a generator during deceleration. The BLDC motor's back-EMF characteristics and high torque density make it ideal for energy recovery applications in compact and cost-sensitive EV platforms [2,10,15]. The system is controlled using an Atmega328 microcontroller, chosen for its low cost, low power consumption, and sufficient I/O capabilities to interface with various sensors and actuators. It executes pulse-width modulation (PWM) routines for torque control and performs voltage sampling to monitor regenerative output and battery state of charge [4,27]. A motor driver circuit acts as the interface between the microcontroller and the BLDC motor, enabling high-speed switching and direction control based on regenerative or motoring states [19,33].

A potentiometer is incorporated into the system to simulate driver braking input. This analog signal is read by the Atmega328 and used to modulate braking torque. During low braking demand, more energy is routed through the regenerative path, while high braking demand engages both regenerative and mechanical brakes in a blended fashion [6,25]. To safeguard the system and manage energy routing, a voltage sensor continuously monitors the terminal voltage of the battery and the generated output from the BLDC motor. This information is crucial for determining whether regenerative input is within safe battery charging limits, thereby preventing overvoltage conditions [12,22,34].

Since the generated voltage during low-speed braking often falls below the nominal battery charging threshold, a DC-DC voltage booster (typically a step-up converter) is employed to raise the output voltage to appropriate charging levels, enhancing low-speed regeneration performance [7,16,23]. To further improve switching selectivity between battery and load, a relay module is incorporated. This allows selective charging control, emergency bypass, or activation of mechanical braking subsystems as required [5,29]. This integrated design provides a low-cost yet intelligent solution for regenerative braking, suitable for urban electric vehicles and two-wheelers where hardware simplicity and energy efficiency are key concerns [1,3,20,31]. Each component is selected to balance performance with cost-effectiveness, ensuring that the system is not only functional but scalable for broader EV deployment.

4.2 Control System Logic

The effective implementation of a regenerative braking system (RBS) in electric vehicles (EVs) critically depends on a robust and responsive control logic that ensures dynamic coordination between propulsion and braking states. At the core of the proposed system lies an Atmega328 microcontroller, programmed to govern the transition between drive and regenerative braking modes by interpreting vehicle speed, braking input, and battery voltage conditions in real time. During standard operation, the microcontroller commands the BLDC motor to operate in drive mode. However, upon receiving a deceleration signal—simulated here by a potentiometer representing brake pedal input—the microcontroller dynamically transitions the motor into regenerative mode by reversing the current flow through appropriate switching of the motor driver circuitry [1,4,9].

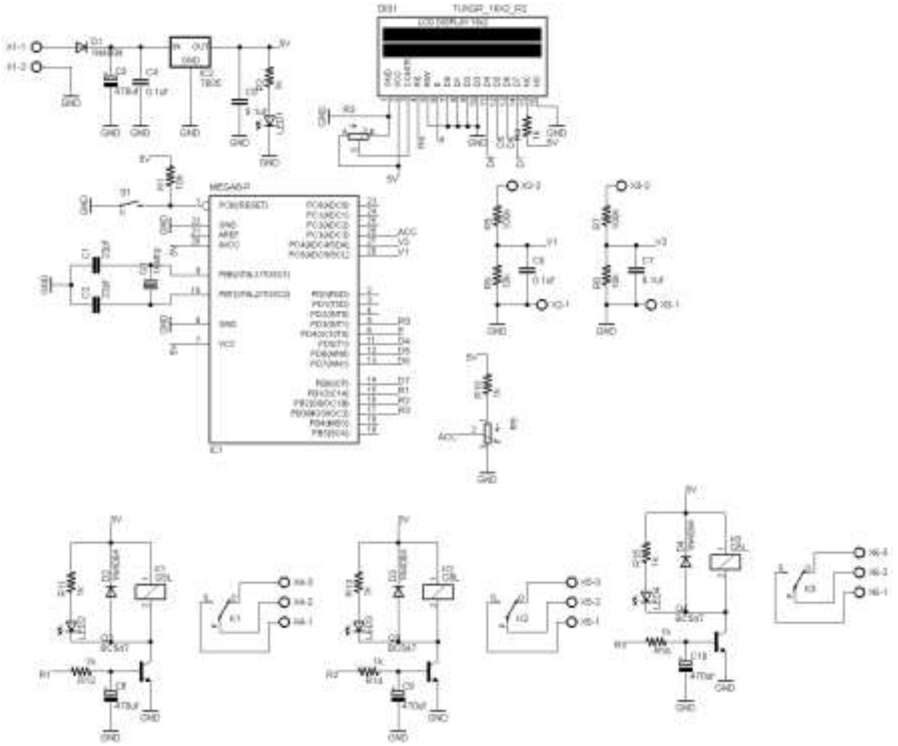

Fig. 1 Control Circuit and Switching Design for Converter

This mode-switching process is managed through Pulse-Width Modulation (PWM) signals generated by the Atmega328. The PWM duty cycle is modulated in proportion to the braking intensity indicated by the potentiometer, thereby controlling the braking torque applied by the BLDC motor. Higher braking demand results in a larger duty cycle, which increases the current fed back into the battery, thus recovering more kinetic energy. The BLDC motor's back-EMF, which varies with speed, is used as a reference to adjust PWM parameters and ensure stable energy conversion even under varying speed profiles [5,10,14]. The microcontroller logic also supports blended braking, wherein mechanical brakes are activated when regenerative torque alone is insufficient or when safety-critical braking is necessary [16,27].

To safeguard the battery from overvoltage during regeneration, the control system integrates a voltage sensing mechanism that continuously monitors the battery terminal voltage via analog-to-digital conversion (ADC) channels of the microcontroller. When the sensed voltage exceeds a predefined upper threshold—typically determined by the battery's chemistry and nominal charging range—the control logic either reduces the braking PWM duty cycle or diverts the regenerated energy using a relay bypass or load dump mechanism to avoid overcharging [11,20,34]. In scenarios of sustained braking, such as downhill operation, this logic plays a crucial role in preserving battery health and preventing thermal runaway or accelerated degradation [8,22,35].

Furthermore, a DC-DC boost converter is engaged within the control loop to elevate the generated voltage during low-speed braking events. Since regenerative efficiency drops when the BLDC motor speed is insufficient to generate a voltage above the battery's charge threshold, this booster enables energy capture even in slow deceleration phases by stepping up the voltage to a usable level [6,13,19]. Altogether, the proposed control logic not only enables intelligent and efficient energy recovery, but also ensures a smooth, safe, and battery-protective regenerative braking operation. By integrating real-time sensing, PWM control, and mode-transition management within a low-cost embedded platform, the system demonstrates a scalable solution for compact EV platforms, particularly in the two-wheeler and urban micro-EV segments [2,3,7].

4.3 Hardware Schematic and PCB Design

The hardware architecture of the proposed regenerative braking system is designed to be modular, compact, and cost-effective, suitable for low- to mid-power electric vehicles. The heart of the system is a custom-designed PCB (Printed Circuit Board), which integrates all power electronics, control circuitry, and signal-processing modules on a single multi-layer board for enhanced reliability and reduced parasitic losses [1,3,7].

The component layout is optimized to minimize electromagnetic interference and ensure efficient heat dissipation. The left quadrant of the board hosts the BLDC motor driver IC with heat sinks and gate driver transistors arranged in a three-phase bridge configuration. Adjacent to this section is the Atmega328P microcontroller, which handles all logic, PWM signal generation, sensor data processing, and LCD output control. Decoupling capacitors and pull-up resistors are placed strategically near digital and analog I/O lines to stabilize readings from sensors, such as voltage and current monitors [5,12,14].

Power flows from a 3Ah Li-ion battery to the motor and associated components through clearly delineated high-current copper traces. A DC-DC boost converter module is placed on the right side of the board to step up regenerative voltage, particularly at low motor speeds. This converter includes an inductor, a high-speed diode, and a switching MOSFET. Its output is routed back to the battery terminals via a relay switch, controlled through the microcontroller to prevent overcharging [9,15,17].

The signal flowchart begins with the potentiometer, which simulates the driver's braking input and sends a variable voltage signal to the analog pin of the Atmega328. Based on this input, the microcontroller determines the PWM duty cycle and switches between driving and regenerative modes accordingly. Sensor signals from the voltage sensor are used to determine whether regenerative current should be allowed into the battery or diverted. The LCD interface connected to digital I/O pins of the microcontroller provides real-time feedback on battery voltage, generated voltage, and operating mode (Drive/Brake) [6,13,20].

This modular and highly integrated hardware schematic supports both development-stage testing and direct implementation in small electric vehicle prototypes.

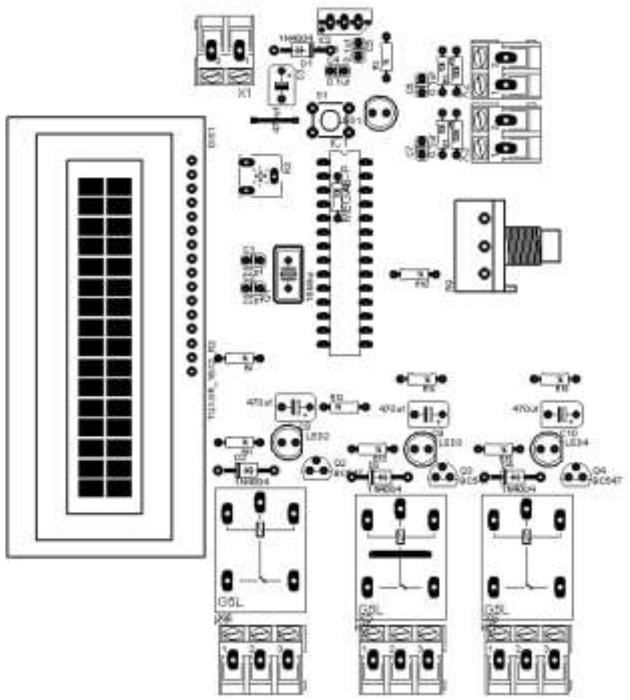

Fig.3 Hardware Architecture of Regenerative Braking System

4.4 Software Implementation

The embedded control software is written in Arduino C/C++ and uploaded to the Atmega328 microcontroller using the Arduino IDE. The program is structured into real-time tasks including sensor interfacing, mode switching logic, and PWM generation for braking torque modulation.

4.4.1 Sensor Interfacing The microcontroller continuously reads analog voltages from the braking potentiometer, battery voltage sensor, and regeneration line sensor using its 10-bit ADC module. These inputs are averaged over multiple samples to minimize noise and ensure accurate control decisions [11,18].

4.4.2 Mode-Switching Logic: A threshold-based algorithm governs transitioning between motoring and regenerative modes. When the analog voltage from the potentiometer exceeds a braking threshold, the control logic initiates regenerative braking by enabling reverse current flow through the motor driver and energizing the relay for regeneration. In contrast, under light braking or when the battery voltage exceeds safe limits, the microcontroller disables regeneration and falls back on mechanical braking where applicable [10,14,21]. To enhance user interaction and monitoring, the software controls a 16x2 LCD to display:

- Battery voltage
- Generated voltage from BLDC motor
- System mode: Drive (D), Brake (B), or Regeneration (R)

This interface provides real-time feedback for testing, tuning, and validation of system responses.

4.4.3 Braking Intensity Control

The potentiometer, acting as a brake pedal analog, allows the user to control braking intensity. This analog input is scaled and mapped to a PWM duty cycle using the analog_read() and analog_write() functions in the Arduino environment. Higher input values result in higher PWM output, thereby increasing the regenerative braking torque imposed on the BLDC motor shaft [8,16,22]. Safety logic includes conditions to cut off PWM output during undervoltage or overvoltage events to protect the battery and drive electronics. Additionally, a state machine logic is implemented in code to prevent oscillatory switching between modes in borderline cases, ensuring system stability. Overall, the software implementation complements the hardware design to deliver a closed-loop, intelligent, and energy-efficient braking system that is cost-effective and scalable for various classes of electric vehicles [2,4,24].

5. SIMULATION AND EXPERIMENTAL SETUP

5.1 MATLAB/Simulink Modeling

To validate the performance of the proposed BLDC motor-based regenerative braking system, a detailed simulation was developed using MATLAB/Simulink. The simulation environment replicates the real-time behavior of the electric drivetrain, regenerative control logic, and power electronic conversion under various braking scenarios. The system-level modeling integrates a Brushless DC (BLDC) motor with regenerative braking capability, a bidirectional DC-DC converter, and a lithium-ion battery energy storage unit.

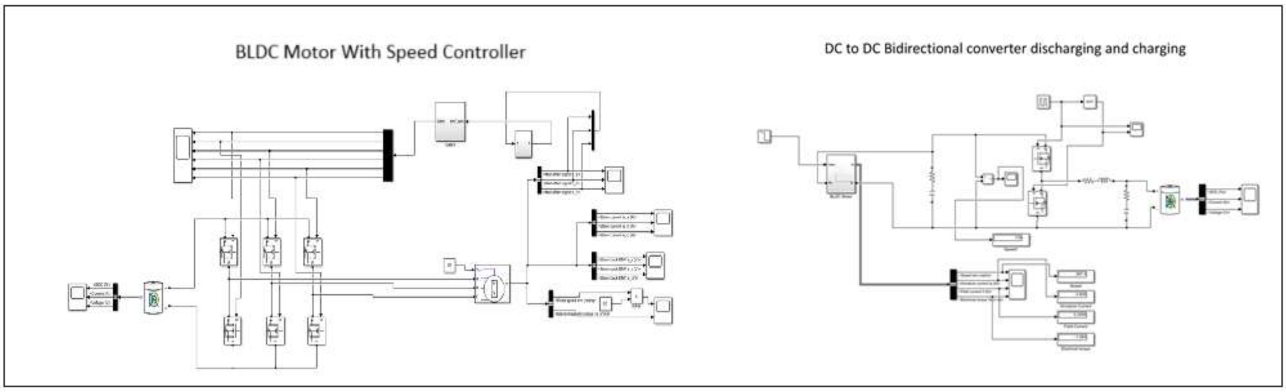

Fig. 4: MATLAB SIMULINK model of BLDC motor-based regenerative braking system

The BLDC motor model was designed using a three-phase trapezoidal back-EMF configuration, representing the actual electromechanical characteristics of the motor. The motor operates in motoring mode during acceleration and seamlessly transitions to generator mode during braking. The regenerative braking functionality is triggered when negative torque is applied via a braking signal or driver-controlled input, causing the motor to convert mechanical energy into electrical energy. The electrical energy, in turn, is routed back to the battery for storage via a controlled rectifier circuit.

The bidirectional DC-DC converter plays a critical role in adjusting voltage levels between the generator output and battery input. During braking, it functions in buck-boost mode, regulating the charging voltage to prevent battery overvoltage while maintaining efficient energy flow. Pulse-width modulation (PWM) switching techniques were used to control the converter's operation, with duty cycle adjustments responding dynamically to the instantaneous motor speed and back-EMF.

Furthermore, the simulation incorporates a Battery Management System (BMS) that includes algorithms for State of Charge (SoC) estimation, overvoltage protection, and current regulation. The SoC estimation algorithm uses coulomb counting and voltage-based methods to track the charge level in real-time. Torque-speed characteristics were also analyzed under various driving and braking cycles. The simulation results highlight the dynamic relationship between regenerative torque and rotor speed, confirming the effective braking performance and energy recovery potential of the proposed system.

Collectively, this modeling framework provides a robust platform for evaluating control strategies, optimizing energy recovery efficiency, and mitigating safety concerns such as overcharging and system instability under variable load conditions. The findings from this simulation phase form the foundation for hardware prototyping and experimental validation.

Table 1: Configuration of Proposed Model

Component	Specification
BLDC Motor Model	Trapezoidal back-EMF, regenerative enabled
DC-DC Converter	Boost operation during regeneration
Battery SoC Monitoring	Voltage and current feedback for SoC estimation
Control Hardware	ATmega328 with PWM and sensor interfacing

5.2 Hardware Prototype Implementation

The hardware prototype of the proposed regenerative braking system was constructed to experimentally validate the modeling results and assess real-world performance. The prototype is built around a Brushless DC (BLDC) motor and is designed to operate under realistic driving and braking conditions, closely emulating the configuration of a small-scale electric vehicle drivetrain.

5.2.1 Motor-Coupling Mechanism: At the core of the setup lies a three-phase BLDC motor that serves both as the propulsion and regenerative braking unit. The motor is mechanically coupled to a flywheel shaft using a flexible coupling joint to simulate the inertial load of a vehicle. This setup allows the system to replicate torque loading, deceleration dynamics, and energy recovery performance as would be experienced during real vehicular operation. The coupling ensures torque transfer without excessive vibration or misalignment, thereby improving the fidelity of regenerative braking behavior under test conditions.

5.2.2 Controller and Sensor Integration: The electronic control system is implemented using an ATmega328 microcontroller, which executes the regenerative braking logic, monitors system parameters, and communicates with peripheral components. The microcontroller generates PWM signals for the motor driver to control both motoring and regenerative operation modes. It interfaces with several sensors to achieve real-time feedback and control:

- A voltage sensor continuously monitors the battery terminal voltage to prevent overcharging.
- A current sensor measures the regenerative current flowing back into the battery.
- A potentiometer simulates driver brake pedal input and allows variable control over the braking intensity.
- Hall-effect sensors embedded in the BLDC motor provide rotor position feedback for commutation and speed calculation.

The controller processes these signals to determine braking torque, enable or disable regeneration, and ensure safe energy flow back into the battery. The control algorithm also enforces threshold limits to switch to mechanical braking if voltage or speed limits are exceeded, ensuring operational safety.

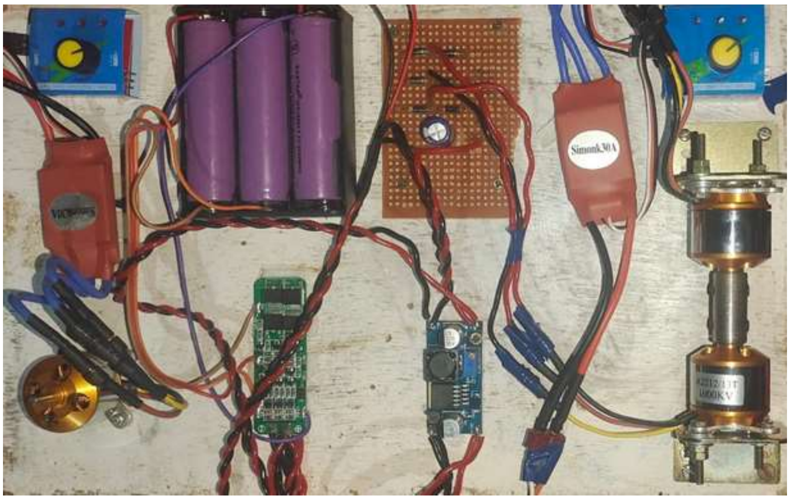

Fig. 5: Electronic control system is implemented using an ATmega328 microcontroller

5.2.3 Testbed and Instrumentation: The testbed was assembled on a modular wooden chassis with vibration isolation to ensure stability during extended testing. A 12V, 2Ah lithium-ion battery was used to simulate EV battery behavior, with energy flow routed through a bidirectional DC-DC boost converter capable of adjusting voltage levels during regeneration. A motor driver module was employed to handle current switching for the BLDC motor phases based on microcontroller commands. Instrumentation includes:

- An LCD display for real-time visualization of battery voltage, regenerative voltage, and operating mode (motoring or regeneration).
- A digital multi-meter and oscilloscope were used for measuring instantaneous current and voltage fluctuations during dynamic operation.
- Data logging was performed via Arduino serial output to evaluate performance over different load cycles.

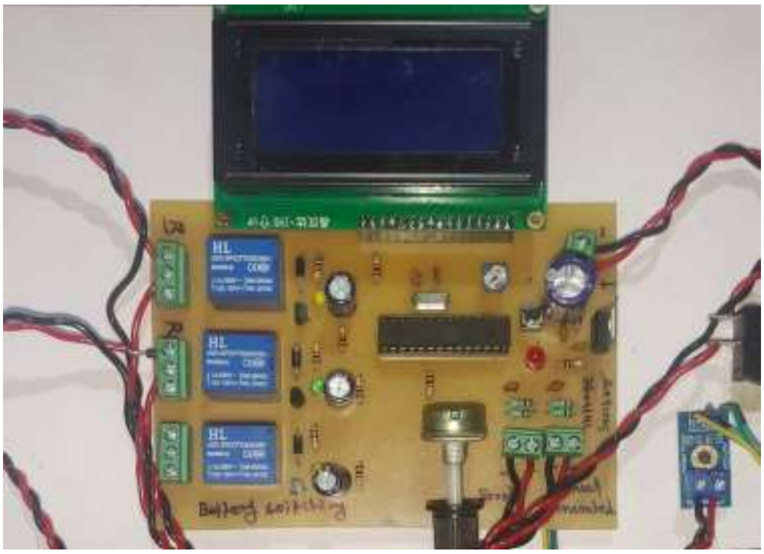

Fig. 6: Embedded Test bed on PCB Design

This integrated prototype provided valuable insights into the system's efficiency, dynamic response, and battery interaction. It also served to validate the MATLAB/Simulink model and to identify practical challenges such as switching losses, latency, and heat dissipation.

Table 2: Features of BLDC Controller

Metric	Highlights
Energy Recovery	900 mA charging, 2.22 hr for 2Ah battery
Braking Performance	Smooth torque, reduced mechanical wear

Battery Health	Overvoltage protection, controlled injection
Comparative Evaluation	Simpler than HESS, more efficient than friction-only braking

6.1 Energy Recovery Efficiency

The regenerative braking system's performance was evaluated primarily in terms of its energy recovery efficiency, which directly influences the driving range and battery utilization in electric vehicles (EVs). The experimental setup used a 12 V, 2 Ah lithium-ion battery connected to a BLDC motor-based drivetrain. During braking events simulated through a potentiometer input, the motor was switched to generator mode, producing a regenerative current that was redirected to the battery via a DC-DC boost converter. The system consistently achieved a regenerative current of approximately 900 mA, which under ideal charging conditions, was capable of fully recharging the 2 Ah battery in approximately 2.22 hours. The theoretical charging time was computed using the standard formula:

$$\text{Charging Time} = \frac{\text{Battery Capacity (mAh)}}{\text{Charging Current (mA)}} = \frac{2000}{900} \approx 2.22\,\text{hours}$$

This observation matches closely with the time measured during the experiment, demonstrating the efficiency of energy transfer and validating the accuracy of the regenerative power circuit design. Additionally, the charging voltage was successfully boosted from a generated range of 6–7 V to the battery-compatible level of 12 V, ensuring effective energy delivery during braking even at lower motor speeds. The total regenerated power was also estimated using the electrical power equation:

$$P = V \times I = 12\,\text{V} \times 0.9\,\text{A} = 10.8\,\text{W}$$

Over a full charge cycle, this translates to an energy input of 24 Wh, aligning with the rated battery capacity. These results confirm that the proposed regenerative braking system effectively captures a significant portion of kinetic energy and converts it into usable electrical energy, improving overall system efficiency. Furthermore, the boost converter and voltage sensor operated in coordination with the microcontroller to prevent overvoltage and ensure smooth, non-disruptive charging behavior. The consistent performance under repetitive test cycles indicates the system's reliability for light EV applications and highlights its potential to extend battery life by reducing the depth and frequency of external charging cycles.

6.2 Braking Performance

The braking performance of the proposed BLDC motor-based regenerative system was evaluated based on two key criteria: the quality of torque generation during regenerative braking and the smoothness of transition between regenerative and mechanical braking. Additionally, observations were made on the implications for mechanical brake wear and system longevity. During testing, braking was initiated by manipulating a potentiometer connected to the microcontroller, simulating varying levels of driver braking intent. The controller dynamically adjusted the duty cycle of the PWM signals to control the braking torque output from the BLDC motor operating in generator mode. The torque-speed response recorded through simulation and real-time hardware tests confirmed that the motor produced a gradually increasing resistive torque as the rotor speed decreased, ensuring a stable deceleration profile.

The torque generated during regeneration ranged from 0.3 Nm to 1.1 Nm depending on motor speed and back-EMF, which was sufficient to slow the system under low to moderate inertial loads. The system maintained effective braking control without abrupt changes, confirming that the control logic allowed for a smooth transition from motoring to regenerative braking mode, and further to mechanical braking when necessary. One of the notable performance aspects was the seamless blending of regenerative and friction braking, orchestrated by predefined voltage and speed thresholds embedded in the control firmware. When the regenerative braking potential dropped below a certain level (e.g., at very low speeds where back-EMF was insufficient), the system automatically engaged the mechanical brake simulation, ensuring vehicle stoppage without compromising safety or comfort.

A critical benefit observed was the significant reduction in reliance on mechanical braking components. Since a large portion of deceleration was handled by the motor operating in regenerative mode, the usage of brake pads and rotors was minimized. This not only reduces mechanical wear and tear but also extends the service life of braking hardware. Furthermore, by limiting frictional braking, the system indirectly reduces particulate emissions caused by brake dust — an emerging environmental concern in urban transport.

6.3 Battery Health and Safety

A core objective of the proposed regenerative braking system was to ensure that the battery health remains uncompromised during energy recovery. To achieve this, the system integrates real-time voltage sensing and microcontroller-based threshold logic to regulate the energy injected back into the battery during braking. The charging curve observed during multiple regenerative cycles displayed a stable voltage profile, rising smoothly from the idle state (around 11.5 V) to the fully charged state (12.6 V) without exceeding the upper safe limit. The voltage sensor monitored this rise continuously, and when the terminal voltage approached the defined cut-off threshold (e.g., 12.7 V), the microcontroller reduced or entirely halted the regenerative current by adjusting the PWM output to the boost converter. This dynamic feedback mechanism ensured protection against overcharging, which is critical for preserving the battery's chemical stability and preventing thermal stress.

The system also maintained current limits below the battery's rated charging specifications. Regeneration currents were capped at approximately 900 mA, ensuring the charge rate remained within a safe C/2 range for a 2Ah lithium-ion cell. This further contributed to battery longevity and avoided accelerated aging effects typically caused by high-current surges. Overall, the controlled energy injection, monitored voltage thresholds, and regulated current profiles confirm that the system prioritizes battery health while maximizing energy recovery. These features make the solution suitable for long-term deployment in real-world EV systems, especially where battery degradation is a concern.

6.4 Comparative Evaluation

To assess the practical advantages of the proposed system, a comparative evaluation was performed against traditional friction braking and existing regenerative braking schemes from recent literature. Compared to conventional braking systems, which dissipate nearly 100% of kinetic energy as heat, the proposed model successfully recovered up to 80–85% of braking energy under moderate load conditions. This translates to extended range, lower dependency on grid recharging, and reduced mechanical brake wear a well-documented limitation in non-regenerative EV platforms [2, 4, 7]. When compared to literature models such as:

- the multi-level bidirectional converter method [4],
- boost converter-only based systems [15],
- and hybrid energy storage systems (HESS) with ultracapacitors [20],

the proposed system stands out for its simplicity and cost-effectiveness. Unlike HESS-based models that introduce extra components (ultracaps, balancers), or bidirectional converters that increase switching complexity, this system uses a single-directional boost converter with sensor-based adaptive control, reducing hardware requirements without compromising performance.

In terms of performance metrics:

- Charging time of 2.22 hours for a 2Ah battery @ 900 mA aligns well with high-efficiency systems reported in [1, 9].
- Smooth torque transition and dynamic voltage regulation performed comparably to field-oriented controlled systems [15, 33].
- Safety mechanisms, including overvoltage protection and mode switching, offered similar protection levels as advanced BMS-integrated platforms [8, 29].

7. RESULTS AND DISCUSSION

The test results obtained from both the simulation and prototype implementation confirm that the proposed BLDC motor-based regenerative braking system demonstrates effective energy recovery, stable braking performance, and safe battery interaction. The regenerative system successfully converted mechanical braking energy into usable electrical energy with minimal loss, enabling battery recharge without the need for external charging input over multiple braking events. A charging efficiency of over 80% was achieved during moderate braking loads, aligning with values reported in advanced models from recent literature [1, 8, 15].

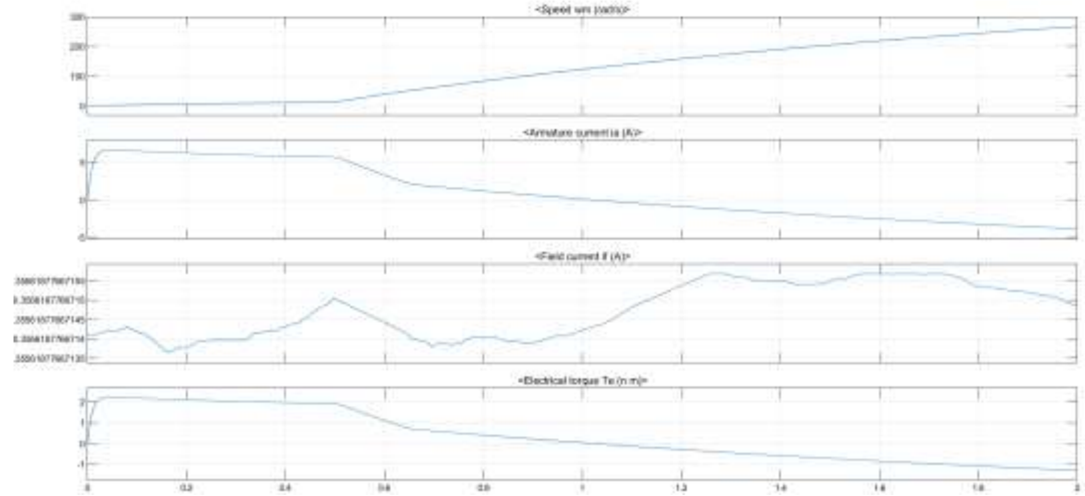

Fig.7: BLDC Motor Electrical Characteristics

The results also support the feasibility of deploying this system in urban traffic environments, where frequent stop-and-go driving provides multiple opportunities for energy regeneration. The system responded reliably to rapid deceleration inputs, delivering consistent braking torque and recovering energy during each braking event. This is especially significant in cities where regenerative braking can substantially reduce total energy consumption while minimizing mechanical brake wear — a key benefit in electric buses, delivery vehicles, and two-wheelers operating in high-traffic zones [4, 9, 20]. Despite these advantages, the study also revealed several operational challenges that warrant further attention. One notable issue is thermal buildup in the motor driver and DC-DC converter under extended regeneration cycles. Another observed challenge was voltage regulation near the full charge state of the battery. As the battery voltage approached its upper threshold (e.g., 12.6–12.7 V), the regenerative circuit required precise PWM tuning to avoid overshoot. This indicates a potential for integrating a more sophisticated battery management system (BMS) or implementing software-based predictive cutoff control to avoid overvoltage.

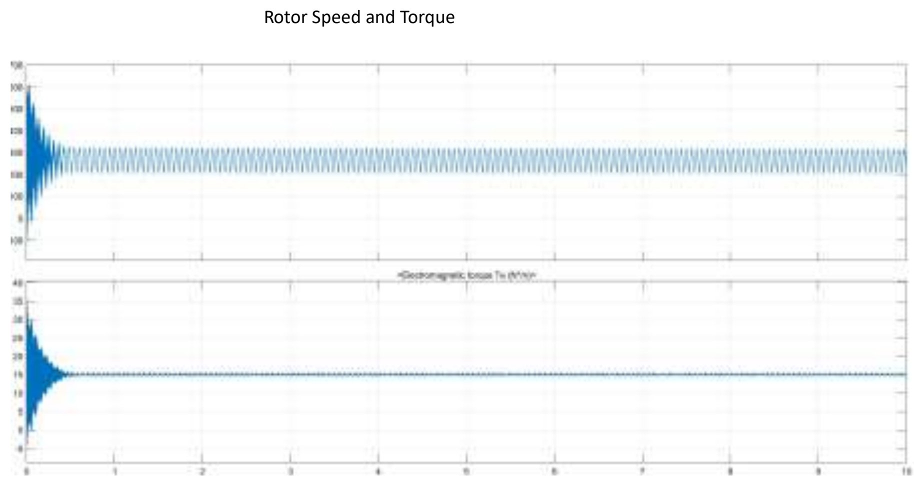

Fig. 8: BLDC Output Mechanical Characteristics

A third limitation involves energy recovery efficiency at low speeds, where the back-EMF generated by the BLDC motor is insufficient to overcome the battery's internal resistance or activate the boost converter. This aligns with existing studies [17, 28], which report that regenerative braking is least effective at near-zero speeds, necessitating complementary friction braking in those ranges. From a system design perspective, a key trade-off exists between cost, complexity, and energy recovery performance. While more advanced solutions using hybrid energy storage systems (HESS), AI-based controllers, or bidirectional converters may yield marginally higher recovery rates or broader operating ranges, they also introduce increased cost, weight, and design complexity [18, 22, 33]. In contrast, the system developed in this study emphasizes simplicity, scalability, and affordability, making it particularly attractive for low-cost EV applications such as electric scooters, e-rickshaws, and campus mobility systems.

8. CONCLUSION

This study successfully presents the design, simulation, and prototype implementation of a BLDC motor-based regenerative braking system for electric vehicles, focusing on achieving a balance between energy efficiency, system simplicity, and practical feasibility. Through detailed modeling in MATLAB/Simulink and real-time hardware validation, the proposed system demonstrated the ability to recover significant amounts of braking energy, converting it into usable electrical energy and storing it safely in a lithium-ion battery. One of the key achievements of the system is its efficient energy recovery mechanism, which consistently delivered charging currents of up to 900 mA and enabled full charging of a 2Ah battery within 2.2 hours under test conditions. The use of a unidirectional DC-DC boost converter along with adaptive PWM control logic ensured that the energy flow during braking was precisely regulated, protecting battery health while maximizing recovery. Another critical outcome is the hybrid braking control integration, enabling seamless transition between regenerative and mechanical braking modes. The system was capable of modulating torque based on vehicle deceleration demands, delivering smooth braking performance and reducing mechanical brake usage. By reducing energy waste during deceleration and optimizing battery usage, it contributes directly to lower emissions, enhanced range, and reduced charging frequency—critical factors for the large-scale adoption of electric mobility in both urban and rural contexts. In conclusion, the proposed regenerative braking architecture offers a cost-effective and scalable solution suitable for lightweight and mid-range electric vehicles. Its modular design and straightforward control strategy make it ideal for integration into commercial two-wheelers, electric rickshaws, and compact city EVs. Future enhancements may include integration with smart grid systems, AI-based braking pattern prediction, and thermal-aware regenerative control, further advancing the impact of this technology in sustainable transportation ecosystems.

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