Development of an Intelligent Regenerative Braking Control Strategy for Electric Vehicles using MATLAB/Simulink

Mayuri Khairnar[1], Sakshi Pandav[2], Shreya Shinde[3], Snehal Gadhave[4],
Dr. Rahul Agrawal[5], Dr. Sunil More[6]
Final Year Student, Department of Electrical Engineering[1,2,3,4]
Professor, Head of Electrical Engineering Department[5]
Assistant Professor, Department of Electrical Engineering[6]
Guru Gobind Singh College of Engineering & Research Centre, Nashik, Maharashtra, India

Abstract: *This paper introduces a detailed MATLAB/Simulink model for simulating a regenerative braking system in an Electric Vehicle (EV). Regenerative braking is a big plus for EVs because it converts the vehicles kinetic energy during slowing down into electrical energy, when is then sent back to the battery. This improves the vehicle's energy efficiency and increases how far it can go in single charge. The simulation model includes important parts of the regenerative braking system such as the vehicle's movement, the electric hub motor, battery, and control system that switches between regenerative and mechanical braking. Different ways of controlling how braking force are shared between regenerative and friction brakes is studied. The results of the simulation show how well the model can capture the energy recovery process under various driving situations, like different slowing rates and vehicle speeds. This focus is particularly relevant to the development of affordable and sustainable transport solutions, such as the retro-fit hybrid E-bike, where an existing Internal Combustion (I.C.) engine motorcycle is converted by adding an electric motor and battery system. The study also looks at how different control strategies for regenerative braking affect energy recovery and overall braking performance. This research offers useful information for designing and improving regenerative braking systems in EVs, which helps in making transportation more energy-efficient and eco-friendly.*

Keywords*:* Electric Vehicle (EV), Regenerative Braking, MATLAB/Simulink, Energy Efficiency, Braking Control Strategy, Simulation

I. INTRODUCTION

Regenerative Braking Systems (RBS) represent a significant leap forward in vehicle efficiency by converting a vehicle's kinetic energy into usable power during deceleration, a process that sharply contrasts with conventional brakes which simply dissipate energy as wasted heat. The system achieves this by utilizing the electric motor in reverse, making it function as an electrical generator. This newly generated power is then efficiently stored in the battery, a capacitor bank, or a mechanical flywheel. This superior mechanism enables the recovery of approximately 70% of the vehicle's kinetic energy. The design of an effective Battery Management System (BMS) is crucial for minimizing various operational faults in Electric Vehicles [1]

The widespread adoption of RBS is essential for extending the range and maximizing the energy efficiency of modern electric and hybrid vehicles, while also decreasing wear on mechanical braking components. Fuelled by governmental incentives and subsidies aimed at promoting eco-friendly transportation and combating rising fossil fuel costs, this technology is a foundational element in the global shift towards sustainable mobility.[2]

A key aspect of Regenerative Braking Systems (RBS) is their ability to store the recovered kinetic energy in various usable forms depending on the vehicle type. For electric and hybrid vehicles, this regenerated energy is typically stored

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 2, November 2025
Impact Factor: 7.67

chemically in the high-voltage battery to extend the driving range. Alternatively, it can be reserved in an electrical form within a capacitor bank or even in a mechanical form using a rotating flywheel. Furthermore, the performance and effectiveness of RBS can be significantly enhanced through the integration of advanced components like ultra-capacitors, which are known for their high-power density and rapid charge/discharge cycles. Furthermore, the vehicle's inertia must be reduced in order for it to accelerate. When the vehicle comes to a halt, the majority of the energy consumed in acceleration is dissipated as heat in the brakes. Finally, the vehicle must be capable of delivering power for acceleration with very little delay when the driver depresses the accelerator, which may necessitate keeping the power source in a standby (energy-using) mode. [5]

II. SYSTEM COMPONENTS AND DESIGN

The proposed system consists of the following major components:

Hub Motor: The hub motor provides instant torque, which means quick acceleration and smooth power delivery it provides 48 Volt, 3000 Rpm, 1200watt. They also enable regenerative braking, capturing energy during deceleration and braking to recharge the battery. Additionally, hub motors can be easily incorporated into existing vehicle platforms without major modifications. They offer flexibility in terms of placement, allowing for optimal weight distribution and handling characteristics.[18]

Electronic Speed Controller (ESC): A regenerative-capable motor controller that manages power flow between the motor and the battery. It also handles current and voltage regulation during both motoring and regenerative modes. The controller monitors and controls the power flow between the electric motor and the internal combustion engine. It ensures smooth transitions between electric and hybrid modes, optimizing efficiency and performance. The controller receives input from various sensors to determine the vehicle's operating conditions. It uses this information to adjust the power output of the electric motor and engine accordingly. The controller also manages the charging and discharging of the hybrid battery pack.[9]

Battery Pack and Battery Management System (BMS): In Battery design used 3.6A 16 number of cells which are connected in series hence it provides 48 Volt 30Ah supply in this by using smart BMS get all information about each cell in mobile app it also shows the battery charging percentage in mobile. Monitoring and reporting on the condition, functionality, and upkeep of the related battery is the responsibility of an intelligent Battery Management System (BMS). [18]

Throttle: It regulates the power delivered to the electric motor. It controls the acceleration of the vehicle by adjusting the motor's power output. When you press the throttle, it sends a signal to the motor to increase power. Releasing the throttle reduces the power and slows down the vehicle. The throttle helps optimize the balance between electric and internal combustion engine power in hybrid vehicles. It allows the driver to control the speed and responsiveness of the vehicle. The throttle position is measured by sensors and used to determine the motor's power output.[18]

Microcontroller Unit (MCU): The central processing unit (CPU), likely represented by a board like the STM32F4 Discovery. It executes the control algorithm to determine when and how much regenerative braking should be applied based on sensor data (speed, throttle/brake input, battery SOC). It has core of ARM Cortex-M4F and up to 168 MHz speed contains 1MB Flash 192KB+ RAM memory. [6]

Miniature Circuit Breaker: In a hybrid electric vehicle (HEV), the main function of the MCB (Main Circuit Breaker) is to protect the high-voltage battery pack and electrical systems from overcurrent conditions. It serves as a safety measure to prevent damage to the vehicle's electrical components and to ensure safe operation. The MCB can disconnect the battery from the vehicle's electrical system in case of a fault or emergency situation, reducing the risk of electrical hazards and ensuring the safety of passengers and technicians working on the vehicle.[18]

Inverter/Driver Circuit: This power stage circuit, often a three-phase bridge utilizing MOSFETs or IGBTs, controls the power flow between the battery and the BLDC motor. In motoring mode, it converts DC from the battery into AC to drive the motor. In regenerative braking mode, it controls the current flow to allow the motor to act as a generator and sends the current back to the boost converter.[18]

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 2, November 2025
Impact Factor: 7.67

III. METHODOLOGY

That's a detailed description of the operation of an Electric Vehicle (EV) propulsion system utilizing a DC motor with regenerative braking capability.

Here is an elaboration of the methodology, organized into more specific points under logical categories:

3.1 Motoring Mode (Vehicle Acceleration/Driving)

- **Energy Source and Conversion**: The system draws electrical energy from the Battery (the primary DC source) to power the vehicle.
- **Motor Function**: The DC Machine acts as a DC Motor, converting the electrical input into mechanical energy (torque and rotation). This mechanical energy drives the wheels.
- **Power Control**: H-Bridge Inverter: The H-Bridge Inverter is the main power electronic interface between the battery and the motor.
- **Speed/Torque Regulation (PWM):** The H-bridge is controlled by a PWM (Pulse Width Modulation) Pulse Generator. The duty cycle of the PWM signal dictates the effective voltage applied to the motor, thus regulating the motor speed and torque. The transistors in the bridge are switched appropriately to manage current flow.
- **Direction Control:** In a full H-bridge, the switching pattern of the transistors to determines the direction of the current through the motor, allowing for forward or reverse operation.

3.2 Transition to Regenerative Braking Mode

- **Braking Initiation:** When the driver initiates braking, a mechanical braking torque is applied to the motor shaft (in addition to or alongside the electrical process).
- **Speed Reduction & Energy Flow Reversal:** This braking action causes the DC Machine to slow down (decelerate). Crucially, the external mechanical energy now being applied to the motor shaft overcomes the back EMF, causing the DC machine to transition from a motor to a generator.
- **Generator Function:** The DC machine now operates as a DC Generator, converting the mechanical energy of the decelerating vehicle back into electrical energy.

3.3 Energy Recovery and Charging

- **Back EMF and Current Flow Reversal:** As the motor rotates under deceleration, it generates a Back EMF that is now greater than the battery voltage. This voltage differential causes the current to flow in reverse (or opposite) to the motoring direction, moving from the motor back toward the battery.
- **Inverter/Converter Role:** The H-bridge, under the specific regenerative control pattern, now functions as a Boost Converter (or a controlled rectifier) to manage the energy flow back to the battery.
- **Filtering and Stabilization:** The generated electrical energy flows back through the bridge and passes through the Inductor and Capacitor .The inductor acts to smooth the current, and the capacitor helps in voltage stabilization and filtering out high-frequency switching harmonics.
- **Battery Recharging:** The filtered and stabilized recovered energy is directed back to the Battery, effectively recharging it. This process improves the overall energy efficiency of the EV.

3.4 Control and Monitoring

- **Dynamic Control Signals:** The Pulse Generator (separate from the main PWM generator) and the NOT Gate are used to create the specific, coordinated Gate Signals required to control the switches dynamically.
- **Mode Management**: These control pulses are essential for ensuring the correct switching pattern is maintained, allowing the system to seamlessly switch and operate correctly in either the Motoring mode or the Regenerative Braking mode.

- **Real-time Performance Visualization**: The Scope block (connected via a Selector block) allows for real-time visualization and analysis of critical operational performance parameters, including:
  - Motor Speed
  - Armature Current
  - Field Current
  - Generated/Applied Torque
- **System Status Monitoring:** The Bus Selector and another Scope block are dedicated to monitoring key parameters of the battery and power system to confirm regeneration is working, such as:
  - Battery Current (to confirm negative/charging current)
  - Battery Voltage
  - SOC (State of Charge)

3.5 Simulation Environment

- **Solver Configuration (Power Gui):** The Power Gui (continuous) block is a critical simulation tool (e.g., in MATLAB/Simulink).
- **Enabling Continuous Simulation:** It provides the necessary solver configuration for electrical systems, allowing for real-time simulation of the circuit's behaviour under continuous-time operation (as opposed to discrete-time steps). This block is essential for the accurate modelling of power electronics and electromechanical systems. [12]

3.6 BLOCK DIAGRAM

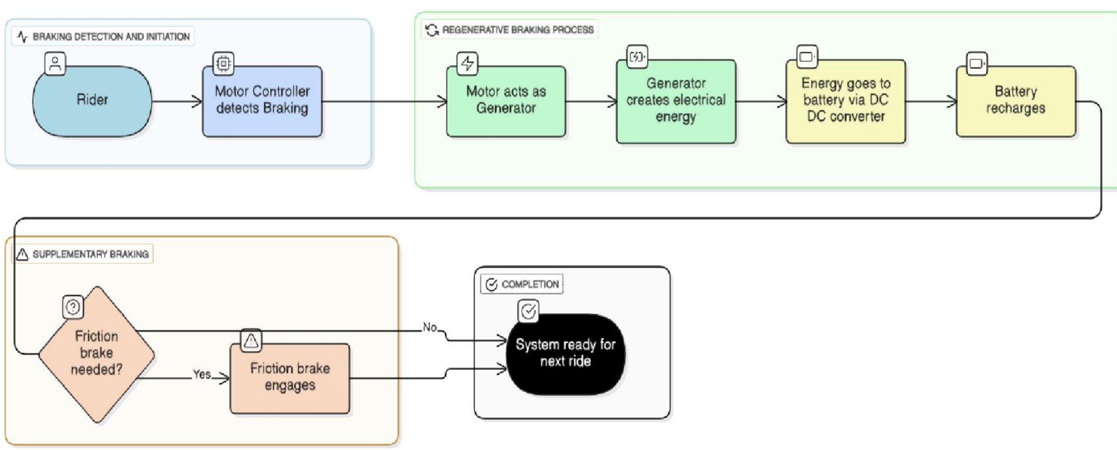

Fig 1: Block Diagram

As shown in Fig.(1) it depicts the functional process flow of an electrified vehicle's braking system, integrating Regenerative Braking with Supplementary Frictional Braking.

Braking Detection and Initiation

The system's operation is initiated when the Rider provides a braking input. This signal is detected by the Motor Controller (a key component of the vehicle's electronic control unit or ECU), which interprets the command to decelerate the vehicle.

Regenerative Braking Process

Upon detection, the control unit immediately commands the traction Motor to act as a Generator. The motor's kinetic energy is converted into mechanical work, which then, through electromagnetic induction, is transformed into electrical energy. This electrical power, typically an alternating current (AC), is then routed to a specialized power electronics module, the DC Converter (or inverter/rectifier), which converts the power into a direct current (DC) suitable for

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 2, November 2025
Impact Factor: 7.67

storage. The DC power is then delivered to the Battery, resulting in recharge (energy recovery). This process serves as the primary deceleration mechanism and enhances overall vehicle energy efficiency.

Supplementary Braking

Concurrently, a decision block assesses the required deceleration rate and state of charge/power limits: Friction brake needed? This determination is crucial for safety and performance.

If the regenerative torque is insufficient to achieve the commanded deceleration (e.g., due to low speed, high braking demand, or a fully charged battery), the decision is yes, and the Friction brake engages (e.g., disc or drum mechanical brakes).

If the regenerative braking is sufficient to meet the demand, the decision is No.

Completion

The operational paths converge, and upon the vehicle reaching a full stop or the rider releasing the braking command, the system enters the Completion state, signifying the System is ready for next ride. This closed-loop control ensures safe deceleration and maximum kinetic energy recovery.

3.7 BIKE CALCULATION

1. Kinetic Energy Conversion

When the scooter is moving, it possesses kinetic energy (E□):

$$E_k = \frac{1}{2}mv^2$$

Where,

m = total mass of scooter + rider (kg)

v = velocity (m/s)

During braking, regenerative braking aims to convert a portion of this kinetic energy into electrical energy stored in the battery:

$$E_{regen} = \eta_{regen} \times E_k$$

where, $Eregen$= regenerative efficiency (typically 0.5 to 0.7).

Example:

For $m = 120$ kg, $v = 15$ m/s, and $\eta_{regen} = 0.6$:

$$E_{regen} = 0.6 \times 0.5 \times 120 \times 15^2 = 8100 \text{ J}$$

$8100 \text{ J} = 2.25 \text{ Wh}$ of recovered energy.

2. Electromechanical Conversion (Motor as Generator)

The back EMF (Eb) when braking, the BLDC/PMSM motor operates as a generator produced is proportional to the motor's angular speed (ω):

Eb = Ke . w

where,

Ke = back EMF constant (Vs/rad)

w = angular velocity(rad/sec)

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 2, November 2025 Impact Factor: 7.67

3. Regenerative Braking Torque

The braking torque generated by the motor in generator mode is given by:

$$T_{regen} = k_t \cdot I_{regen}$$

where,

- k_t = torque constant (N·m/A),
- I_{regen} = regenerative current (A)

The negative torque (opposing rotation) slows down the wheel:

$$T_{net} = T_{load} - T_{regen}$$

Thus, higher regenerative current produces stronger braking effect.

4. Power Flow Equations

Instantaneous electrical power recovered is:

$$P_{regen} = V_{bat} \cdot I_{regen}$$

and mechanical power converted from the wheel is:

$$P_{mech} = T_{regen} \cdot \omega$$

The efficiency of the energy conversion is:

$$\eta = \frac{P_{regen}}{P_{mech}} = \frac{V_{bat} I_{regen}}{T_{regen} \omega}$$

5. Battery Charging Current Limit

During regeneration, the battery's maximum charge current Imax limits the braking strength:

$$I_{regen} \leq I_{max,BMS}$$

and the charging power cannot exceed:

$$P_{regen,max} = V_{bat} \times I_{max,BMS}$$

If the battery is near full SOC, the BMS commands the controller to reduce or disable regenerative torque.

6. Deceleration Relation

The braking deceleration (a) from regenerative torque is found from:

$$T_{regen} = F_{brake} \cdot r = (m \cdot a) \cdot r$$

$$\Rightarrow a = \frac{T_{regen}}{m \cdot r}$$

where,

r = wheel radius in m.

7. Total Braking Force (Hybrid Braking)

When combining mechanical and electrical braking:

DOI: 10.48175/IJARSCT-29723

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 2, November 2025
Impact Factor: 7.67

$$F_{total} = F_{regen} + F_{mech}$$

$$a_{total} = \frac{F_{total}}{m}$$

The control algorithm blends these two to maintain a smooth and safe stop while maximizing energy recovery.[8,13]

3.8 CALCULATION AND DESIGN PROCESS

Requirements & specs: target top speed, range, curb weight, battery capacity, max regen current.
Select motor & controller: choose FOC-capable controller with regenerative current/voltage margins.
Battery & BMS design: cell count/config, thermal management, regen charge acceptance.
Prototype electronics: MCU + inverter + sensors + display. Implement FOC and regen modes in firmware.
Brake blending & safety: define thresholds and mechanical overrides.
Integration & calibration: tune current loops, speed loops, regen torque mapping, and ride feel.
Testing: unit tests on bench (motor controller with dynamometer), vehicle tests, edge cases (full battery, low temp).
Certification: follow local EV standards, EMC, safety, and battery transport rules.
Pilot production: refine BOM for cost and manufacturability.
OTA & post-market support monitoring and software updates.[13]

3.9 SYSTEM ARCHITECTURE

1. Lithium-ion Battery Pack

As shown in fig (2) the battery design used 3.6A 16 number of cells which are connected in series hence it provides 48 Volt 30Ah supply in this by using smart BMS to get all information about each cell in a mobile app it also shows the battery charging percentage in mobile. In this battery LifePO4 cells are used in this battery. This cell has high recycling capacity, good in any thermal condition. In this the battery case is made for storing the battery which is made up of steel and insulated with tape the length of steel case is of 27cm & width is of 30 cm. The battery pack is designed with a proper Cell Balancing mechanism through the BMS to ensure that all cells maintain equal voltage levels during charging and discharging, which increases the overall lifespan of the battery. The LiFePO4 chemistry provides enhanced thermal and chemical stability, making the battery safe from overheating, fire, or explosion risks. This type of battery also offers a longer cycle life compared to conventional lead-acid or lithium-ion batteries, typically sustaining more than 2000+ charge cycles. The pack includes high-quality nickel strips for strong series connections and is enclosed with a PVC heat shrink layer for extra insulation. Additionally, ventilation slots are provided in the steel case to avoid heat accumulation, ensuring the battery remains safe and efficient during continuous operation. This battery pack is lightweight, requires low maintenance, and is environmentally friendly due to its non-toxic and recyclable cell composition.

Fig 2 : Lithium-ion Battery

DOI: 10.48175/IJARSCT-29723

2. Motor Controller

As shown in Fig (3) the controller also manages engine start/stop functionality, deciding when to shut off the ICE to save fuel during idle or low-load conditions. Additionally, it can prioritize electric-only operation at low speeds or when sufficient battery charge is available. Overall, the controller plays a pivotal role in parallel HEVs by seamlessly integrating the power sources to deliver a smooth and efficient driving experience. It integrates with the throttle, transmission, and other vehicle systems to achieve seamless operation. The controller also plays a role in controlling the hybrid system during start-up and shutdown sequences.

Fig3:Controller

3. Battery Management System (BMS)

As shown in Fig (4), the Battery Management System (BMS) plays a crucial role in ensuring the safety, performance, and long life of the battery pack. By using the JK BMS, users can easily monitor and manage their scooter's battery in real time through a smartphone. The app provides detailed information such as individual cell voltages, total pack voltage, current flow, temperature, and the state of charge (SOC). It also helps protect the battery by automatically balancing cell voltages and preventing overcharging, over-discharging, or overheating. Through the JK BMS interface, riders can access performance data, set protection parameters, and view fault alerts to maintain the health and efficiency of the battery. This intelligent BMS integration not only improves the reliability of the electric scooter but also enhances the overall riding experience by ensuring consistent power delivery and extended battery life.

Fig 4: BMS

DOI: 10.48175/IJARSCT-29723

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 2, November 2025
Impact Factor: 7.67

4. Hub Motor

As shown in Figure 5, the hub motor provides instant torque, which means quick acceleration and smooth power delivery. This setup simplifies the powertrain system and reduces energy losses during power transfer. Overall, the hub motor contributes to the efficiency, performance, and overall experience of riding a hybrid electric motorcycle. A hub motor for a parallel hybrid electric vehicle offers several advantages. Firstly, it integrates the motor directly into the wheel hub, reducing the need for complex drivetrain components. This simplifies the vehicle's design and improves overall efficiency. Secondly, hub motors provide instant torque, enhancing acceleration and responsiveness.

Fig 5: Hub Motor

3.10 SYSTEM DESIGN

Hybrid Electric Vehicle (HEV) is an advanced vehicle having a feature that operates on battery and inbuilt ignition motor. This motor helps to drive the wheel in recent years, the hybrid electric two wheelers have targeted the market due to less CO2 emission by the hybrid vehicles. The aim is to reduce the cost and complexity which is involved in the existing hybrid vehicle. This hybrid electric vehicle includes conventional, hybrid, plug-in hybrid and electric variants. The main aim of this paper is to structure and manufacture a hybrid two wheelers such as scooty, bikes which can be operated by means of fuel and battery. The integration of both the battery and the fuel make the vehicle dynamic. In HEV, the battery alone can be used at low-speed driving conditions whereas the interior fuel-based motors are least productive. In case of quickening, long runs or slope climbing, the Internal Combustion (IC) engine gives extra force to drive the motor. HEV configuration are dealing with different vitality source, exceedingly subject to driving cycles, battery measuring and battery on the board. HEVs take the upsides of electric drive to remunerate the inborn shortcoming of ICE, to be specific staying away from the lingering for expanding the eco-friendliness and decrease emanation amid beginning and speeding tasks.. These vehicles are of mind-boggling expense and certain program ought to be upheld by the particular government for promoting HEVs. As shown in Figure 6 presents a schematic diagram showing the key components added to a conventional internal combustion (I.C.) engine motorcycle to convert it into a hybrid. This design integrates an electric powertrain, consisting of a Battery pack, a Controller unit, a Motor HUB (likely a hub motor on the rear wheel), and a Throttle for input, alongside the original I.C. Engine. Figure 7, provides a physical image of the final converted motorcycle, clearly showing the externally mounted battery box and the overall integration of the electric components onto the existing two-wheeler chassis, validating the conceptual design.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 2, November 2025
Impact Factor: 7.67

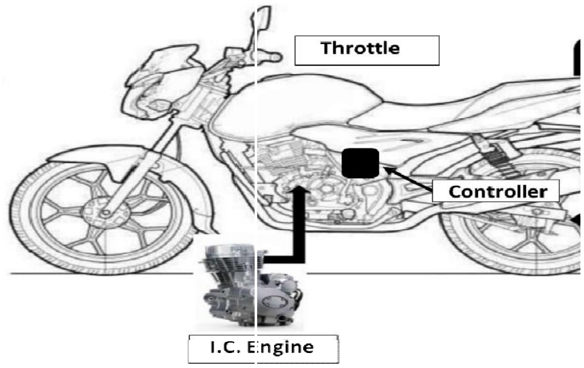

Fig 6 : Design of Vehicle

Fig 7 : Retro-fit Hybrid E-Vehicle

3.11 MATLAB SIMULATION

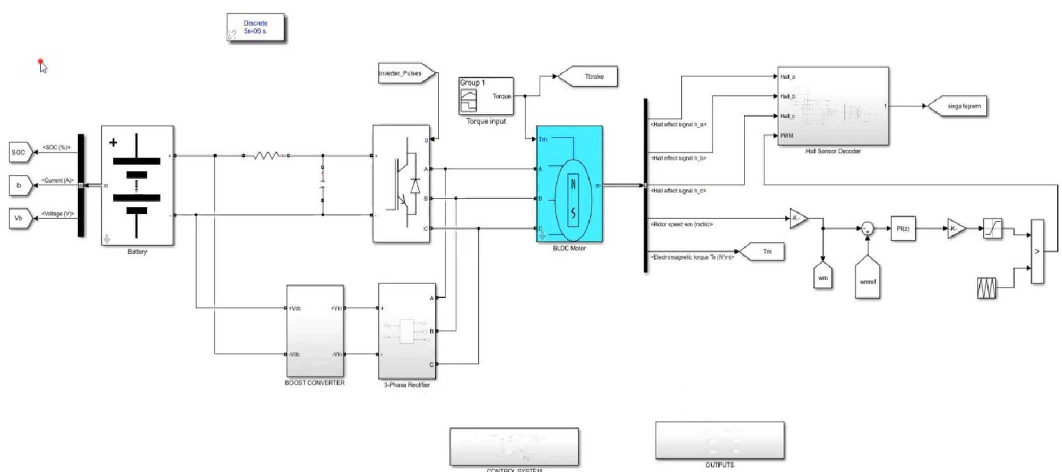

Fig 7 : MATLAB simulation

This section varies the control strategy and Type-II current compensator designed in the preceding section via simulation in the MATLAB/Simulink environment. The simulation aims to show the dynamic response of the proposed regenerative braking circuit and validate its working as a topology. Fig. 7 shows the arrangement of the inverter model, BLDC motor, rectifier, and Li-Ion battery blocks taken from the MATLAB/Simulink library. The various parameters for the BLDC motor and boost converter used for the simulation.

The BLDC motor is driven with mechanical torque (Tm) as its input. The Tm is positive during the motoring mode, and for the regenerative mode, Tm is negative. This negative Tm emulates the effect of Tgh due to the Fgh. Tgh force is assumed to be a constant force during the regenerative mode. Using MATLAB/ Simulink signal builder block, the load torque is predefined.

In the real-world physical drive scenario, the rider is both the reference speed generator and the regulator. Depending on the brake force given by the rider, the speed is slowed and maintained. For the simulation purpose, to emulate the riders braking action, a PI controller block is used to regulate the speed to produce the braking current reference from the difference between the actual motor speed and the reference speed input. The desired reference motor speed is generated using a signal builder.

The simulation is for a short 6 s, just enough to show the dynamic behaviours. That is because of power electronics components like the MOSFET with a switching frequency of 100 kHz; the simulation time step is 1 10 6, which slows the computational speed.[8]

IV. RESULT AND DISCUSSION

4.1 WAVEFORMS OF DYNAMIC RESPONSES

As shown in Figure 8 (a) plots the mode command signal input, which is the command given to the controller to switch between motoring mode and the regeneration mode. As seen from Fig. 8 (a), initially, the mode signal is HIGH, indicating the motoring mode, i.e., the normal forward motion. Here, in this mode, the motor controller is active, and the inverter pulses are ON while the regenerative braking circuit is inactive and the converter pulses are OFF. Then, at 2 s, the mode signal is turned LOW, indicating regeneration mode is ON. Here, in this mode, the regenerative braking circuit is active, and the converter pulses are ON while the inverter pulses are OFF, and the motor controller is inactive. Then again, at 4.5 s, the system is back to motoring mode. This shows that the control strategy given to the simulation system to swap between motoring and regeneration mode is working and effective.

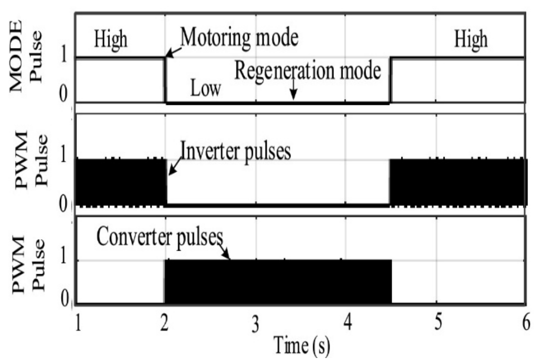

Fig 8 (a)

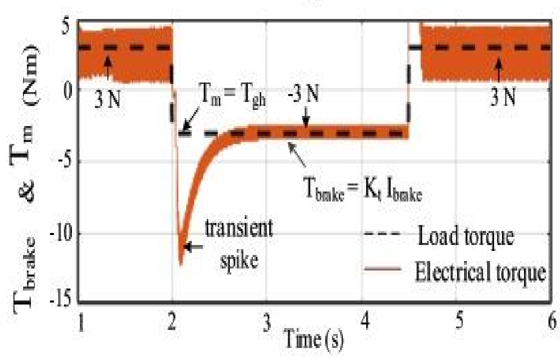

Fig 8 (b)

Figs. 8 (b) and (c), respectively. As seen from the Fig. 8 (b)

plot during the motoring mode, the Tm is a positive 3 Nm which acts as the load to the motor. At 2 s, when the regeneration braking commences, the Tm is-3 Nm; the negative Tm value emulates the effect of the free torque due to the gravitational acceleration force Fgh. The motor generates T brake equal to kt Ibrake to reach the desired speed. The response waveform of T brake is shown in Fig. 8 (b).

At 2s, the regenerative braking commences upon receiving the braking command and braking force applied by the rider.

The converter controller then tracks the braking current reference. The desired braking current starts owing in the circuit, generating the desired braking torque required to oppose Tgh due to the slope. As seen from Figs. 8 (b) and (d) for Tgh 3 Nm input, the braking current drawn is 2.6 A (Tgh kt 1165) and braking torque 3 Nm is generated**.**

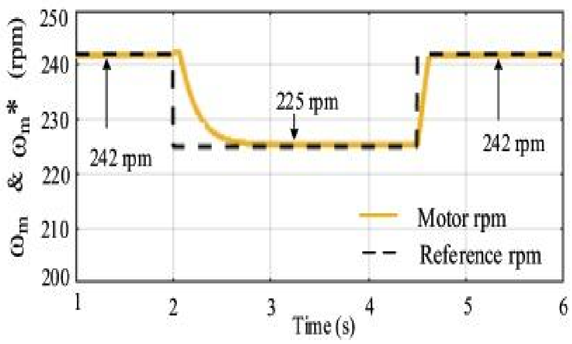

Fig 8 (c)

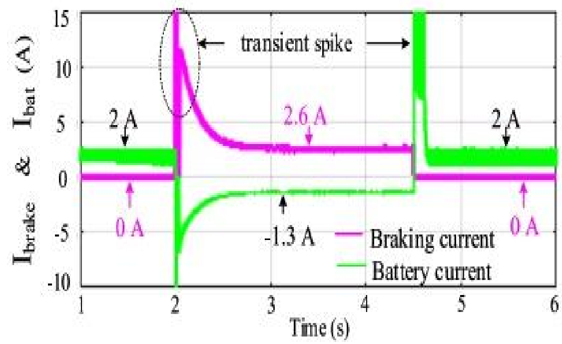

Fig 8 (d)

Due to the opposing electromagnetic braking torque, the speed of the motor drops from 242 rpm to 225 rpm as shown in Fig. 8 (c). The voltage generated corresponding to 225 rpm is 25V,as showninFig.8(e).The duty cycle generated by the converter controller is 0.46. The boost converter will boost the input voltage 25 V to a voltage slightly higher than the battery voltage (42 V, SOC30%) so that the required current can flow to charge the battery.

Fig. 8 (d) plots the braking current and the battery charging current respectively. The negative battery current indicates the charging of the battery, which can also be validated from the battery SOC pro le given in Fig. 8 (f).

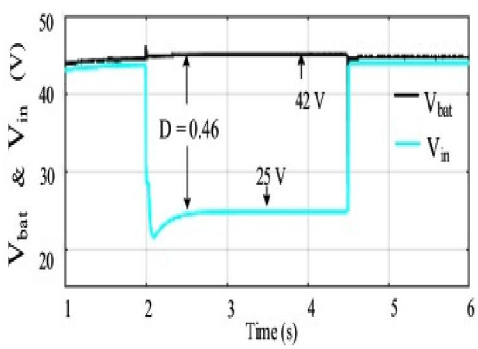

Fig 8 (e)

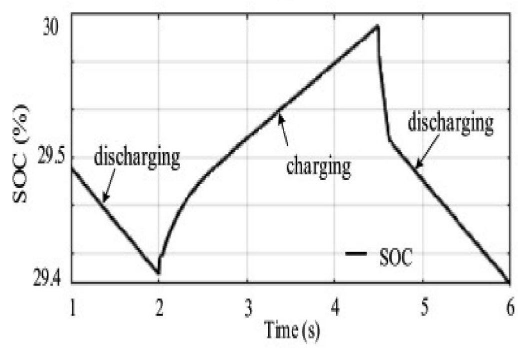

Fig 8 (f)

The above discussion shows that the control strategy(mode selection) and Type-II compensator performs as desired by the designer. The dynamic response shows that the designed controller gives us a good transient response, steady-state performance, and stability. The simulation results validates that the proposed regenerative braking circuit topology effectively tracks the braking current and generates the braking torque to slow down the speed of the motor and simultaneously charge the battery.

4.2 SIMULATION RESULT DISCUSSION

To validate the performance of the proposed regenerative braking circuit, simulations were conducted in the MATLAB/Simulink environment using parameters listed in Appendix I and II. The study evaluated the dynamic transition between motoring and regenerative braking modes. Initially, the drive operated in motoring mode, after which a control signal triggered the transition to regenerative braking. The simulation demonstrated a smooth and instantaneous shift between both modes, confirming the effectiveness of the designed control logic.

During braking, a negative mechanical torque (–3 Nm) was applied to emulate the gravitational force on a downhill slope. The braking current reached approximately 2.6 A, producing a braking torque of nearly 3 Nm. This electromagnetic torque slowed the BLDC hub motor speed from 242 rpm to 225 rpm. The corresponding input voltage to the DC–DC boost converter was approximately 25 V, which was raised to slightly above the 42 V battery level with a duty ratio of 0.46. The resulting negative battery current verified energy recovery through battery charging. The simulation further indicated an increase in the state of charge (SOC) of the battery, validating the regenerative effect.

The Type-II current compensator effectively regulated the braking current, yielding a well-damped transient response and excellent steady-state accuracy. The system showed fast tracking of the reference current and ensured stable operation with minimal overshoot. The steady-state analysis revealed that as vehicle speed decreases, the converter's duty cycle increases to maintain constant braking torque, though converter efficiency slightly drops at lower speeds due to increased switching losses.

The simulation and experimental investigations collectively validate the proposed modular regenerative braking circuit for electric two-wheelers operating on hilly roads. The design achieves:

- Fast and reliable switching between motoring and regeneration modes without additional power switches.
- Effective energy recovery even at low vehicle speeds (15–25 km/h).
- Compact, low-cost implementation, compatible with existing EV architectures.
- Enhanced controller performance using a compensator for stable current regulation.

The findings confirm that the proposed configuration is not only efficient and robust but also adaptable for real-world electric scooters requiring consistent braking on slopes.[8]

V. CONCLUSION

This paper presented the design and simulation of an intelligent electric vehicle equipped with a regenerative braking system, developed and analysed using MATLAB/Simulink. The proposed system effectively converts the kinetic energy of the vehicle during deceleration into electrical energy, which is then stored in the battery to enhance the vehicle's range and energy efficiency. The integration of a BLDC hub motor, a DC–DC boost converter, and a Type-II current compensator ensured smooth mode transition, stable operation, and effective control of braking torque and current.

Simulation results confirmed that the system achieves seamless switching between motoring and regenerative modes without the need for additional switching devices. The braking current and torque were accurately regulated, enabling the recovery of a substantial portion of the vehicle's kinetic energy even at lower speeds. The observed increase in battery state of charge validated the effectiveness of the proposed regenerative control approach.

The developed intelligent control strategy, supported by the Battery Management System (BMS) and microcontroller-based supervision, demonstrated the feasibility of integrating regenerative braking into existing two-wheeler platforms. The system not only reduces mechanical brake wear and energy wastage but also contributes significantly to improving the sustainability and overall efficiency of electric mobility solutions.

Future work will involve hardware prototyping and road testing to evaluate performance under real driving conditions, along with the implementation of adaptive braking algorithms and IoT-based monitoring for advanced energy management and predictive maintenance.

REFERENCES

[1]. Sunil Magan More, "Design & Development of Battery Management System for Electric Vehicles to Minimize Various Faults", 2024 Second International Conference Computational and Characterization Techniques in Engineering & Sciences (IC3TES), Date Added to IEEE Xplore: 17 February 2025, DOI: 10.1109/IC3TES62412.2024.10877533, Date of Conference: 15-16 November 2024.

[2]. P. B. Karandikar, D. B. Talange, A. Sarkar, A. K. Kumar, G. R. Singh and R. Pal, "Feasibility Study and Implementation of Low Cost Regenerative Braking Scheme in Motorized Bicycle Using Supercapacitors," *J. Asian Electric Vehicles*, vol. 9, no. 2, pp. 1497-1504, 2011. doi:10.4130/jaev.9.1497. J-STAGE+2cir.nii.ac.jp+2

[3]. M. K. Dubey and P. B. Bobba, "Variable Switch Regenerative Braking Technique for PM BLDC Motor Driven Electric Two-wheeler," in *E3S Web of Conferences*, vol. 87, 2019, Art. no. 01029. doi:10.1051/e3sconf/20198701029. E3S Conferences

[4]. L. Soni, S. Venkateswaran and V. Ramachandran, "Performance and Comfort Optimization from ABS/CBS/Motor Regenerative Braking in an Electric Two Wheeler during Heavy and Mild Braking Respectively," SAE Technical Paper 2019-26-0122, Jan. 2019. saemobilus.sae.org

[5]. N. M. Mohd Noor, S. F. Toha, M. Abdullah, S. Ahmad and M. A. Rahman, "Regenerative Braking System (RBS) MOSFET Switching-Based Drive Cycle for an Electric Motorcycle," *IIUM Engineering Journal*, vol. 26, no. 2, pp. 286–304, May 2025. doi:10.31436/iiumej.v26i2.3413. IIUM Journals

[6]. S. Ganesh, K. V. Nivas, A. Kavya, S. Arunteja, P. Guruvulunaidu and B. R. Kumar, "Designing of Electric Vehicle with Regenerative Braking System," *i-manager's Journal on Electrical Engineering*, vol. 16, no. 3, pp. 1–10, 2023. doi:10.26634/jee.16.3.19419. i-manager publications

[7]. R. K. Mainali, K. Kafle, S. Bhattarai, R. Buyo and R. L. Karn, "Enhancing Electric Bicycle Efficiency: Investigating Regenerative Braking and Pedal Charging Systems," *International Journal on Engineering Technology*, vol. 2, no. 1, pp. 117–134, Dec. 2024. doi:10.3126/injet.v2i1.72561. Nepjol

[8]. S. Tripathi, A. K. Tiwari, S. Jain and P. Tomar, "Regenerative Braking System: Why is Energy Regeneration System Required?" *IJRASET*, vol. 2321-9653, 2025. doi:10.22214/ijraset.2025.69917. IJRASET

[9]. Kanak Sunil Patil and Prasad Pandhareenath Desai, "Regenerative Braking Systems," *International Journal of Innovative Science & Research Technology*, vol. 9, no. 1, Jan. 2024. doi:10.5281/zenodo.10538787. IJISRT

[10]. P. Stawczyk, "Costless Improvement of Converter Efficiency in a Regenerative Braking System with a Brushless DC Machine," *Electronics*, vol. 14, no. 12, 2390, June 2025. doi:10.3390/electronics14122390. MDPI

[11]. M. Arun Noyal Doss, T. A. Anuja, K. N. D. V. Sai Eswar, M. Vinoth Raja, V. S. Ramasubramanian, E. Shalini and S. Priya, "Regenerative Braking of BLDC Motor applied to Electric Vehicles," *International Journal of Vehicle Structures & Systems*, vol. 15, no. 3, 2023.

[12]. S. Mehta and D. Guan, "A Dual Control Regenerative Braking Strategy for Two-Wheeler Applications," *Energy Procedia*, vol. 107, pp. 130-137, 2017. ScienceDirect

[13]. P. B. Bobba and K. R. Rajagopal, "Compact Regenerative Braking Scheme for a PM BLDC Motor Driven Electric Two-Wheeler," in *Proc. 2010 Joint International Conf. on Power Electronics, Drives and Energy Systems & 2010 Power India (PEDES/PowerIndia)*, pp. 1-5, Dec. 2010. ResearchGate+1

[14]. M. K. Dubey and P. B. Bobba, "Variable Switch Regenerative Braking Technique for PM BLDC Motor Driven Electric Two-wheeler," in *E3S Web of Conferences*, vol. 87, Art. no. 01029, 2019. ResearchGate+1

[15]. C. Phan, "Electric Motorcycle Acceleration, Braking, and Regenerative Coast-Down Deceleration Testing & Analysis," SAE Technical Paper 2023-01-0631, 2023. SAE International

[16]. S. Szumska, "Regenerative Braking Systems in Electric Vehicles: A Literature Review (2005-2024)," *Energies*, vol. 18, no. 10, Art. 2422, 2025. MDPI

[17]. C. Li, L. Zhang, and S. Lian, "Research on Regenerative Braking Control of Electric Vehicles Based on Game Theory Optimization," *PeerJ Computer Science*, 2024. PMC

[18]. Suyanto, P. A. Darwito, R. A. Wahyuono, M. S. Arifin & B. Sudarmanta, "Design of Regenerative Braking System for Electric Motorcycle Based on Supercapacitor with Fuzzy PID," *Int. J. Automotive Technology*, vol. 24, pp. 187-194, 2023. SpringerLink

[19]. S. Ganesh, K. V. Nivas, A. Kavya, S. Arunteja, P. Guruvulunaidu & B. R. Kumar, "Designing of Electric Vehicle with Regenerative Braking System," *i-manager's Journal on Electrical Engineering*, vol. 16, no. 3, pp. 1-10, Jan.–Mar. 2023. i-manager publications

[20]. S. Karyś, "High-efficiency BLDC-motor Regenerative Braking System for Light Electric Vehicles," *Applied Energy*, 2025 (in press). ScienceDirect

[21]. "Regenerative Braking System for an Electric Motorcycle Model Sakura M500," E. A. Manzano & W. M. Narciso, in *22nd LACCEI Int. Multi-Conference for Engineering, Education, and Technology*, San José, Costa Rica, July 17-19 2024