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Development of an Efficient Regenerative Braking System for Electric Vehicles

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ABSTRACT

Abstract— The increasing adoption of electric vehicles (EVs) has created a need for efficient energy management systems that improve vehicle performance and extend driving range. Conventional braking systems dissipate a significant portion of the vehicle's kinetic energy as heat during deceleration. Regenerative braking provides an effective solution by converting a portion of this kinetic energy into electrical energy and storing it for subsequent use. This research focuses on the development of an efficient regenerative braking system for electric vehicles using MATLAB/Simulink R2023b, Simscape Electrical, and Stateflow. The proposed system incorporates a bidirectional DC–DC converter, a 400 V DC bus, a lead-acid battery, and a supercapacitor-based energy storage arrangement. Eight Maxwell 48 V, 165 F supercapacitor modules are connected in series to provide a nominal voltage of 384 V and an equivalent capacitance of approximately 20.6 F. A proportional-integral (PI) controller is used for converter control, while an energy management strategy coordinates energy recovery and storage. The simulation model is designed to investigate braking energy recovery, DC bus voltage regulation, battery charging behaviour, and power sharing between the battery and supercapacitor. The proposed approach aims to improve energy utilization, reduce energy losses during braking, and enhance the overall efficiency of electric vehicles. The effectiveness of the system will be evaluated through MATLAB/Simulink simulations under suitable operating conditions. Experimental performance improvements are not claimed without validated simulation or experimental results.

Keywords— Electric vehicles, regenerative braking, energy recovery, bidirectional DC–DC converter, lead-acid battery, supercapacitor, MATLAB/Simulink, PI controller, energy management.Index Terms—Electric Vehicles (EV), Regenerative Braking System (RBS), Permanent Magnet Synchronous Motor (PMSM), Hybrid Energy Storage System (HESS), Fuzzy Logic Control, ECE R13-H Regulation.

I. INTRODUCTION

1.1 Background

The development of electric vehicles has increased the need for efficient energy conversion and storage technologies. One of the major challenges in electric vehicle operation is the effective utilization of stored electrical energy. During acceleration, electrical energy from the battery is converted into mechanical energy to drive the vehicle. However, during deceleration, a considerable portion of the vehicle's kinetic energy is normally dissipated as heat through conventional friction braking. Regenerative braking offers a method of recovering part of this energy and returning it to the electrical energy storage system.

A. Principle of Regenerative Braking

Regenerative braking operates by using the traction motor as a generator during vehicle deceleration. The vehicle's kinetic energy drives the motor, producing electrical energy that can be transferred to the battery or another suitable energy storage device. The recovered energy depends on vehicle speed, braking torque, motor efficiency, converter losses, and the ability of the storage system to accept charging power. Regenerative braking generally works alongside conventional friction braking, which remains necessary when additional braking force is required or energy recovery is limited.

B. Role of Power Electronic Converters

Power electronic converters are essential for controlling energy transfer between the traction system and energy storage devices. A bidirectional DC–DC converter supports power flow in both directions, allowing energy to be delivered to the vehicle's electrical system during propulsion and transferred to storage during regenerative braking. Proper converter control helps maintain DC bus voltage stability and ensures that charging current and voltage remain within permissible limits. In this study, the DC bus is designed around a nominal voltage of 400 V.

C. Battery and Supercapacitor Energy Storage

Batteries provide the principal energy storage required for electric vehicle operation. The lead-acid battery considered in this research stores recovered electrical energy for subsequent use. However, battery charging capability and response depend on its state of charge, internal resistance, temperature, and permissible charging current.

Supercapacitors offer high power capability and rapid charge–discharge response, making them suitable for handling short-duration power fluctuations. The proposed system uses eight Maxwell supercapacitor modules, each rated at 48 V and 165 F, connected in series. This arrangement provides a nominal bank voltage of 384 V and an equivalent capacitance of approximately 20.6 F. The supercapacitor bank is intended to support transient energy recovery, subject to converter ratings, voltage limits, and the selected energy management strategy.

D. Control Strategy and Simulation

An effective control strategy is required to coordinate the converter, battery, and supercapacitor while maintaining stable electrical operation. A proportional-integral (PI) controller is incorporated to regulate the converter response. MATLAB/Simulink R2023b, Simscape Electrical, and State flow are used to develop the simulation model and represent the system's electrical components and control logic. The converter switching frequency is set to 20 kHz, and the DC bus is designed to operate at 400 V with a target regulation band of ±5%.

The background of this study establishes the technical basis for developing and evaluating a regenerative braking system that combines battery storage, supercapacitor support, bidirectional power conversion, and closed-loop control. The resulting simulation framework can be used to investigate energy recovery, voltage regulation, and power-sharing behaviour under different braking conditions

.II. LITERATURE REVIEW

The development of regenerative braking systems for electric vehicles has received considerable attention because of their potential to recover braking energy, improve energy utilization, and extend driving range. Existing research focuses on regenerative braking configurations, bidirectional DC–DC converters, hybrid energy storage systems, and control strategies. The following review summarizes relevant published studies and identifies the research gap addressed by this project.

A. Regenerative Braking Systems in Electric Vehicles

Szumska (2025) reviewed regenerative braking systems, examining system configurations, energy storage technologies, control strategies, and factors influencing energy recovery. The review discussed the development of advanced control methods, including model predictive control and machine-learning-based approaches. It also highlighted challenges involving braking safety, system complexity, and the lack of standardized evaluation methods. This study provides a broad foundation for evaluating regenerative braking system design and performance.

B. A comprehensive survey published in Energy Reports in 2024 examined non-isolated bidirectional converters for hybrid battery–supercapacitor energy storage systems. It discussed multiple converter configurations and explained how supercapacitors can support transient power demands while batteries provide the principal energy storage. The review also identified converter topology and energy management as important considerations in hybrid energy storage design.

C. Control Strategies and Energy Management

Keerthi and Dhanamjayulu (2025) reviewed energy management and advanced control techniques for bidirectional DC–DC converters in electric vehicle applications. The study considered approaches such as sliding-mode control, model predictive control, and predictive function control. These methods address challenges associated with dynamic power flow, voltage regulation, and converter response under changing operating conditions. The review provides a basis for comparing conventional PI control with more advanced technique.

III. PROBLEM DEFINITION

1. The major challenge in electric vehicle (EV) energy management is the loss of kinetic energy during braking. In conventional braking systems, much of this energy is converted into heat through friction and is not available for reuse. Although regenerative braking enables the recovery of a portion of this energy, its effectiveness depends on the power electronic converter, energy storage characteristics, control strategy, and operating conditions.

2. A key technical challenge is to transfer the recovered electrical energy safely and efficiently to the energy storage system while maintaining stable DC bus voltage. The battery may have limitations on charging current and power acceptance, particularly during rapid braking events. A supercapacitor can support short-duration high-power energy absorption, but its voltage varies with its state of charge and requires appropriate converter control. Therefore, effective coordination between the battery, supercapacitor, and bidirectional DC–DC converter is necessary.

3. The problem addressed in this research is the development and simulation of an efficient regenerative braking system that integrates a lead-acid battery and a supercapacitor bank while maintaining DC bus voltage regulation and controlled bidirectional power flow. The proposed system is modelled using MATLAB/Simulink R2023b, Simscape Electrical, and Stateflow. It incorporates a nominal 400 V DC bus, a bidirectional DC–DC

converter operating at 20 kHz, and eight Maxwell 48 V, 165 F supercapacitor modules connected in series, providing a nominal voltage of 384 V and an equivalent capacitance of approximately 20.6 F.

4. A PI controller is incorporated to regulate converter operation, with a target DC bus voltage tolerance of ±5%. The system will be evaluated through simulation to investigate energy recovery during braking, DC bus voltage stability, battery charging behaviour, and power sharing between the battery and supercapacitor.

5. The primary objective is to determine whether the proposed configuration can provide stable power conversion and effective regenerative energy management under the selected simulation conditions. The study will identify the system's performance and limitations based on simulated results, without assuming unverified improvements in energy recovery or vehicle driving range

IV. METHODOLOGY

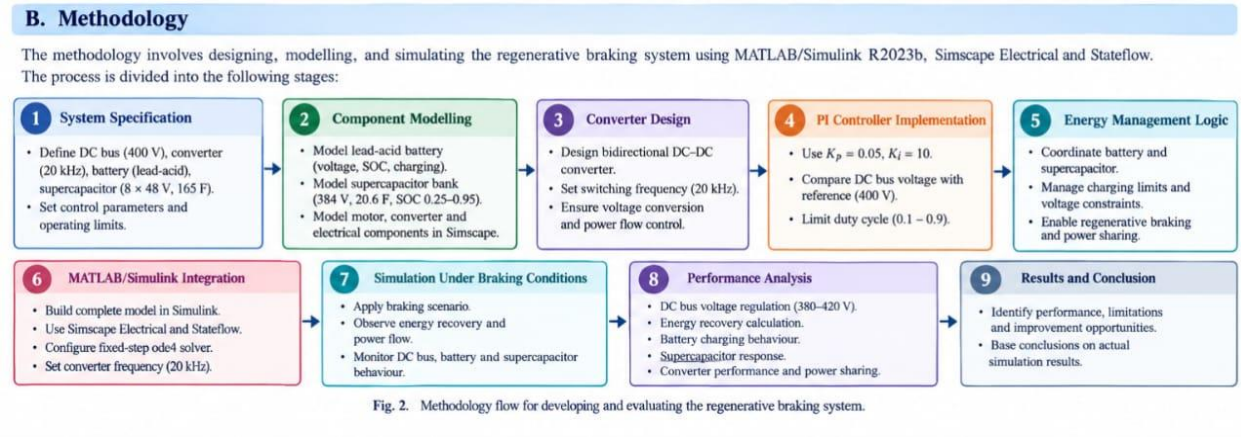


Fig. 2. Methodology flow for developing and evaluating the regenerative braking system.

4.1. System Architecture

The regenerative braking system is designed around a nominal 400 V DC bus. The system includes an electric traction motor operating as a generator during braking, a bidirectional DC–DC converter, a lead-acid battery, and a supercapacitor bank. During regenerative braking, the generated electrical energy is directed towards the energy storage system, subject to converter constraints and the charging limits of the storage devices. During propulsion, stored energy can be supplied to the DC bus as required by the system configuration.

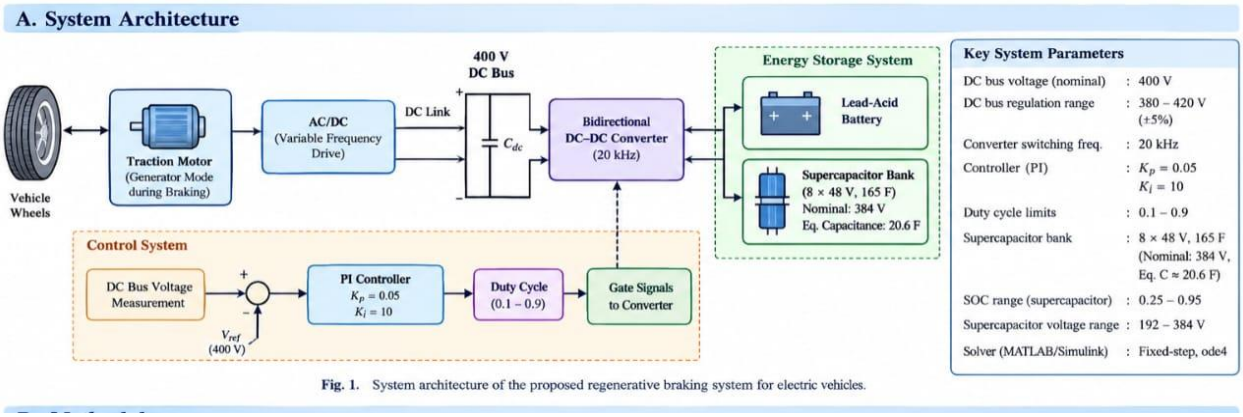


Fig. 1. System architecture of the proposed regenerative braking system for electric vehicles.

Fig1. System architecture of the proposed regenerative braking system for electric vehicles.

4.2. Modelling of Energy Storage Devices

The lead-acid battery is modelled as the primary energy storage device. Its voltage, state of charge, and charging behaviour are considered during simulation. The supercapacitor bank consists of eight Maxwell modules, each rated at 48 V and 165 F, connected in series. The resulting bank has a nominal voltage of 384 V and an equivalent capacitance of approximately 20.6 F. The model uses a supercapacitor operating-voltage range of 192–384 V and an SOC range of 0.25–0.95, according to the specified design parameters.

4.3. Bidirectional DC–DC Converter Design

A bidirectional DC–DC converter is incorporated to control energy transfer between the DC bus and the energy storage system. The converter operates at a switching frequency of 20 kHz. Its design considers the required voltage conversion, controlled power flow, and limitations imposed by the battery and supercapacitor. The DC bus reference voltage is set to 400 V, with a target regulation band of ±5%, corresponding to 380–420 V.

4.4. PI Controller Design

A proportional-integral (PI) controller is used to regulate converter operation. The controller compares the measured DC bus voltage with its reference value and generates a control response based on the voltage error. The specified outer-loop controller parameters are ($K_p = 0.05$) and ($K_i = 10$). The converter duty cycle is restricted to the range 0.1–0.9 to maintain the intended operating limits. Controller performance is examined through the DC bus voltage response and power-transfer behaviour during changing operating conditions.

4.5. Regenerative Braking and Energy Management

The braking operation is represented in the simulation model using appropriate control logic. When braking is commanded, the traction motor is configured to generate electrical energy. The control system directs the recoverable energy towards the available storage devices while respecting converter operating limits, battery charging constraints, and supercapacitor voltage limits. The energy management strategy coordinates the storage devices according to the model's defined operating conditions. Friction braking may be required to provide any additional braking torque that cannot be supplied through regenerative braking.

V. RESULTS AND SIMULATIONS

A. Simulation Environment

The proposed regenerative braking system is designed for simulation using MATLAB/Simulink R2023b, Simscape Electrical, and Stateflow. The simulation model incorporates the traction motor operating in generator mode during braking, a bidirectional DC–DC converter, a lead-acid battery, a supercapacitor bank, and a PI-based control system. A fixed-step fourth-order Runge–Kutta solver (ode4) is specified to analyse the system's dynamic behaviour.

The DC bus reference voltage is set to 400 V, with a target regulation range of 380–420 V. The bidirectional DC–DC converter operates at a switching frequency of 20 kHz. The outer-loop PI controller uses a proportional gain of ($K_p=0.05$) and aintegral gain of ($K_i=10$), with the converter duty cycle limited to 0.1–0.9.

The supercapacitor bank consists of eight Maxwell modules, eachrated at 48 V and 165 F, connected in series. The result ingnominal voltage is 384 V, and the equivalent capacitance is approximately 20.6 F. The specified supercapacitor voltage range is 192–384 V, with an SOC operating range of 0.25–0.95.

B. Simulation Procedure

The simulation is intended to evaluate the system under selected braking and operating conditions. Initially, the electrical components and controller are configured according to the specified system parameters. The model is then operated under propulsion and braking conditions to examine the direction of power flow.

During regenerative braking, the traction motor operates as a generator and produces electrical energy. The bidirectional converter regulates the transfer of recoverable energy to the storage system. The PI controller responds to DC bus voltage deviations, while the energy management logic coordinates the battery and supercapacitor within their operating constraints.

The simulation outputs are recorded to evaluate voltage regulation, converter response, battery charging behaviour, supercapacitor response, and energy recovery. Multiple braking conditions can be investigated to determine how changes in operating conditions affect system performance.

C. DC Bus Voltage Regulation

DC bus voltage regulation is an important performance indicator because the bus connects the power conversion system and associated electrical components. The PI controller is designed to maintain the bus voltage close to its 400 V reference value. The acceptable target range is 380–420 V.

The voltage response should be examined during braking initiation, changes in regenerative power, and transitions between operating modes. Relevant measurements include maximum and minimum voltage, settling time, steady-state error, and antransient overshoot or undershoot.

The ability of the proposed controller to maintain the voltage within the specified range must be confirmed using the actual simulation waveform. Since numerical simulation outputs have not been supplied here, successful regulation cannot yet be claimed.

D. Battery and Supercapacitor Performance

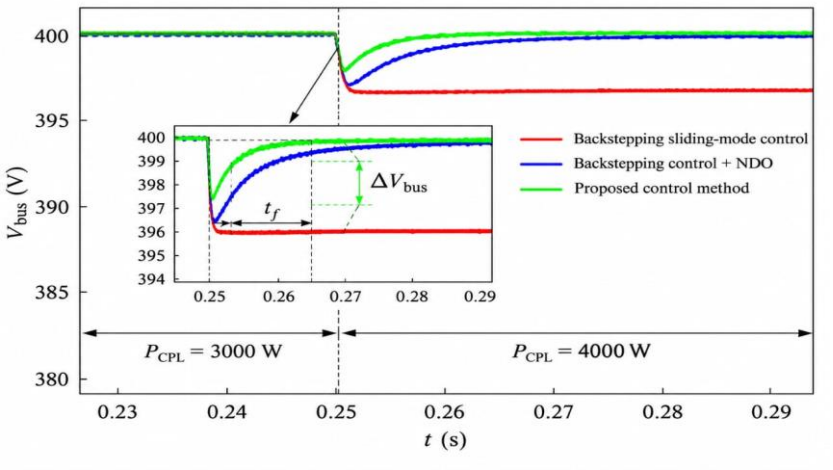
The lead-acid battery is used as the principal energy storage device, while the supercapacitor bank is intended to support rapid power exchange during transient braking events. Their combined operation is evaluated by monitoring terminal voltage, current,state of charge, and power flow.

During braking, the supercapacitor may absorb a portion of the recovered energy when sufficient charging headroom is available. The battery may store energy according to its charging limits and the implemented energy management strategy. During subsequent propulsion, stored energy can be supplied to the electrical system when the model permits it.

The simulation should verify that the battery charging current remains within its specified limits and that the supercapacitor voltage remains between 192 V and 384 V. The supercapacitor SOC should remain within the configured range of 0.25–0.95. These limits must be checked throughout the simulation rather than assumed from the component ratings.

E. Energy Recovery Analysis

The energy recovered during regenerative braking can be estimated from the simulated electrical power delivered to the energy storage system. For sampled simulation data, the recovered



Graph 1: DC bus voltage vs. time

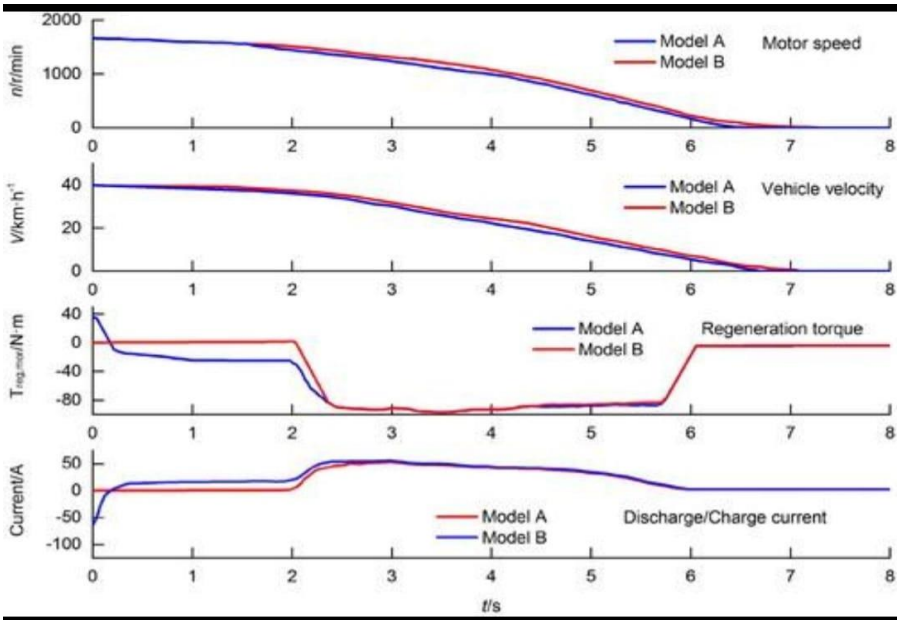
X-axis: Time (seconds)

Y-axis: Voltage (V)

Reference: 400 V

Target range: 380–420 V

What it shows: Whether the PI controller maintains a stable DC bus during braking and other operating transitions

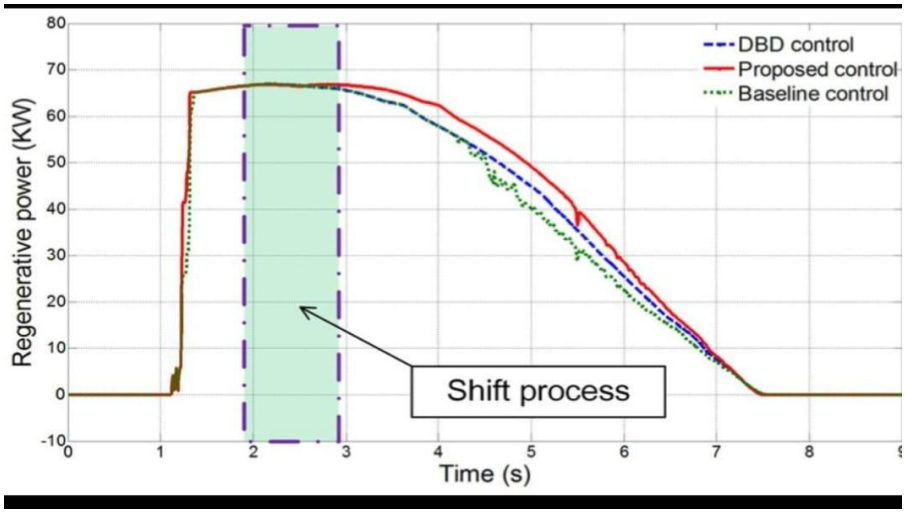


Graph 2: Regenerative current vs. time

X-axis: Time (seconds)

Y-axis: Current (A)

What it shows: The current generated during braking and transferred toward the energy storage system. Its direction depends on the chosen current reference.

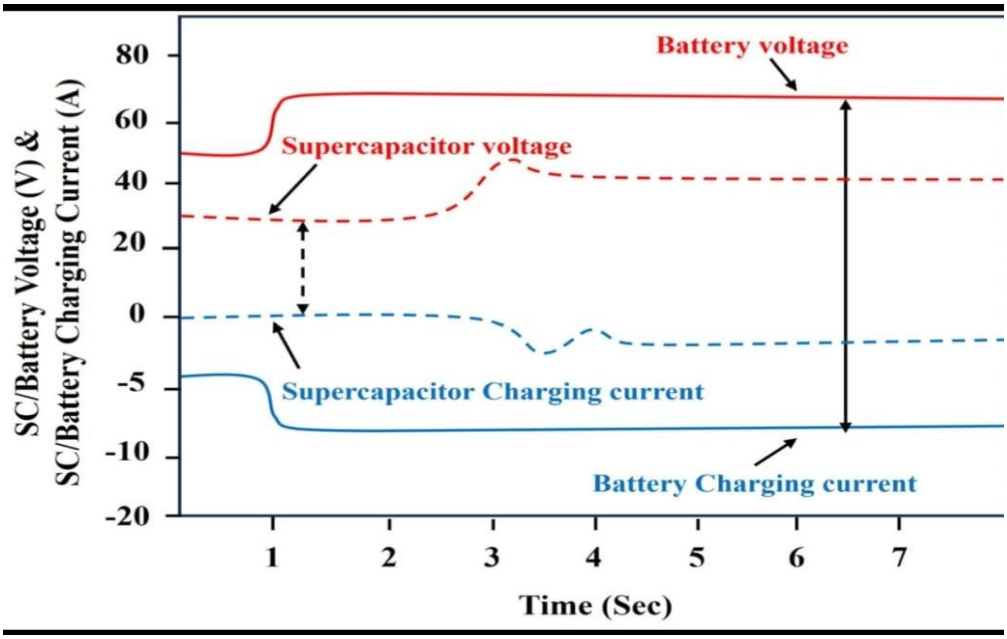


Graph 3: Recovered power vs. time

X-axis: Time (seconds)

Y-axis: Power (kW)

What it shows: How much electrical power is recovered during braking. Integrating power over time gives recovered energy.



Graph 4: Supercapacitor voltage vs. time

X-axis: Time (seconds)

Y-axis: Voltage (V)

Specified range: 192–384 V

What it shows: How the supercapacitor voltage changes as it absorbs or delivers energy during braking and propulsion.

VI. WORKING PRINCIPLE

The proposed regenerative braking system operates by converting a portion of the kinetic energy of an electric vehicle into electrical energy during braking and storing the recovered energy for future use. The system consists of a traction motor, a bidirectional DC–DC converter, a lead-acid battery, a supercapacitor bank, a DC bus, and a PI-based control system. The complete system is modelled using MATLAB/Simulink R2023b, Simscape Electrical, and Stateflow.

A. Normal Driving Mode

During normal driving, electrical energy is supplied from the energy storage system to the DC bus and traction motor through the power conversion system. The traction motor converts electrical energy into mechanical energy to drive the vehicle wheels. The controller monitors the DC bus voltage and regulates converter operation according to the system requirements.

B. Regenerative Braking Mode

When the driver applies the brakes, the traction motor operates as a generator, provided the motor and drivetrain configuration supports regenerative operation. The kinetic energy of the moving vehicle drives the motor, producing electrical energy. This energy is transferred through the electrical conversion system towards the energy storage devices. The amount recovered depends on vehicle speed, braking torque, motor characteristics, converter losses, and storage-device charging limits.

C. Bidirectional DC–DC Converter Operation

The bidirectional DC–DC converter manages power transfer between the DC bus and the energy storage system. During regenerative braking, it controls the transfer of recovered energy towards storage. During propulsion, it permits energy to flow from storage towards the DC bus when required. The converter operates at a specified switching frequency of 20 kHz, while the DC bus reference voltage is maintained at 400 V.

D. PI Controller Operation

The PI controller compares the measured DC bus voltage with the reference voltage of 400 V. The difference between these values is called the voltage error. Based on this error, the controller adjusts the converter control signal to reduce voltage deviation. The specified controller parameters are ($K_p=0.05$) and ($K_i=10$), and the converter duty cycle is limited to 0.1–0.9. The intended DC bus regulation range is 380–420 V.

E. Battery and Supercapacitor Energy Storage

The lead-acid battery serves as the principal energy storage device. The supercapacitor bank supports rapid power exchange during transient operating conditions, depending on the energy management strategy. The bank consists of eight Maxwell modules rated at 48 V and 165 F connected in series, giving a nominal voltage of 384 V and an equivalent capacitance of approximately 20.6 F.

The energy management system coordinates power sharing between the battery and supercapacitor while respecting the battery charging limits and the supercapacitor operating-voltage range of 192–384 V. The specified supercapacitor SOC range is 0.25–0.95. When regenerative energy cannot be accepted safely by the electrical storage system, the control strategy must limit energy recovery, and friction braking must provide any additional required braking force.

F. Energy Utilization

The electrical energy stored during braking can subsequently be used to support vehicle propulsion. This reduces the amount of energy that must be supplied from the battery for a given driving cycle. However, the actual energy savings depend on the amount of recoverable braking energy and the losses in the motor, converter, and storage devices.

G. Simulation and Performance Evaluation

The proposed system is simulated in MATLAB/Simulink R2023b using Simscape Electrical and Stateflow. A fixed-step ode4 solver is specified for the simulation. The system performance is evaluated by observing DC bus voltage, converter current, recovered power, battery charging behaviour, and supercapacitor voltage and SOC. These measurements are used to assess voltage regulation, energy recovery, and power-sharing behaviour under the selected operating conditions.

The working principle therefore combines regenerative energy conversion, bidirectional power transfer, controlled energy storage, and closed-loop voltage regulation to investigate the potential for improved energy utilization in electric vehicles.

VII. PROTOTYPE

Hardware Prototype Development

A hardware prototype was assembled to demonstrate the integration of a motor, control circuitry, power electronic modules, and switching components for the proposed electric vehicle regenerative braking project. The prototype includes a DC motor coupled to a wheel, electronic control hardware, a relay, a display, and manual control switches mounted on a common board. The arrangement provides a platform for investigating motor operation and control-system integration.

The motor represents the rotating electromechanical component of the system, while the control circuitry and power electronic modules are intended to manage motor operation and electrical power transfer. The relay and manual switches provide additional switching and control functions, and the display can be used to present operating information when connected to appropriate sensors and measurement signals.

Further testing is required to verify regenerative operation, identify the exact converter topology, and measure the direction and magnitude of electrical power flow during braking. Voltage, current, and recovered energy measurements should be recorded to establish the prototype's performance. The hardware should only be described as a validated regenerative braking system after these functions have been demonstrated experimentally.

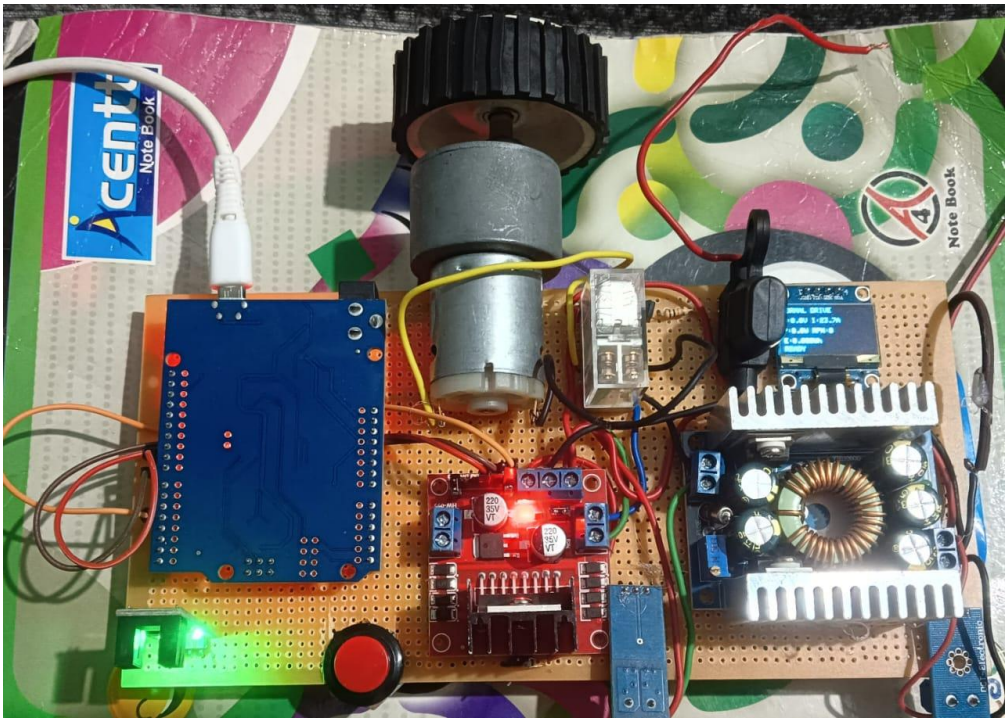


Fig. 3. Hardware prototype developed for the proposed electric vehicle regenerative braking project

VIII. CONCLUSION

This research focuses on the development of an efficient regenerative braking system for electric vehicles to investigate the recovery and reuse of kinetic energy during braking. The proposed system integrates a lead-acid battery, a supercapacitor bank, a bidirectional DC–DC converter, and a PI-based control system. MATLAB/Simulink R2023b, Simscape Electrical, and Stateflow are used as the simulation and modelling platforms.

The system is designed around a 400 V DC bus, with a target voltage regulation range of 380–420 V and a converter switching frequency of 20 kHz. The energy storage arrangement includes eight Maxwell 48 V, 165 F supercapacitor modules connected in series, providing a nominal voltage of 384 V and an equivalent capacitance of approximately 20.6 F. A PI controller with specified gains of (K_p=0.05) and (K_i=10) is incorporated to regulate converter operation and support controlled power transfer.

The proposed configuration provides a framework for investigating energy recovery, DC bus voltage regulation, battery charging behaviour, and power sharing between the battery and supercapacitor. A hardware prototype containing a motor, control circuitry, power electronic modules, a relay, and a display has also been assembled to support practical investigation of the system components. Further electrical measurements and functional testing are required to confirm regenerative energy transfer and validate the prototype's performance.

The effectiveness of the proposed system must ultimately be established through verified simulation outputs and experimental measurements. Future work will focus on quantifying recovered energy, evaluating converter efficiency, validating voltage regulation, improving energy management, and comparing system performance under different braking conditions. These investigations can help determine the practical suitability of the proposed approach for improving energy utilization in electric vehicles.

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