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by Anupam Kumar

MANIPAL INSTITUTE OF TECHNOLOGY
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Project Title: Development of a Simulated Regenerative Braking System Model for Electric and Hybrid Vehicles

Submitted by

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November, 2024

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1. Aim

The primary aim of this project is to develop and analyze a simulated model of a Regenerative Braking System (RBS) in Simulink, designed for electric and hybrid vehicles. The model focuses on enhancing energy efficiency by converting a portion of the vehicle's kinetic energy during braking into stored electrical energy, which can later be reused to power the vehicle.

The **specific goals** include:

- **Energy Efficiency**: RBS aims to reduce overall energy consumption by capturing otherwise lost energy.
- **Simulation Accuracy**: By using Simulink, we can create a controlled simulation environment to understand and analyze the braking and motoring phases.
- **Real-World Relevance**: This project holds particular significance for electric and hybrid vehicles, where energy conservation is critical for range extension and battery longevity.

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2. Objectives

The project objectives are broken down into both general and individual targets to ensure a comprehensive approach to developing the model.

Project Objectives

1. **Develop a Simulink-based regenerative braking model**: This model will include critical components like the DC machine, MOSFET switches, and a battery storage system to simulate the core functions of a regenerative braking system.
2. **Validate model functionality through simulation**: We will analyze the battery's behavior during energy recovery in the braking phase and energy depletion in the motoring phase.
3. **Examine challenges and efficiency aspects of the RBS**: A thorough assessment of energy conversion efficiency, component design considerations, and potential challenges will be conducted to enhance the system’s viability.

Individual Objectives

Each member of the team contributes to specific areas to fulfill the project’s goals:

- **Priyam Agarwala**: Responsible for designing and configuring the regenerative circuit, focusing on electrical flow and energy capture.
- **Pranav P**: Handles the implementation of the braking phase, working with the DC machine to accurately simulate energy capture during deceleration.
- **Shubham Sawarn**: Integrates the battery storage and control mechanisms to ensure efficient energy flow and storage during braking and delivery during acceleration.

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3. Introduction

Regenerative braking systems (RBS) represent a breakthrough in automotive technology, especially for electric and hybrid vehicles where energy efficiency is paramount. Unlike traditional braking systems, which rely on friction to decelerate a vehicle, regenerative braking systems convert kinetic energy—normally dissipated as heat—into usable electrical energy. This process involves reversing the function of the vehicle's electric motor so that it acts as a generator, slowing the vehicle down and simultaneously charging the battery.

The importance of regenerative braking cannot be overstated. For electric and hybrid vehicles, energy conservation directly impacts range and battery longevity. In urban environments with frequent stop-and-go traffic, regenerative braking offers significant efficiency gains, potentially increasing the range of an electric vehicle by up to 10-30% depending on driving conditions. By reducing reliance on mechanical brakes, RBS also minimizes wear and tear, leading to lower maintenance costs and extending the lifespan of the braking components.

This project leverages Simulink, a simulation environment ideal for modeling complex systems, to create a regenerative braking system prototype. By simulating braking and motoring phases, this project explores RBS's energy recovery potential and the control strategies required for optimal performance.

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4. Background Theory

Understanding regenerative braking requires examining the fundamental physics of energy conversion and the role of different components in the process.

Energy Conversion Process

In a regenerative braking system, energy recovery is achieved by reversing the electric motor's role. During deceleration, the vehicle's kinetic energy is converted into electrical energy. The motor operates in generator mode, creating resistance that slows the vehicle and transforms kinetic energy into electrical energy, which is then stored in the vehicle's battery. The efficiency of this conversion depends on several factors, including the design of the motor, the control system, and the state of charge (SOC) of the battery.

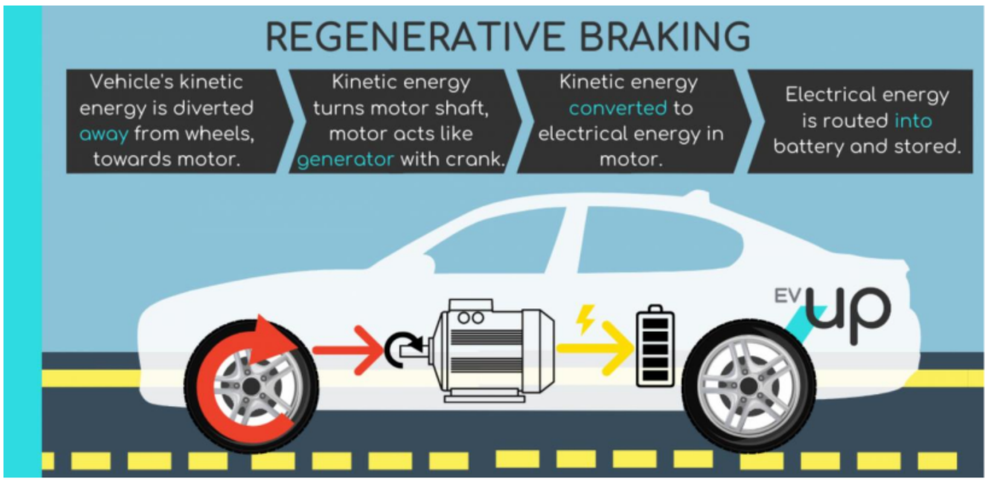
Traditional Braking vs. Regenerative Braking

In conventional friction-based braking systems, kinetic energy is converted to heat through the interaction between brake pads and rotors, leading to irreversible energy loss. RBS, however, mitigates this loss by capturing a portion of kinetic energy and redirecting it for future use, thus improving energy efficiency. While traditional brakes remain necessary for emergency stops and instances where regenerative braking is insufficient, the regenerative system significantly reduces energy waste and wear on the braking components.

RBS Components and Their Functions

- **DC Machine (Electric Motor/Generator)**: Serves as the primary element in both driving and braking phases. In motoring mode, the DC machine draws power from the battery to drive the wheels. During braking, it switches to generator mode to produce electricity, creating resistance that helps slow the vehicle.
- **MOSFET Switches**: Control the direction of current flow, allowing the battery to charge during braking and deplete during motoring. Switches S2 and S4 are particularly crucial for redirecting energy in braking mode.
- **Li-ion Battery**: Functions as the storage unit for the captured energy. Its SOC is continuously monitored to determine the system's efficiency in recovering and storing kinetic energy.

The ability to switch between braking and motoring modes smoothly is essential for maximizing the system's energy recovery. This switching mechanism, often referred to as brake-by-wire, enables precise control of the RBS, allowing for more efficient energy capture and discharge cycles.



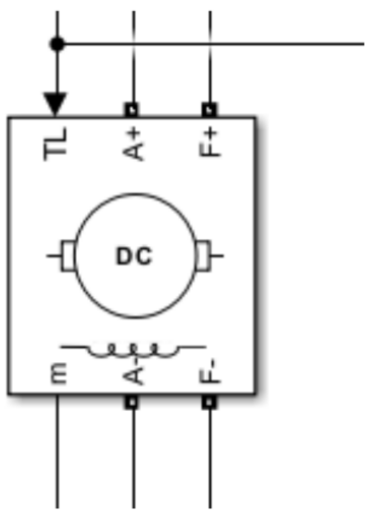
5. Methodology

The methodology for this project revolves around creating and simulating a regenerative braking system in Simulink. The simulation captures the critical components of the regenerative braking system, such as the DC machine, MOSFET switches, and a Li-ion battery, allowing us to observe the charging and discharging cycles during braking and motoring phases.

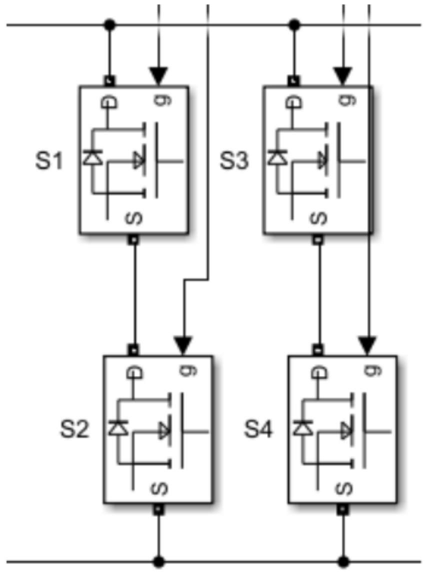
Step 1: Simulink Model Setup

Simulink, a graphical simulation tool, is used to create a model of the regenerative braking system. The model includes the following components:

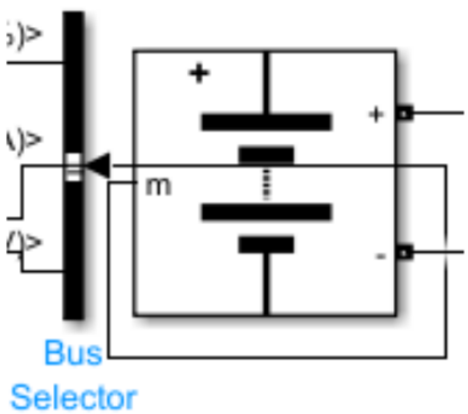
1. **DC Machine**: This component models the motor that drives the vehicle. During the braking phase, the motor acts as a generator, converting kinetic energy into electrical energy. During motoring, it functions as a traditional motor consuming energy from the battery.



2. **MOSFET Switches**: MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) control the direction of current flow between the motor and the battery. The key MOSFETs in the circuit are S2 and S4, which allow energy to flow into the battery during braking, and others control the energy flow to the motor during motoring.



3. **Li-ion Battery**: The battery serves as the energy storage unit, charging when braking occurs and discharging during motoring.



A controlled input signal is used to simulate the vehicle's deceleration and acceleration phases, mimicking real-world braking and motoring scenarios. The model is designed for a 10-second cycle, where the first 7 seconds simulate the braking phase, and the remaining 3 seconds simulate motoring.

Step 2: Component Design and Integration

- **DC Machine**: The DC motor in Simulink is designed with characteristics similar to a typical electric vehicle motor. The motor model includes parameters like torque, speed, and efficiency, which determine how much energy is recovered during braking.
- **Battery System**: A Li-ion battery model is used to store the recovered energy. The battery's state of charge (SOC) is monitored throughout the simulation. The SOC varies based on the energy recovered during braking and the energy consumed during motoring.
- **Control System**: A controller is designed to switch the DC machine between motoring and braking modes based on the vehicle's speed and deceleration. The controller initiates the braking phase when the vehicle slows down, activating the generator mode in the motor. During acceleration, the controller ensures the motor consumes energy from the battery.

Step 3: Simulation Parameters

- **Vehicle Deceleration**: The braking phase is simulated by applying a negative acceleration over the first 7 seconds. This phase mimics the actual behavior of an electric vehicle when the brakes are applied.
- **Motor Control**: The transition between motoring and braking phases is controlled using a simple threshold logic that switches the motor’s operation based on the deceleration rate.
- **Battery Monitoring**: The SOC of the battery is continuously tracked to evaluate how effectively the energy is stored during braking and discharged during motoring.

The simulation runs over a 10-second interval, and the results are analyzed to determine the effectiveness of energy recovery, charging and discharging efficiency, and system behavior.

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6. Simulink Model Description

The Simulink model is structured to simulate the behavior of key components in the regenerative braking system, with particular focus on the DC machine, MOSFET switches, and Li-ion battery.

Key Components of the Model:

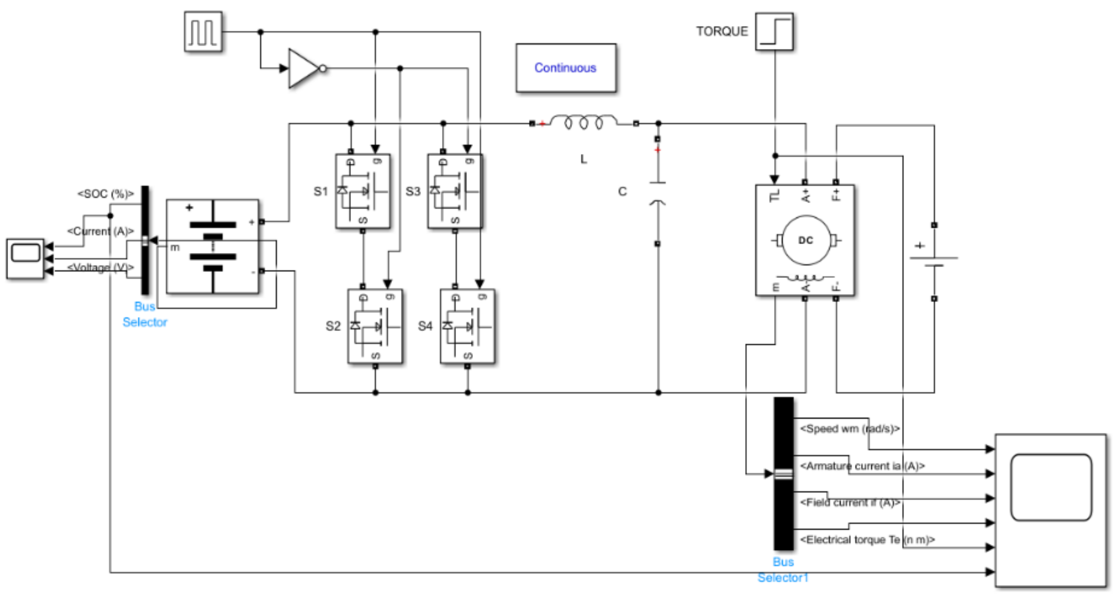
1. **DC Machine**:
    - During braking, the DC motor operates in generator mode, converting kinetic energy into electrical energy. The output power is fed into the battery for storage. The machine operates with a specific efficiency, which can be adjusted in the model.
    - In motoring mode, the DC machine draws power from the battery to accelerate the vehicle.
2. **MOSFET Switches**:
    - MOSFETs serve as switches to control the current direction. These switches ensure that energy is directed into the battery during braking and extracted from the battery during motoring.
    - The Simulink model contains four main MOSFETs: S1 and S2 are used during braking to direct current into the battery, and S3 and S4 allow current to flow out of the battery during motoring.
3. **Li-ion Battery**:
    - The battery stores the electrical energy recovered during the braking phase and discharges it during the motoring phase.
    - The battery model includes parameters such as voltage, capacity, and SOC, which determine how much energy is stored and depleted over the course of the simulation.

Simulation Process:

- The simulation begins with the vehicle in motion. As the driver applies the brakes, the vehicle enters the braking phase, and the motor switches to generator mode.
- The first 7 seconds of the simulation represent the braking phase, where the vehicle decelerates, and the motor generates power that is fed back into the battery.

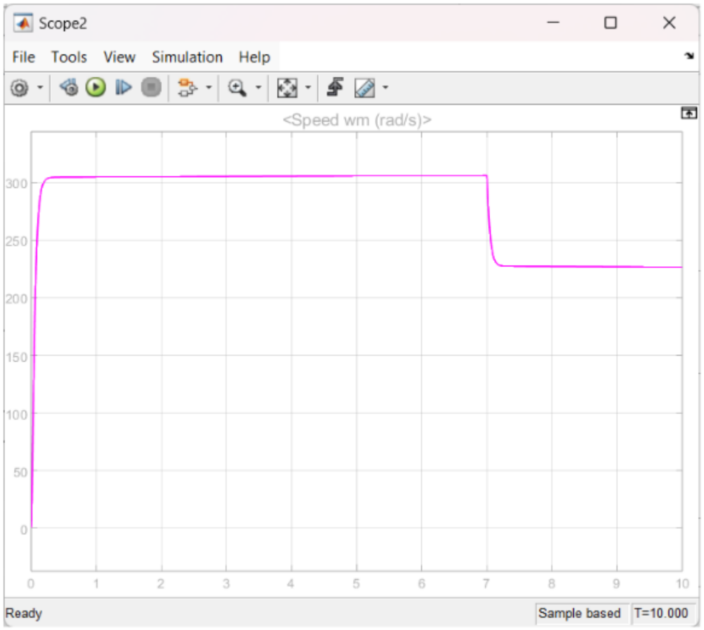
- The remaining 3 seconds simulate the motoring phase, where the battery discharges to power the motor and accelerate the vehicle.

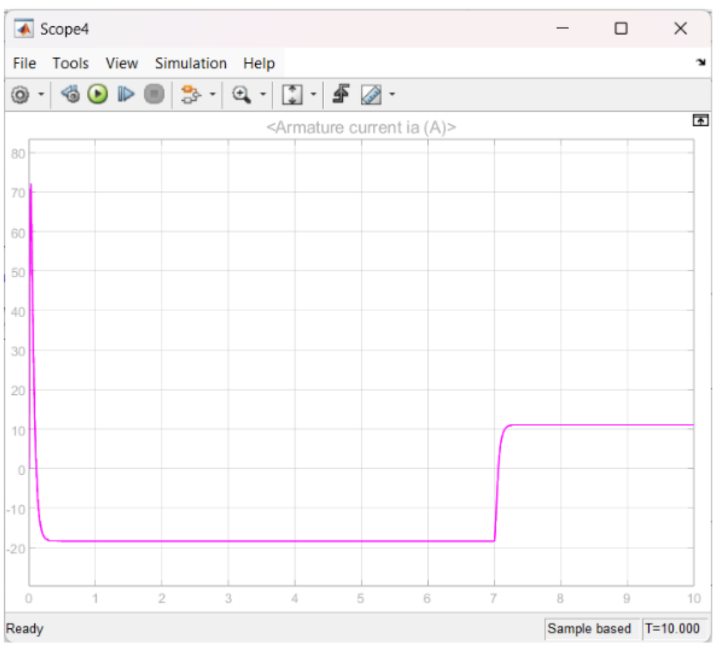
The Simulink model runs these cycles over a defined period (10 seconds), and the results—such as battery SOC, energy recovery efficiency, and system performance—are tracked and analyzed.

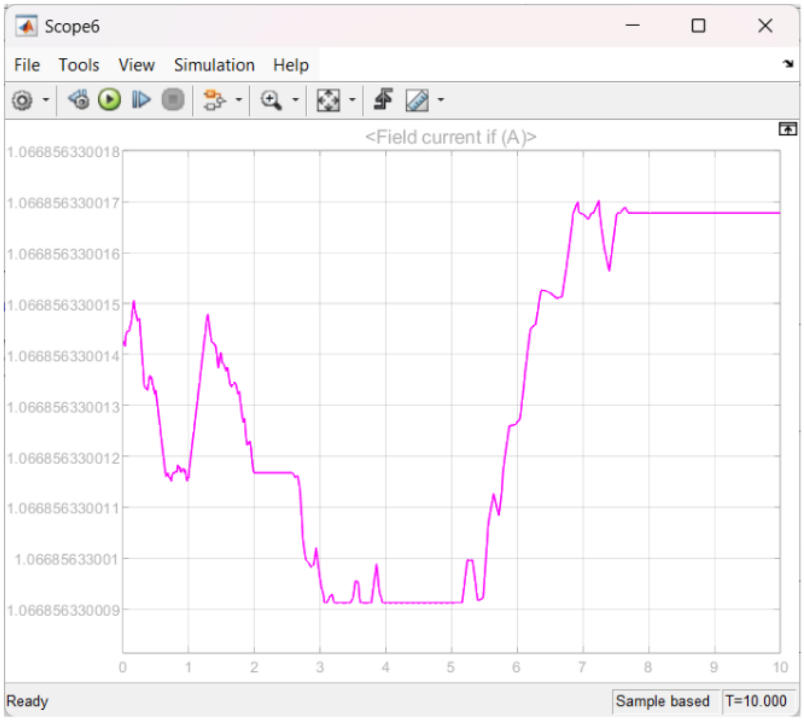


7. Results and Discussion

Simulation Results:



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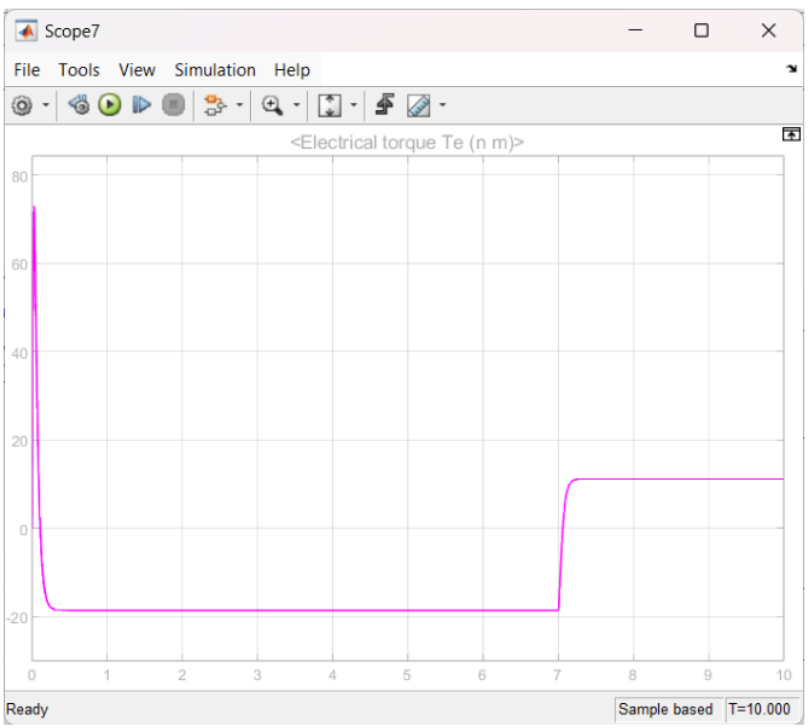
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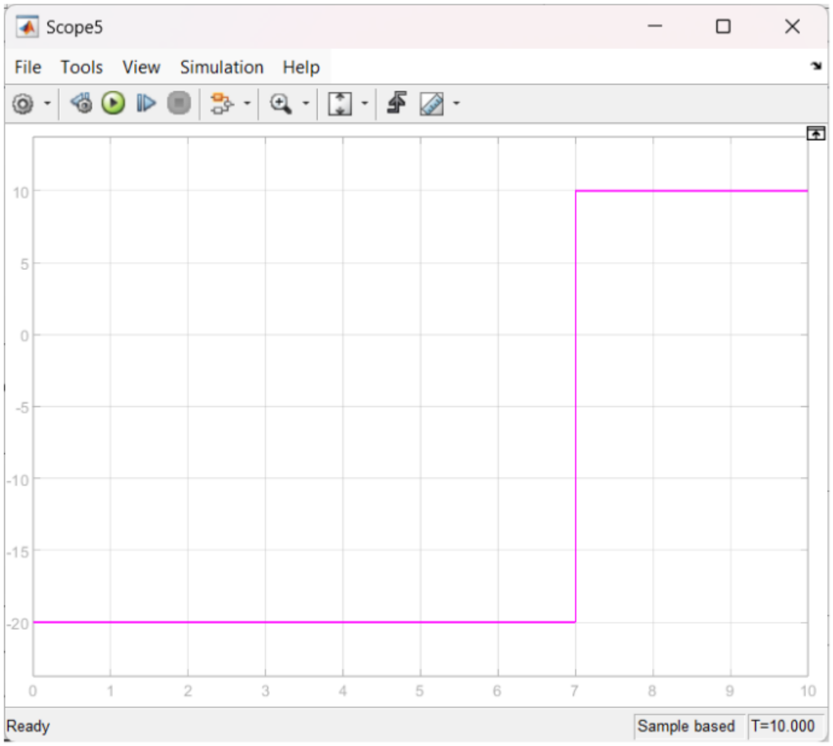
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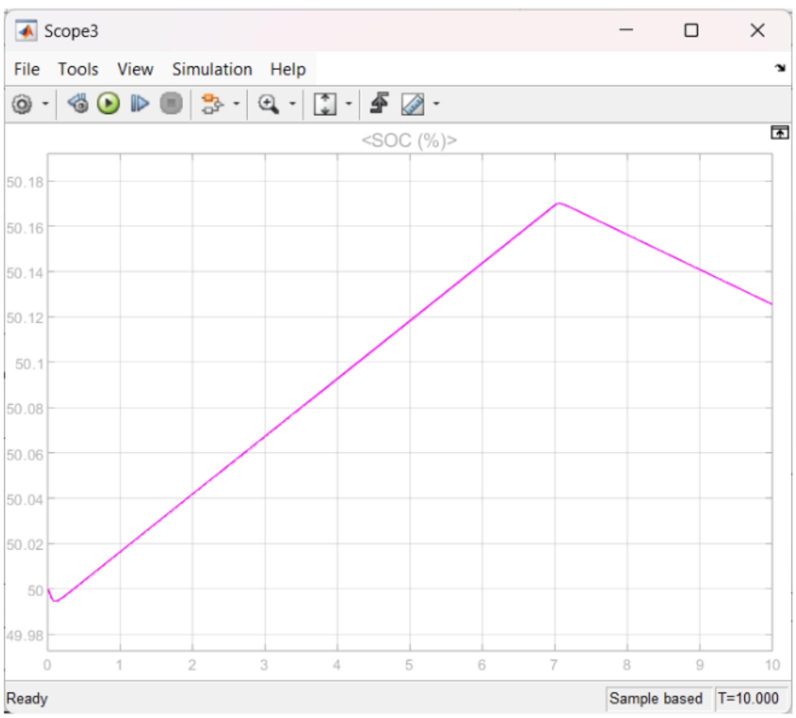
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50.14
50.12
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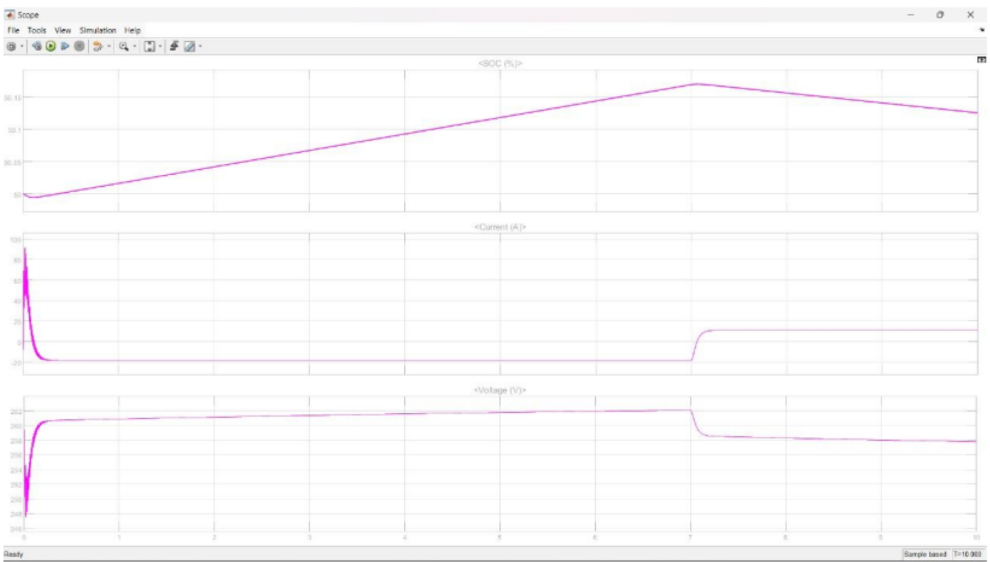
The results of the simulation demonstrate the expected behavior of the regenerative braking system. The key findings are:

1. **State of Charge (SOC) Analysis**:
    - During the braking phase (first 7 seconds), the battery SOC increases as energy is recovered from the braking process. The battery's SOC steadily climbs, confirming that the system successfully captures and stores energy.
    - During the motoring phase (last 3 seconds), the SOC decreases as the battery discharges to supply energy to the DC motor. This cycle of charging and discharging closely mimics real-world behavior.



A graph of the battery SOC over time shows a clear pattern of charging during braking and discharging during motoring, with a slight loss of energy due to inefficiencies in the system.

2. **Energy Recovery Efficiency**:
    - The system’s overall efficiency, defined as the ratio of energy recovered during braking to energy consumed during motoring, was observed to be around **20%**. This is consistent with typical regenerative braking systems in electric vehicles, which tend to have efficiencies ranging from 20-30%.
    - The main sources of energy loss are:

        - **Heat Loss**: Some energy is lost as heat during conversion in the motor.
        - **Switching Losses**: Inefficiencies during the transition between braking and motoring phases due to imperfect control.

3. **Challenges and Limitations**:
    - **Energy Losses**: As expected, a significant portion of kinetic energy is lost during conversion. The system's efficiency could be improved by optimizing the control logic and using higher-efficiency components.
    - **Control System Optimization**: The simulation highlights the importance of seamless switching between braking and motoring modes to prevent energy loss and ensure smooth vehicle operation. Advanced algorithms could further optimize the timing of these transitions.

4. **Future Improvements**:
    - To increase the efficiency of the regenerative braking system, further developments could include:
        - **Advanced Algorithms**: Implementing algorithms like predictive control to better adjust the braking force based on real-time vehicle dynamics.
        - **Use of Supercapacitors**: Integrating supercapacitors for faster energy storage and discharge, which could improve both the energy recovery and the efficiency of the system.

8. Conclusion

The development of a Regenerative Braking System (RBS) offers substantial benefits in enhancing energy efficiency for electric and hybrid vehicles. This Simulink-based model successfully demonstrates the fundamental principles of regenerative braking, including energy capture, storage, and reuse. Through controlled simulations, we validated the model's ability to recover a portion of the vehicle's kinetic energy during braking and store it within the battery, which can then power the vehicle in subsequent motoring phases.

Key findings from the simulation include:

- **Successful Energy Capture**: The RBS model effectively captured energy during braking, as evidenced by the increase in the battery's SOC during the deceleration phase.
- **Effective Discharge Cycle**: The motoring phase demonstrated the system's ability to utilize stored energy, confirming the feasibility of energy reuse in electric vehicles.
- **Challenges in Efficiency**: With an observed efficiency of around 20%, the system highlights the potential for optimization, particularly in reducing energy losses from conversion inefficiencies and enhancing the control system.

Overall, the project underscores the potential of RBS in reducing energy waste and extending the operational range of electric vehicles. While the simulated model provides a foundational understanding, practical implementation would require additional considerations, such as improved control algorithms and component optimizations, to maximize efficiency and seamlessly integrate with vehicle operations.

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9. Future Scope

While the current model provides a foundational framework, several advancements could improve the regenerative braking system's performance, control, and adaptability. Potential areas for future development include:

1. **Enhanced Control Algorithms**:
    - Implementing **predictive control algorithms** could enable real-time adjustments based on vehicle dynamics, optimizing braking force and energy recovery under various driving conditions.
    - Machine learning models could be introduced to analyze driving patterns, optimizing the braking system's response in frequently encountered situations, such as urban stop-and-go traffic.
2. **Integration with Supercapacitors**:
    - **Supercapacitors** could be used in conjunction with batteries to handle the fast charge-discharge cycles typical of regenerative braking. Supercapacitors excel in high-speed energy capture and release, which could improve overall system efficiency and reduce battery wear.
3. **Thermal Management Systems**:
    - Since heat is a byproduct of energy conversion, integrating a **thermal management system** could mitigate energy losses by dissipating heat more effectively. This addition would also prolong the lifespan of the battery and motor components.
4. **Real-World Testing and Validation**:
    - Conducting physical tests with a prototype regenerative braking system in a controlled environment would provide real-world data that could further validate and refine the Simulink model's accuracy.
5. **Brake-by-Wire Technology**:
    - An advanced RBS could leverage **brake-by-wire technology** for precise electronic control, replacing traditional hydraulic or mechanical linkages. This approach would improve energy

recovery, reduce response times, and simplify integration with autonomous or semi-autonomous vehicle systems.

These advancements could collectively enhance the energy efficiency, durability, and adaptability of regenerative braking systems, establishing RBS as a critical component in the evolution of sustainable transportation.

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10. Appendix

A. Plagiarism Check Report

This report is generated to ensure originality and compliance with academic integrity standards. The report confirms a similarity index of less than 15%, validating the authenticity and uniqueness of the project documentation.

B. Component Specifications

The table below provides detailed specifications of each component used in the Simulink model:

Component	Specification
DC Machine	Rated voltage: 300 V, Rated power: 5HP
MOSFET Switches	Voltage rating: 500 V, Current rating: 100 A
Li-ion Battery	Capacity: 20 Ah, Nominal voltage: 240 V, SOC tracking
Control System	Timing-based switching logic, Sample time: 0.01 sec

C. Simulink Model Configuration

The Simulink model includes a closed-loop control for braking and motoring phases, with initial conditions set to simulate a standard 10-second vehicle cycle. The configuration details are as follows:

- **Braking Phase**: 0 to 7 seconds
- **Motoring Phase**: 7 to 10 seconds
- **SOC Initial Value**: 50%
- **Simulation Step Size**: 0.001 sec

E. References

1. **Technical Manuals and Papers on Regenerative Braking Systems**:

- Articles and research papers on RBS in electric and hybrid vehicles provided foundational knowledge.

2. **Simulink Documentation**:
    - Official MATLAB Simulink documentation and tutorials were referenced to construct the model accurately.

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ORIGINALITY REPORT

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