



INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

DESIGN OF EV REGENERATIVE BRAKING

Prof. Raghavendra Nagaralli⁽¹⁾
Assistant Professor

Department of Electronics and communication Engineering,
KLS VEDIT (Affiliated to VTU Belagavi), Haliyal, Karnataka, India.
India.

Mr. Raveendra Bharamesh Chougale⁽²⁾
PG Student

Department of Electronics and communication Engineering,
KLS VEDIT (Affiliated to VTU Belagavi), Haliyal, Karnataka,

Abstract: The rapid advancement of Electric Vehicle (EV) technology has increased the demand for accurate modelling, simulation, and optimization techniques to improve vehicle performance, energy efficiency, and reliability. In modern transportation, electric mobility is gaining significant importance due to government initiatives aimed at reducing greenhouse gas emissions. Among various EV technologies, regenerative braking plays a crucial role in enhancing energy efficiency by recovering kinetic energy during deceleration and converting it into electrical energy for battery charging. Unlike conventional braking systems, which dissipate energy as heat, regenerative braking improves energy utilization and reduces mechanical brake wear. This paper presents the modelling and simulation of an Advanced Regenerative Braking System (RBS) for an electric vehicle using MATLAB. The proposed model incorporates vehicle longitudinal dynamics, blended braking control, regenerative torque generation, battery State of Charge (SOC) monitoring, and energy recovery estimation. Numerical modelling enables efficient real-time analysis of EV performance under different driving conditions while reducing development time and cost. Simulation results demonstrate effective braking performance and energy recovery capability. The proposed system recovers approximately 30% of the vehicle's initial kinetic energy and stores it in the battery, thereby improving overall energy efficiency and extending the driving range of the vehicle. The developed model provides a reliable platform for further research and optimization of regenerative braking strategies in electric vehicles.

Index Terms: Electric Vehicle (EV), Regenerative Braking System (RBS), MATLAB Simulation, Energy Recovery, Battery State of Charge (SOC), E-Mobility, Vehicle Dynamics.

I. INTRODUCTION

The increasing demand for sustainable transportation and the growing concern over greenhouse gas emissions have accelerated the development of Electric Vehicles (EVs) worldwide. Governments and automotive industries are actively promoting electric mobility (e-mobility) as an alternative to conventional internal combustion engine vehicles due to its potential to reduce environmental pollution and dependence on fossil fuels. However, one of the major challenges associated with EVs is the efficient utilization of stored battery energy to maximize driving range and overall vehicle performance. Regenerative braking has emerged as one of the most important technologies for improving the energy efficiency of EVs. In conventional braking systems, the kinetic energy generated during vehicle deceleration is dissipated as heat through friction brakes, resulting in significant energy loss. In contrast, regenerative braking systems (RBS) recover a portion of this kinetic energy and convert it into electrical energy using the electric motor operating in generator mode. The recovered energy is then stored in the battery for future use, thereby improving energy efficiency, extending driving range, and reducing mechanical brake wear.

The performance of regenerative braking depends on several factors such as vehicle speed, braking force distribution, motor characteristics, battery State of Charge (SOC), and driving conditions. Therefore, accurate modelling and simulation of regenerative braking systems are essential for analyzing vehicle behavior and optimizing braking strategies. Numerical modelling provides a cost-effective and time-efficient platform for real-time testing and performance evaluation without the need for extensive experimental setups. In addition, simulation-based approaches assist in optimizing the configuration and sizing of EV powertrain components under varying operating conditions. Recent advancements in MATLAB/Simulink have enabled the development of detailed EV models incorporating vehicle longitudinal dynamics, battery management, motor control, and braking strategies. Blended braking techniques, which combine regenerative braking with conventional friction braking, are widely adopted to ensure vehicle safety, braking stability, and efficient energy recovery. Effective implementation of these techniques can significantly enhance the regenerative braking capability and overall system performance.

This paper presents the modelling and simulation of an Advanced Regenerative Braking System for an electric vehicle using MATLAB. The proposed model integrates vehicle longitudinal dynamics, regenerative torque generation, blended braking control, battery SOC monitoring, and energy recovery estimation. The developed system is evaluated under different operating conditions to analyze braking performance and regenerative energy recovery. Simulation results demonstrate that approximately 30% of the vehicle's initial kinetic energy can be recovered and stored in the battery, leading to improved energy efficiency and

extended driving range. The proposed model provides an effective platform for further research and optimization of regenerative braking strategies in electric vehicles.

II. SYSTEM ARCHITECTURE

Proposed Architecture: The proposed Advanced Regenerative Braking System (RBS) for the electric vehicle is designed to recover kinetic energy during braking and convert it into electrical energy for battery charging. The system consists of several major components, including the driver input unit, brake controller, electric motor/generator, battery pack with State of Charge (SOC) monitoring, mechanical braking system, vehicle longitudinal dynamics model, and energy recovery estimation unit. The driver input unit provides acceleration and braking commands based on the operation of the accelerator and brake pedals. These inputs are processed by the brake controller, which implements a blended braking strategy to distribute the required braking force between regenerative braking and conventional mechanical braking. The controller determines the regenerative braking torque depending on vehicle speed, braking demand, and battery SOC.

During normal driving conditions, the electric motor operates in motoring mode by drawing electrical energy from the battery to propel the vehicle. When braking is applied, the motor switches to generator mode and converts the kinetic energy of the vehicle into electrical energy. The recovered energy is then supplied to the battery pack for storage. The battery management and SOC monitoring system continuously supervises the charging condition of the battery to avoid overcharging and maintain safe operation. The vehicle longitudinal dynamics model is used to simulate the motion of the vehicle by considering parameters such as vehicle speed, traction force, rolling resistance, and aerodynamic drag. In situations where regenerative braking alone cannot provide the required braking torque, the mechanical braking system assists in achieving safe and stable braking performance.

An energy recovery estimation unit is incorporated to calculate the amount of recovered braking energy and evaluate the efficiency of the regenerative braking process. The proposed system architecture improves overall vehicle energy efficiency, reduces mechanical brake wear, and enhances driving range. Furthermore, the MATLAB-based simulation model provides an effective platform for analyzing and optimizing regenerative braking strategies under different driving conditions.

III. METHODOLOGY

The methodology adopted for the development of the Advanced Regenerative Braking System (RBS) involves modelling, simulation, and performance evaluation of the electric vehicle braking system using MATLAB/Simulink. The proposed approach focuses on recovering kinetic energy during vehicle deceleration and improving the overall energy efficiency of the electric vehicle. The methodology consists of vehicle dynamics modelling, regenerative braking control, battery modelling, and energy recovery analysis. Initially, the vehicle longitudinal dynamics model is developed to represent the motion of the electric vehicle under different driving conditions. The model considers important parameters such as vehicle mass, rolling resistance, aerodynamic drag, traction force, and braking force. These parameters are used to calculate vehicle speed, acceleration, and braking characteristics during operation.

The regenerative braking system is then integrated with the vehicle model. During braking conditions, the electric motor operates in generator mode and converts the kinetic energy of the moving vehicle into electrical energy. A blended braking control strategy is implemented to distribute braking torque between regenerative braking and conventional mechanical braking. The controller continuously monitors vehicle speed, braking demand, and battery State of Charge (SOC) to determine the amount of regenerative braking torque that can be safely applied. A battery model with SOC monitoring is incorporated to analyze the charging and discharging behavior of the battery during regenerative braking operation. The recovered electrical energy generated by the motor-generator is supplied to the battery pack for storage. The SOC monitoring system ensures safe charging operation and prevents battery overcharging during energy recovery.

The entire regenerative braking model is developed and simulated in MATLAB/Simulink. Different braking conditions and driving scenarios are applied to evaluate the performance of the proposed system. Parameters such as braking torque, vehicle speed, recovered energy, battery SOC variation, and braking efficiency are analyzed during simulation. Finally, the energy recovery efficiency of the regenerative braking system is calculated by comparing the recovered electrical energy with the initial kinetic energy of the vehicle. The simulation results demonstrate the effectiveness of the proposed system in recovering braking energy, improving vehicle efficiency, and extending the driving range of the electric vehicle. The developed methodology provides a reliable framework for further optimization and implementation of regenerative braking strategies in modern EV applications.

IV. IMPLEMENTATION

The software implementation of the proposed Advanced Regenerative Braking System (RBS) is developed to simulate and analyze the operation of regenerative braking in an electric vehicle. The software model consists of virtual representations of an electric motor, motor controller, rechargeable battery, braking control algorithm, sensors, monitoring modules, and user interface components. The implemented software enables the simulation of kinetic energy recovery during braking and the storage of recovered energy within the battery model. An electric DC motor model is used to represent the traction motor of the electric vehicle. During normal operation, the motor model drives the vehicle dynamics using energy supplied by the battery model. During braking conditions, the motor model operates in generator mode and converts rotational kinetic energy into electrical

energy. The generated electrical energy is then routed back to the battery model for charging. A rechargeable battery model serves as the primary energy storage component of the system. The battery model supplies power during acceleration and stores the recovered energy during regenerative braking. Battery monitoring algorithms are incorporated to evaluate battery voltage, state of charge (SOC), and charging conditions.

The braking operation is managed through a software-based control algorithm implemented within the simulation environment. The controller continuously monitors braking input, motor speed, and battery condition. Based on the braking command, the control algorithm activates regenerative braking and manages the transition between motoring and generating modes. A motor control module regulates motor behavior and controls operating speed and torque characteristics. The control logic also ensures a smooth transition between acceleration and regenerative braking modes. Virtual speed sensors are used to measure wheel or motor speed for evaluating braking performance and energy recovery.

In the proposed software model, braking input is provided through user-defined simulation parameters or graphical interface controls. During deceleration, the generated electrical energy is fed back to the battery model through a charging algorithm. The recovered energy and system parameters such as motor speed, battery voltage, and SOC can be monitored using graphical dashboards, plots, or simulation output interfaces. The software implementation validates the functionality of the regenerative braking system and demonstrates effective energy recovery during braking conditions. The developed simulation platform provides a flexible environment for analyzing braking efficiency, battery charging performance, and real-time control strategies for regenerative braking in electric vehicles.

V. CONTROL STRATEGY

The proposed regenerative braking system employs a rule-based blended braking control strategy to effectively coordinate regenerative braking and conventional mechanical braking. The primary objective of the controller is to maximize braking energy recovery while ensuring vehicle stability, braking safety, and driver comfort under varying operating conditions. The control system continuously monitors important vehicle parameters such as brake pedal input, vehicle speed, motor speed, battery State of Charge (SOC), regenerative braking capability, and battery charging limits. Based on these inputs, the controller dynamically distributes braking torque between regenerative and mechanical braking systems. During light braking conditions, when the driver applies a small braking force and the battery SOC is below the maximum charging limit, the controller prioritizes regenerative braking. In this mode, the electric motor operates as a generator and converts the vehicle's kinetic energy into electrical energy, which is stored in the battery. The total braking torque is primarily provided by regenerative braking and can be represented as: $T_{total} = T_{regen}$

This operating mode maximizes energy recovery and minimizes the use of mechanical brakes, thereby reducing brake wear. During medium braking conditions, regenerative braking alone may not be sufficient to generate the required braking torque. Therefore, the controller combines regenerative braking with mechanical braking to achieve the desired vehicle deceleration. In this condition, the total braking torque is expressed as: $T_{total} = T_{regen} + T_{mech}$

Here, regenerative braking is utilized to its maximum possible capability, while the additional braking torque is supplied by the mechanical braking system to ensure stable braking performance. Under heavy or emergency braking conditions, rapid deceleration is required to maintain vehicle safety. Since regenerative braking capability is limited by motor torque and battery charging constraints, the controller activates maximum mechanical braking torque while regenerative braking operates only within safe operating limits. This ensures effective braking performance during sudden stopping conditions. At low vehicle speeds, regenerative braking becomes less effective due to the reduction in motor-generator speed. Consequently, the controller gradually decreases regenerative braking torque and transfers braking responsibility to the mechanical braking system to ensure smooth vehicle stopping.

When the battery SOC reaches the maximum allowable limit, regenerative braking is disabled to prevent battery overcharging. Under this condition, the regenerative braking torque becomes zero: $T_{regen} = 0$

Therefore, the complete braking torque required for vehicle deceleration is supplied entirely by the mechanical braking system. Similarly, if the total braking torque demanded by the driver exceeds the maximum regenerative braking capability of the motor, the regenerative braking system provides its maximum available torque, while the remaining braking torque is generated using the mechanical braking system. The required mechanical braking torque is calculated as: $T_{mech} = T_{req} - T_{regen}$

This blended braking approach ensures safe and stable braking performance during medium and heavy braking conditions while maximizing regenerative energy recovery. The proposed control strategy is implemented in MATLAB/Simulink using switch and logic operators, relational operators, lookup tables, and PID/control blocks. The controller continuously evaluates real-time operating conditions and dynamically adjusts braking torque distribution between regenerative and mechanical braking systems. The proposed rule-based control strategy offers several advantages, including improved regenerative energy recovery, reduced mechanical brake wear, enhanced battery charging efficiency, improved overall vehicle efficiency, and stable braking operation. Simulation results indicate that the proposed system is capable of recovering approximately 30% of the vehicle's kinetic energy during braking events, thereby extending the driving range and improving the performance of the electric vehicle.

VI. VEHICLE PARAMETERS AND DESIGN ASSUMPTIONS

Vehicle Parameters - The simulation parameters used in the proposed Advanced Regenerative Braking System (ARBS) are selected based on a typical midsize electric vehicle. These parameters are used for vehicle dynamics modelling, regenerative braking analysis, and battery charging evaluation in MATLAB/Simulink.

Design Assumptions - To simplify the mathematical modelling and simulation of the proposed regenerative braking system, several assumptions are considered during system development. These assumptions reduce modelling complexity while preserving the essential characteristics of regenerative braking operation. The proposed model considers only longitudinal vehicle motion. Therefore, the vehicle is assumed to move in a straight-line direction, while lateral dynamics such as steering effects, yaw motion, cornering, and side-slip are neglected. This assumption simplifies the vehicle dynamic equations and allows the braking analysis to focus only on acceleration and deceleration behavior.

The road surface is assumed to be completely flat throughout the simulation. Hence, road gradient effects such as uphill and downhill driving conditions are neglected. Under this assumption, gravitational force components due to road inclination are ignored, and the vehicle resistance includes only rolling resistance and aerodynamic drag. The battery voltage is assumed to remain constant during charging and discharging operations. Although practical battery voltage varies with State of Charge (SOC), charging current, temperature, and internal resistance, these variations are neglected for simplified battery modelling and regenerative power calculations.

The efficiency of the electric motor is assumed to remain constant during both motoring and regenerative braking operations. In real applications, motor efficiency varies with motor speed, load torque, operating temperature, and switching losses. However, an average efficiency value is used throughout the analysis to simplify regenerative power estimation and braking torque calculations.

The proposed model assumes ideal wheel-road contact without wheel slip during braking operation. Therefore, tire traction is considered sufficient, and anti-lock braking effects are neglected. This assumption simplifies braking force calculations while maintaining acceptable accuracy for regenerative braking analysis. These assumptions provide a practical balance between simulation accuracy and modelling simplicity while enabling effective analysis of regenerative braking system performance.

Parameter	Symbol	Value
Vehicle Mass	M	1500 kg
Wheel Radius	R _w	0.30 m
Drag Coefficient	C _d	0.29
Frontal Area	A	2.2 m ²
Air Density	ρ	1.225 kg/m ³
Rolling Resistance Coefficient	C _r	0.015
Gear Ratio	G	9
Motor Efficiency	η _m	0.90
Battery Voltage	V _{bat}	350 V
Battery Capacity	Q _{bat}	50 Ah
Initial Battery SOC	SOC ₀	60%
Maximum Battery SOC	SOC _{max}	95%
Maximum Regenerative Torque	T _{max}	180 Nm
Simulation Time	T _{end}	20 s
Sampling Time	dt	0.1

VII. RESULTS AND DISCUSSION

This section presents the simulation results obtained from the MATLAB/Simulink implementation of the proposed Advanced Regenerative Braking System (ARBS). The primary objective of the simulation is to evaluate the effectiveness of regenerative braking in recovering vehicle kinetic energy during deceleration while maintaining safe braking performance and battery charging constraints. The developed model integrates vehicle longitudinal dynamics, regenerative braking control, mechanical braking assistance, battery charging characteristics, and energy recovery estimation. Important performance parameters such as vehicle speed, braking force distribution, regenerative power, battery SOC variation, and recovered energy are analyzed in detail. The simulation is conducted for a duration of 20 seconds with a sampling interval of 0.1 seconds. A braking demand is applied during the interval from 5 s to 15 s to emulate a realistic braking event under moderate-to-heavy braking conditions.

Simulation Environment

The simulation model is developed using MATLAB R2024a with a fixed-step time-domain solver.

Parameter	Specification
Software	MATLAB
Simulation Type	Time-domain
Solver	Fixed Step
Sampling Time	0.1 s
Simulation Duration	20 s

Simulation Scenario

The vehicle is initially operated at a speed of: $V_0=25$ m/s which is approximately equal to 90 km/h. This operating condition represents a typical highway driving scenario for an electric vehicle. A braking demand of 0.8 is applied during the interval: $5s \leq t \leq 15s$

This braking demand corresponds to moderate-to-heavy braking conditions where both regenerative braking and mechanical braking participate in vehicle deceleration. The blended braking controller continuously evaluates braking requirements and distributes braking torque between regenerative and mechanical braking systems.

Vehicle Speed Analysis

Initially, before brake application, the vehicle speed decreases slowly due to rolling resistance and aerodynamic drag. Since no active braking force is applied during the interval from 0–5 s, the deceleration rate remains relatively small. When braking begins at $t=5s$, rapid deceleration occurs due to the combined action of regenerative braking torque and mechanical braking assistance. The vehicle speed decreases continuously and reaches approximately zero at $t \approx 12s$, indicating successful vehicle stopping. The obtained speed profile confirms stable vehicle deceleration, smooth braking operation, effective braking torque control, and absence of oscillatory behavior. The linear reduction in vehicle speed demonstrates proper implementation of the blended braking controller.

Regenerative Braking Force Analysis- The regenerative braking force is calculated as: $F_{regen} = T_{regen} G \frac{Nm}{R_w} = 4860N$ The simulation results indicate that the regenerative braking force remains approximately constant at: $F_{regen} \approx 4860N$ during the braking interval. The regenerative braking system effectively absorbs vehicle kinetic energy and converts it into electrical energy for battery charging. The obtained force profile confirms stable regenerative braking operation, efficient energy conversion, and proper controller functionality.

Energy Recovery Performance- The simulation results obtained from the proposed regenerative braking system are summarized below:

Parameter	Value
Initial Kinetic Energy	468750 J
Recovered Energy	140625 J
Recovery Percentage	30%
Recovered Energy kWh	0.039062 kWh
Final Battery SOC	60.52%

The results indicate that approximately 30% of the vehicle's initial kinetic energy is successfully recovered and stored in the battery during braking operation. The battery SOC increases from 60% to 60.52%, confirming successful regenerative charging operation.

Recovered Regenerative Power Analysis- The instantaneous regenerative power generated during braking is calculated based on regenerative torque and motor speed. At the beginning of braking, vehicle speed and kinetic energy are maximum; therefore, regenerative power reaches its peak value. The maximum recovered regenerative power observed during simulation is approximately: $P_{regen, max} \approx 41 \text{ kW}$. As braking continues and vehicle speed decreases, regenerated power gradually reduces until it reaches zero when the vehicle stops completely. The power profile confirms efficient kinetic-to-electrical energy conversion, stable regenerative power generation, and proper operation of the motor-generator system.

Performance Comparison- The proposed Advanced Regenerative Braking System is compared with conventional braking systems as shown below.

Parameter	Conventional Braking	Proposed ARBS
Energy Recovery	0%	30%
Battery Charging	No	Yes
Brake Wear	High	Low
Heat Loss	High	Reduced
Vehicle Efficiency	Lower	Higher

The comparison confirms that the proposed ARBS significantly improves energy efficiency, reduces mechanical brake wear, minimizes heat loss, and enhances overall electric vehicle performance.

VIII. CONCLUSION

This paper presented the modelling and simulation of an Advanced Regenerative Braking System (ARBS) for electric vehicles using MATLAB/Simulink. The proposed system employed a rule-based blended braking control strategy to effectively coordinate regenerative braking and mechanical braking under different operating conditions. The developed model incorporated vehicle longitudinal dynamics, regenerative torque generation, battery State of Charge (SOC) monitoring, braking force distribution, and energy recovery estimation. Simulation results demonstrated that the proposed regenerative braking system effectively recovered a significant portion of the vehicle's kinetic energy during braking events while maintaining stable and safe braking performance. The blended braking controller successfully distributed braking torque between regenerative and mechanical braking systems based on braking demand, vehicle speed, and battery charging conditions. The results confirmed smooth vehicle deceleration, stable regenerative power generation, and efficient battery charging operation. The proposed system achieved approximately 30% recovery of the vehicle's initial kinetic energy, which was successfully stored in the battery. In addition, the regenerative braking system reduced dependence on mechanical braking, thereby minimizing brake wear and reducing energy losses in the form of heat. The obtained results indicate improved overall vehicle efficiency and extended driving range compared to conventional braking systems.

The MATLAB/Simulink-based model provides a flexible and reliable platform for further research and optimization of regenerative braking strategies in electric vehicles. Future work may include incorporation of thermal effects, battery aging characteristics, adaptive braking control algorithms, anti-lock braking integration, and real-time hardware implementation for enhanced regenerative braking performance under practical driving conditions.

IX. REFERENCES

- [1] C. C. Chan, "The State of the Art of Electric and Hybrid Vehicles," *Proceedings of the IEEE*, vol. 90, no. 2, pp. 247–275, Feb. 2002.
- [2] J. Larminie and J. Lowry, *Electric Vehicle Technology Explained*, 2nd ed. Hoboken, NJ, USA: Wiley, 2012.
- [3] I. Husain, *Electric and Hybrid Vehicles: Design Fundamentals*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2011.
- [4] M. Ehsani, Y. Gao, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2010.
- [5] S. Onori, L. Serrao, and G. Rizzoni, *Hybrid Electric Vehicles: Energy Management Strategies*, London, U.K.: Springer, 2016.
- [6] Y. Gao and M. Ehsani, "Electronic Braking System of EV and HEV—Integration of Regenerative Braking, Automatic Braking Force Control and ABS," in *Proc. SAE Future Transportation Technology Conf.*, Costa Mesa, CA, USA, 1999, pp. 1–8.
- [7] J. Wang, C. Zhang, and H. Zhao, "Research on Regenerative Braking Control Strategy for Electric Vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 1243–1248, Mar. 2008.

- [8] H. Zhang, J. Li, and Y. Lv, "Simulation and Analysis of Regenerative Braking System for Electric Vehicles," *International Journal of Automotive Technology*, vol. 15, no. 5, pp. 757–764, Oct. 2014.
- [9] K. T. Chau, *Electric Vehicle Machines and Drives: Design, Analysis and Application*, Hoboken, NJ, USA: Wiley, 2015.
- [10] S. M. Lukic and A. Emadi, "Effects of Drivetrain Hybridization on Fuel Economy and Dynamic Performance of Parallel Hybrid Electric Vehicles," *IEEE Trans. Veh. Technol.*, vol. 53, no. 2, pp. 385–389, Mar. 2004.
- [11] Y. He, M. Chowdhury, and P. Pisu, "An Energy Optimization Strategy for Power-Split Drivetrains," *IEEE Trans. Veh. Technol.*, vol. 61, no. 8, pp. 3555–3564, Oct. 2012.
- [12] M. Fitri, N. Hannan, and A. Mohamed, "Battery Storage Systems in Electric Vehicles," *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 132–145, Aug. 2017.
- [13] R. Rajamani, *Vehicle Dynamics and Control*, 2nd ed. New York, NY, USA: Springer, 2012.
- [14] B. K. Powell, K. E. Bailey, and S. R. Cikanek, "Dynamic Modeling and Control of Hybrid Electric Vehicle Powertrain Systems," *IEEE Control Systems Magazine*, vol. 18, no. 5, pp. 17–33, Oct. 1998.

