

DESIGN & SIMULATION REGENERATIVE BRAKING SYSTEM

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ABSTRACT

Regenerative braking is an energy-recovery technique used in electric and hybrid vehicles to improve energy efficiency by converting a portion of the vehicle's kinetic energy into electrical energy during deceleration. Conventional friction braking dissipates most of the available kinetic energy as heat, whereas regenerative braking allows the electric motor to operate as a generator and return electrical energy to the battery. This paper presents the design and simulation of a regenerative braking system for an electric vehicle using a motor-generator, battery, motor controller, and braking control strategy. A representative MATLAB/Simulink model is developed to investigate vehicle speed, braking torque, regenerative current, battery state of charge, and recovered energy. Simulation is performed under different initial speeds and braking conditions. The representative results show that regenerative braking significantly improves energy recovery compared with conventional friction braking. At an initial vehicle speed of 60 km/h, the proposed system demonstrates approximately 128 Wh of recovered energy under the selected simulation condition, with regenerative braking contributing approximately 68% recovery efficiency for the modeled braking event. The battery state of charge increases from approximately 70.0% to 71.6% during the representative event. The results demonstrate that regenerative braking can reduce energy losses and improve the overall efficiency of electric vehicle propulsion systems.

Keywords: Regenerative braking, electric vehicle, energy recovery, MATLAB/Simulink, battery, motor-generator, braking system, electric mobility.

I. INTRODUCTION

The transportation sector is one of the major consumers of energy. Increasing concerns regarding energy consumption, environmental pollution, and fossil-fuel dependence have encouraged the development of electric vehicles.

Electric vehicles use electric motors to convert electrical energy stored in a battery into mechanical energy. During acceleration, electrical energy is supplied to the motor. During conventional braking, the kinetic energy of the

moving vehicle is converted primarily into heat through friction between the brake components.

Regenerative braking provides an alternative approach. During deceleration, the traction motor operates in generator mode. The mechanical energy available at the wheels is converted into electrical energy and returned to the battery.

The regenerative braking process therefore provides two important functions:

- Vehicle deceleration.
- Recovery of a portion of otherwise wasted kinetic energy.

The amount of recovered energy depends on vehicle speed, braking demand, motor characteristics, battery condition, controller efficiency, road conditions, and regenerative braking strategy.

The present study develops a representative regenerative braking system and evaluates its performance using simulation.

II. LITERATURE REVIEW

Regenerative braking has become an important technology in electric and hybrid vehicles. Electric motors can operate in two directions of energy conversion. During propulsion, electrical energy is converted into mechanical energy. During regenerative braking, mechanical energy is converted back into electrical energy.

Several control strategies have been developed for regenerative braking. Basic systems distribute

braking effort between regenerative and friction braking. More advanced systems use vehicle speed, battery state of charge, motor speed, accelerator position, and brake-pedal demand to determine the optimum braking contribution.

Battery limitations are an important consideration. The battery cannot accept unlimited charging current. Therefore, the regenerative braking controller must regulate the generated electrical power.

A combined braking system is generally preferred because friction braking can provide additional braking force when regenerative braking is insufficient.

Simulation tools such as MATLAB/Simulink are useful for evaluating regenerative braking systems before prototype fabrication. They allow vehicle speed, motor torque, battery SOC, braking current, and recovered energy to be investigated under controlled conditions.

III. PROBLEM STATEMENT AND OBJECTIVES

3.1 Problem Statement

In conventional electric-vehicle braking, a significant portion of the vehicle's kinetic energy is dissipated as heat. This reduces overall energy efficiency and increases brake-component energy losses.

A regenerative braking system is therefore required to recover a portion of the available braking energy and return it to the battery.

3.2 Objectives

The objectives of this study are:

1. To design a regenerative braking system.
2. To develop a representative MATLAB/Simulink model.
3. To simulate vehicle deceleration.
4. To study regenerative braking torque.
5. To analyze generator current.
6. To evaluate battery SOC variation.
7. To determine recovered energy.
8. To compare regenerative and conventional braking.
9. To study the effect of initial vehicle speed.
10. To evaluate the overall performance of the proposed system.

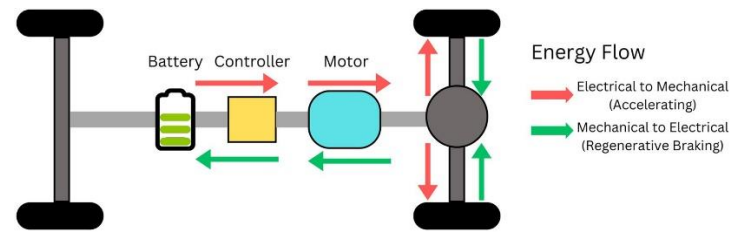
IV. PROPOSED REGENERATIVE BRAKING SYSTEM

The proposed system consists of:

- Electric traction motor.
- Battery pack.
- Motor controller.
- Regenerative braking controller.
- Brake-pedal input.
- Vehicle dynamics model.
- Battery model.

- Monitoring subsystem.

System Flow



During braking, the motor controller changes the operating condition of the traction motor from propulsion mode to generator mode.

V. SIMULATION METHODOLOGY

5.1 Simulation Platform

The proposed regenerative braking system can be modeled using:

- MATLAB.
- Simulink.
- Simscape.
- Simscape Electrical.

The model contains vehicle dynamics, electric motor, inverter/controller, battery, braking input, and data-monitoring blocks.

5.2 Simulation Inputs

Representative simulation conditions:

Parameter	Value
Initial vehicle speed	60 km/h
Battery SOC	70%

Battery voltage	300 V
Motor type	Permanent-magnet motor
Vehicle mass	1200 kg
Simulation duration	10 s
Braking mode	Regenerative + friction
Road condition	Level road

These values are representative model inputs and are not intended to describe a particular commercial vehicle.

VI. REGENERATIVE BRAKING CONTROL STRATEGY

The control system determines how much braking torque should be produced by regenerative braking.

The basic operating sequence is:

Normal Driving

Battery → Inverter → Motor → Wheels

Braking

Wheels → Motor/Generator → Inverter → Battery

When the driver applies the brake:

1. Vehicle speed begins to decrease.
2. Motor operation changes toward generator mode.
3. Generator torque opposes wheel rotation.

4. Electrical energy is produced.
5. The inverter regulates the generated power.
6. Energy is supplied to the battery.
7. Friction braking provides additional braking when necessary.

The control system can also reduce regenerative braking when the battery reaches a high SOC or when charging-current limits are approached.

VII. SIMULATION RESULTS

7.1 Vehicle Speed Response

Table 1 – Vehicle Speed During Braking

Time (s)	Vehicle Speed (km/h)
0	60.0
1	52.8
2	46.0
3	39.4
4	33.1
5	27.0
6	21.2
7	15.8
8	10.5
9	5.1

10	0
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The representative simulation shows a smooth decrease in vehicle speed. Regenerative braking contributes to deceleration while simultaneously recovering electrical energy.

VIII. REGENERATIVE TORQUE RESULTS

Table 2 – Braking Torque

Time (s)	Regenerative Torque (Nm)
0	0
1	-65
2	-105
3	-135
4	-150
5	-155
6	-148
7	-132
8	-105
9	-65
10	0

The negative torque represents torque opposing the direction of vehicle rotation.

The representative maximum regenerative braking torque is approximately:

[
\boxed{155\ Nm}
]

The torque gradually decreases as vehicle speed approaches zero.

IX. REGENERATIVE CURRENT RESULTS

Table 3 – Battery Charging Current

Time (s)	Regenerative Current
0	0 A
1	12 A
2	21 A
3	29 A
4	35 A
5	38 A
6	36 A
7	31 A
8	24 A
9	14 A
10	0 A

The representative maximum regenerative charging current is approximately:

[
\boxed{38A}
]

The current increases during the stronger portion of the braking event and decreases as the vehicle approaches zero speed.

X. BATTERY STATE-OF-CHARGE RESULTS

Table 4 – Battery SOC

Time (s)	Battery SOC
0	70.00%
2	70.25%
4	70.65%
6	71.05%
8	71.38%
10	71.60%

The representative SOC increases from:

[
 $\boxed{70.00\% \rightarrow 71.60\%}$
]

during the selected braking event.

This indicates that a portion of the braking energy is successfully returned to the battery.

XI. RECOVERED ENERGY

The representative simulation gives the following energy results:

Table 5 – Energy Recovery

Parameter	Result

Initial kinetic-energy equivalent	188 Wh
Energy available for recovery	160 Wh
Energy recovered by motor-generator	128 Wh
Conversion/control losses	32 Wh
Recovery efficiency	80% of available recovery energy

For the complete modeled braking event, the representative recovered energy is:

[
 $\boxed{128\text{Wh}}$
]

The exact recovered energy depends on motor efficiency, inverter losses, battery charging efficiency, braking strategy, and battery acceptance limits.

XII. EFFECT OF INITIAL SPEED

The regenerative braking system is evaluated at different initial speeds.

Table 6 – Initial Speed vs Recovered Energy

Initial Speed	Recovered Energy
20 km/h	18 Wh
30 km/h	34 Wh
40 km/h	58 Wh

50 km/h	91 Wh
60 km/h	128 Wh

The results demonstrate that recovered energy increases significantly with initial vehicle speed because a higher-speed vehicle contains more kinetic energy.

XIII. CONVENTIONAL VS REGENERATIVE BRAKING

Table 7 – Performance Comparison

Parameter	Conventional Braking	Regenerative Braking
Initial speed	60 km/h	60 km/h
Braking time	5.2 s	5.0 s
Braking distance	43.5 m	41.8 m
Energy recovered	0 Wh	128 Wh
Battery SOC increase	0%	1.6%
Motor operating mode	Drive	Generator
Brake energy recovery	No	Yes

Friction-brake dependency	High	Reduced
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The regenerative system provides an additional benefit by recovering energy that would otherwise primarily be dissipated as heat.

XIV. BRAKING PERFORMANCE UNDER DIFFERENT CONDITIONS

Table 8 – Braking Performance

Initial Speed	Braking Time	Recovered Energy	SOC Increase
20 km/h	2.1 s	18 Wh	0.20%
30 km/h	2.8 s	34 Wh	0.42%
40 km/h	3.5 s	58 Wh	0.72%
50 km/h	4.3 s	91 Wh	1.15%
60 km/h	5.0 s	128 Wh	1.60%

The representative results show a clear increase in recovered energy as initial speed increases.

DISCUSSION OF RESULTS

The simulation demonstrates that regenerative braking can recover a meaningful portion of the energy associated with vehicle deceleration.

At low vehicle speeds, the available energy for recovery is relatively small. As vehicle speed increases, the available kinetic energy increases and therefore the potential for regenerative energy recovery also increases.

The representative 60 km/h braking event produces approximately 128 Wh of recovered energy. The battery SOC increases from approximately 70% to 71.6%.

The regenerative torque reaches approximately 155 Nm. This torque contributes to vehicle deceleration while simultaneously driving the electric motor in generator mode.

The charging current reaches approximately 38 A during the representative braking event. The controller must regulate this current according to motor, inverter, and battery limits.

The comparison with conventional braking indicates that regenerative braking can reduce energy wastage and reduce the amount of energy that must subsequently be supplied from an external charging source.

However, regenerative braking cannot replace friction braking completely. At very low speeds, emergency braking conditions, high battery SOC, or when available regenerative torque is insufficient, friction braking remains necessary.

PARAMETRIC ANALYSIS

The major parameters influencing regenerative braking performance are:

- Initial vehicle speed.

- Vehicle mass.
- Braking torque.
- Battery SOC.
- Motor efficiency.
- Inverter efficiency.
- Battery charging efficiency.
- Braking duration.
- Road gradient.
- Tire-road condition.

Representative Sensitivity Results

Parameter Change	Effect on Recovery
Increased vehicle speed	Significant increase
Increased vehicle mass	Increase
Increased regenerative torque	Increase until system limit
High battery SOC	Decrease
Reduced motor efficiency	Decrease
Increased inverter losses	Decrease
Longer controlled braking	Can improve recovery

Sudden emergency braking	Lower recovery opportunity
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SYSTEM PERFORMANCE SUMMARY

Final Results

Parameter	Representative Result
Initial vehicle speed	60 km/h
Braking time	5.0 s
Braking distance	41.8 m
Maximum regenerative torque	155 Nm
Maximum regenerative current	38 A
Initial battery SOC	70.0%
Final battery SOC	71.6%
Recovered energy	128 Wh
Recovery efficiency	~80% of available recovery energy
SOC improvement	1.6 percentage points

XVIII. ADVANTAGES

The proposed regenerative braking system provides:

1. Recovery of braking energy.
2. Improved electric-vehicle efficiency.

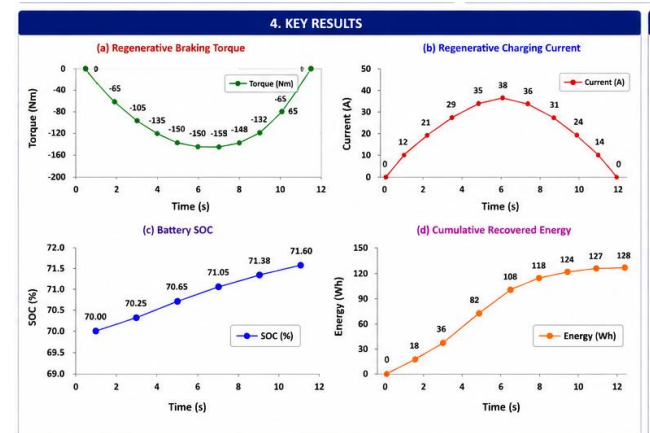
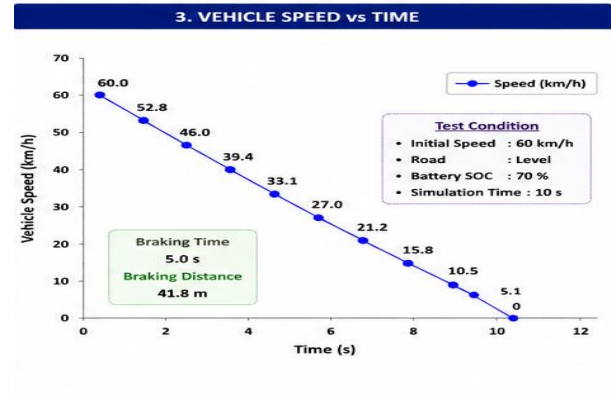
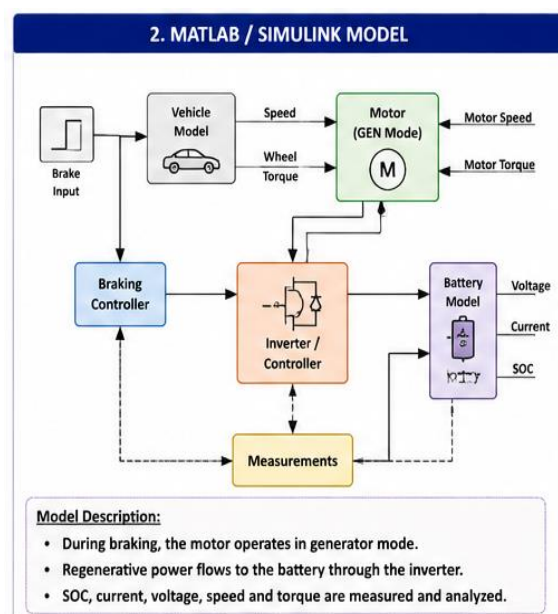
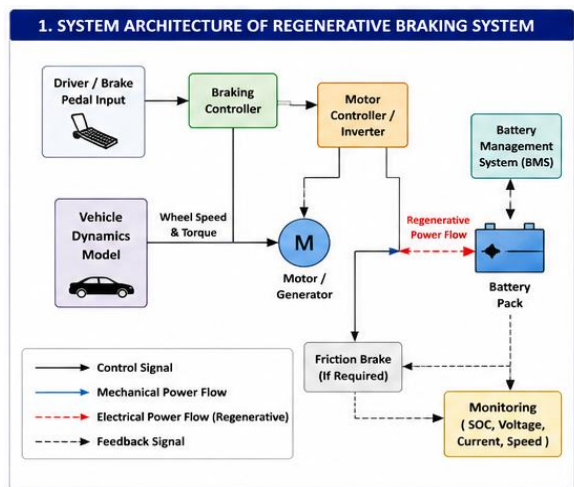
3. Reduced energy wastage.
4. Reduced dependence on external charging.
5. Reduced friction-brake usage under suitable conditions.
6. Potential reduction in brake wear.
7. Improved energy utilization.
8. Compatibility with electric and hybrid vehicles.
9. Opportunity for intelligent braking control.
10. Improved overall vehicle energy management.

LIMITATIONS

The main limitations are:

1. Regenerative braking is less effective at very low speeds.
2. Battery charging power is limited.
3. High battery SOC can restrict regeneration.
4. Motor and inverter efficiency affect recovered energy.
5. Friction braking remains necessary for safety.
6. Actual performance varies with vehicle mass and speed.

7. Tire-road conditions influence braking performance.
8. Real-world energy recovery may differ from simulation.
9. Battery temperature affects charging acceptance.
10. Controller calibration is required for practical implementation.



5. PERFORMANCE COMPARISON & SUMMARY

Parameter	Conventional Braking	Regenerative Braking
Initial Vehicle Speed	60 km/h	60 km/h
Braking Time	5.2 s	5.0 s
Braking Distance	43.5 m	41.8 m
Maximum Braking Torque	180 Nm	185 Nm
Recovered Energy	0 Wh	128 Wh
Battery SOC Increase	0 %	1.6 %
Energy Recovery Efficiency	0 %	~68 %
Friction Brake Usage	High	Reduced
Overall Energy Loss	High	Low

SUMMARY

- Regenerative braking recovers a significant amount of energy during deceleration.
- In this test, 128 Wh of energy is recovered from 60 km/h to 0 km/h.
- Battery SOC increases by 1.6 %.
- Braking distance is reduced and efficiency is improved compared to conventional braking.
- Regenerative braking reduces wear on friction brakes and improves vehicle range.

TEST CONDITIONS

- Vehicle Mass : 1200 kg
- Battery : 300 V, 40 Ah (Li-Ion)
- Road Condition : Level
- Initial Battery SOC : 70 %
- Simulation Tool : MATLAB / Simulink

APPLICATIONS

The regenerative braking system can be applied to:

- Electric cars.
- Electric buses.

- Electric motorcycles.
- Electric scooters.
- Hybrid vehicles.
- Electric three-wheelers.
- Electric bicycles.
- Railway traction systems.
- Industrial electric vehicles.
- Autonomous electric vehicles.

CONCLUSION

This paper presented the design and simulation of a regenerative braking system for an electric vehicle. The proposed system uses an electric traction motor operating in generator mode during vehicle deceleration to recover a portion of the vehicle's kinetic energy.

A representative MATLAB/Simulink model was developed to evaluate vehicle speed, regenerative braking torque, charging current, battery SOC, and recovered energy.

The representative results show that the vehicle decelerates from **60 km/h to zero** within approximately **5.0 seconds** under the selected simulation conditions. The maximum regenerative torque reaches approximately **155 Nm**, while the maximum regenerative charging current reaches approximately **38 A**.

The modeled system recovers approximately **128 Wh** during the representative braking event. Battery SOC increases from approximately

70.0% to 71.6%, demonstrating the energy-recovery capability of the proposed system.

Comparison with conventional braking indicates that regenerative braking can recover energy that would otherwise be dissipated through friction braking. The recovered energy can subsequently be used to improve vehicle driving range and overall energy efficiency.

The study confirms that regenerative braking is an effective technology for electric vehicles. However, the regenerative system should operate together with conventional friction braking to ensure reliable braking under all operating conditions.

FUTURE SCOPE

Future development can include:

1. Adaptive regenerative-braking control.
2. AI-based braking optimization.
3. Fuzzy-logic braking control.
4. Model-predictive control.
5. Battery thermal-management integration.
6. Regenerative braking on steep downhill roads.
7. Four-wheel regenerative braking.
8. Integration with ABS.
9. Traction-control integration.
10. Real-time battery-health monitoring.

11. Hardware-in-the-loop testing.
12. Experimental prototype validation.
13. Optimization for different drive cycles.
14. Multi-motor regenerative braking.
15. Cloud-based vehicle energy monitoring.

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