

Analysis and Enhancement of Electric Vehicle Range and Battery Life using Regenerative Braking

Mayuri Khairnar¹, Sakshi Pandav², Shreya Shinde³, Snehal Gadhav⁴, Dr. Rahul Agrawal⁵, Dr. Sunil More⁶

Final Year Student, Department of Electrical Engineering^{1,2,3,4}

Professor, Head of Electrical Engineering Department⁵

Assistant Professor, Department of Electrical Engineering⁶

Guru Gobind Singh College of Engineering & Research Centre, Nashik, Maharashtra, India

Abstract: This paper presents the design and hardware implementation of a Regenerative Braking System (RBS) for an Electric Vehicle (EV), with a specific focus on a hybrid E-bike retrofit application. Unlike purely theoretical models, this study details the integration of a 60V,1200W,25A brushless DC (BLDC) hub motor, a Regenerative Braking controller, and a lithium-ion battery of 60V,28Ah with battery management system (BMS) onto an existing Internal Combustion (I.C.) engine motorcycle chassis. The hardware architecture utilizes a dedicated regenerative controller to manage the transition between mechanical friction braking and electromagnetic regenerative braking. By implementing a sensor-based feedback loop, the system monitors real-time parameters such as battery voltage rating, charging current and regenerative current while decelerating. Experimental results obtained from road tests demonstrate the system's ability to reclaim kinetic energy and improve overall battery range under various load conditions and terrain gradients. This work provides a practical framework for developing affordable, sustainable transport solutions through the electrification of legacy vehicular platforms.

Keywords: *Electric Vehicle (EV), Regenerative Braking, Energy Efficiency, Braking Control Strategy.*

I. Introduction

Regenerative Braking System (RBS) lies in its ability to reclaim kinetic energy that would otherwise be lost to the atmosphere as thermal dissipation via friction. In a hardware implementation, this is achieved by operating the traction motor in a generative quadrant. During deceleration, the back-electromotive force (back-EMF) of the motor is leveraged to redirect current through a bi-directional DC-DC converter, facilitating energy storage. While theoretical limits suggest a kinetic energy recovery potential of up to 70%, actual hardware efficiency is governed by the duty cycle of the power switches and the internal resistance of the storage medium.[3]

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]

In the context of vehicle dynamics, the energy consumed during the acceleration phase is stored as momentum. In conventional internal combustion (I.C.) platforms, this momentum is wasted during braking. By contrast, an RBS-equipped vehicle treats this inertia as a secondary power source. To ensure seamless drivability, the control hardware must maintain a minimal latency response between the accelerator input and torque delivery. This necessitates a "ready-state" power management mode where the inverter remains synchronized with the motor's rotor position, ensuring that the transition from energy recovery (braking) to energy consumption (acceleration) is instantaneous and efficient.[1]

II. SYSTEM COMPONENTS AND DESIGN

The proposed system consists of the following major components:

1. Lithium-ion Battery pack:

The battery design used 30A, 19 number of cells which are connected in series hence it provides 60 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 27cms & width is of 30cms. Stores regenerated current. Must support regenerative charging (BMS should allow charge current input). The integration of regenerative braking within the propulsion subsystem allows for the kinetic-to-electrical energy recovery, significantly improving the overall tank-to-wheel efficiency. Must support regenerative charging (BMS should allow charge current input).



Fig 1: Battery

2. Hub Motor

A hub motor delivers instant torque, providing quick acceleration and smooth power delivery in a hybrid electric motorcycle. Since the motor is directly integrated into the wheel hub, it eliminates complex drivetrain components, reduces transmission losses, and improves overall system efficiency. This simplified powertrain design enhances performance while also lowering maintenance requirements and mechanical wear. In a parallel hybrid setup, hub motors also support regenerative braking, recovering energy during deceleration to recharge the battery. Their compact size, quiet operation, and flexible placement allow better weight distribution and easy integration into existing vehicle platforms without major modifications.



Fig 2: HUB Motor

3. Motor Controller (Bidirectional Controller)

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. It regulates the regenerative braking system, converting kinetic energy into electrical energy to recharge the battery. The controller constantly analyse data to make real-time decisions, maximizing fuel efficiency and reducing emissions. It monitors various parameters

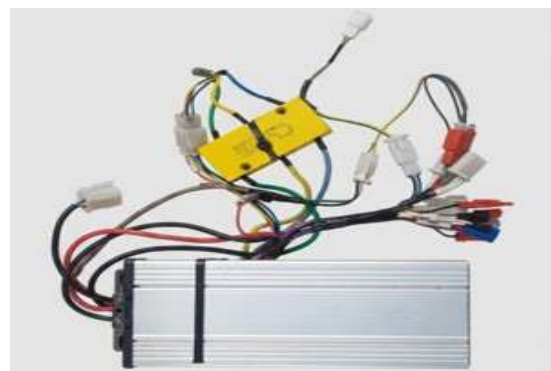


Fig 3: Controller

such as vehicle speed, throttle position, battery state of charge, and engine load. Overall, the controller acts as the brain of the electrical hybrid vehicle, ensuring optimal performance, efficiency, and integration of all the hybrid component.

4. Throttle + brake Sensor input

The throttle and brake inputs are key control elements in an electric vehicle equipped with a regenerative braking system. The throttle, usually a twist-grip or thumb lever, sends a variable signal to the motor controller to regulate motor power and control vehicle speed smoothly. Releasing the throttle reduces torque, allowing controlled deceleration and stable operation. The brake input not only slows down the vehicle but also activates regenerative braking. During braking, the motor operates as a generator converting kinetic energy into electrical energy and storing it back in the battery. The coordination between throttle and brake ensures smooth speed control and efficient regenerative braking.



Fig 4: Controller wiring



Fig 5 : Brake Sensor and Lever

5. Battery Management System (BMS)

In an electric vehicle, the JK BMS (Battery Management System) ensures battery safety, performance, and long service life. It allows real-time monitoring through a smartphone app, displaying key parameters such as cell voltage, total pack voltage, current, temperature, and State of Charge (SOC). The system protects the battery by preventing overcharging, over-discharging, overheating, and by automatically balancing individual cells.

The JK BMS also helps in analysing regenerative braking performance. When the current value becomes positive, it indicates that power is flowing from the motor back to the battery, confirming energy recovery during braking.



Fig 6 : BMS Reading

6. Human interface (Display)

The human interface in the electric vehicle consists of the instrument cluster and Bluetooth-enabled mobile app, providing the rider with clear and convenient access to essential information. The instrument cluster displays real-time data such as speed, battery level, state of charge (SOC), trip details, and warning indicators for immediate monitoring. Through the mobile app, users can access advanced features including detailed battery analytics, ride history, system alerts, and remote diagnostics. This

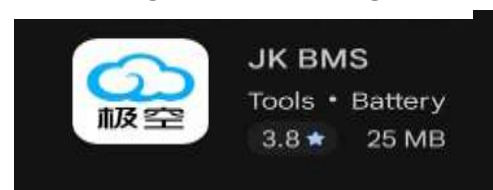


Fig 7 : BMS Application

integrated interface enhances safety, improves user control, and ensures better performance monitoring and maintenance of the vehicle.

III. METHODOLOGY

3.1 Regenerative Braking in E-Vehicle

Electric Vehicle equipped with regenerative braking use the motor as both a drive unit and a generator.

the rider brakes or releases the throttle, the motor's role

reverses, converting kinetic energy into electrical energy and feeding it back into the battery. In practice, this means energy that would normally be lost as heat is captured, slightly extending the Vehicle range and reducing wear on the friction brakes in other words, regenerative braking is an energy-recovery system that slows the Vehicle while recharging its battery. The Bidirectional controller (MCU) manages this process: as soon as the brake lever is pulled (or throttle released), it cuts power to the motor and switches the inverter so the spinning motor generates electricity. This creates a natural drag on the Vehicle, aiding deceleration, and routes current back into the battery. Overall, an intelligent regen-braking system improves efficiency by reusing energy and sparing the mechanical brakes while still allowing the Vehicle to be brought to a complete stop when needed. [5,13,9]

- **Rider Applies Brake:** When the rider pulls the brake lever (or releases the throttle on some Vehicle), this input signals the Vehicle control system that deceleration is needed. The controller immediately cuts power to the motor's drive even though the Vehicle is still moving. In other words, the Vehicle knows it must start slowing down, and the electronics prepare to recover energy.
- **Motor Controller Detects Braking:** The motor controller receives the brake command and switches into regenerative mode. It stops supplying forward power to the motor and configures the drive circuitry so that the motor can now generate electricity. In effect, the controller has put the motor into "generator" mode in anticipation of capturing energy.
- **Motor Acts as Generator:** Even after power is cut, the Vehicle wheels keep spinning due to inertia. Those spinning wheels drive the brushless DC (BLDC) motor's rotor, so the motor behaves like a generator. In this mode, the rotor's magnets moving past the stator windings induce an alternating current in the coils – the motor is now converting kinetic motion into electrical output.
- **Generator Creates Electrical Energy (Regeneration):** As the motor acts as a generator, it converts the Vehicle kinetic energy into electrical energy. The induced current (typically three- phase AC in a BLDC motor) flows out of the motor windings. The controller's power electronics capture this electricity: the AC is rectified to DC and prepared for charging the battery.
- **Energy Goes to Battery via DC-DC Converter:** The generated DC power is routed back into the battery, but first it passes through the controller's DC-DC conversion stage. Since the motor can generate a voltage that is lower or higher than the battery voltage, a boost converter raises the motor's output voltage above the battery's terminal voltage so current

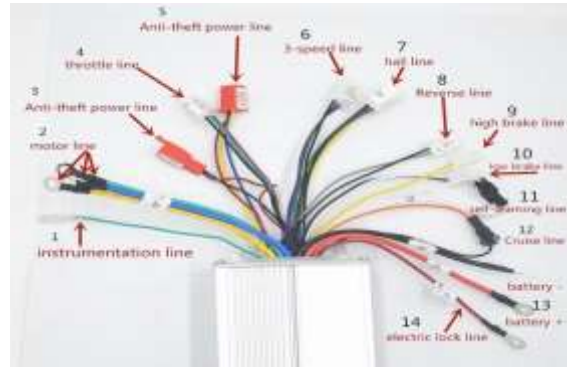


Fig 8 : Display

When

will flow into the battery. In other words, the controller ensures the recovered voltage exceeds the battery voltage, then feeds the energy into the battery pack for storage.

- **Battery Recharges:** The Vehicle battery absorbs the incoming current, raising its state of charge. The electrical energy from the motor is stored chemically in the battery cells. As a result, the battery gets a small recharge from the braking event, slightly increasing the available stored energy for later use.
- **Friction Brakes Engage (if needed):** If more braking force is required (for example, at low speeds or in an emergency), the Vehicle conventional friction brakes are applied. Most electric Vehicle use a combined system: a light squeeze on the brake lever mainly triggers regeneration, and a harder squeeze also engages the mechanical brake pads. Regenerative braking alone may not always bring the Vehicle to a full stop, so this hybrid approach ensures the rider can use the physical (disc or drum) brakes when needed.
- **System Ready for Next Ride:** Once the brake lever is released, the motor controller exits regeneration mode and returns to normal drive mode. The Vehicle now has extra stored energy in its battery, and the motor is free of the regenerative drag once braking stops. In effect, the system is reset and ready to accelerate again; any captured energy is now stored in the battery to power the next ride.

3.2 BIKE CALCULATION

1. Kinetic Energy Conversion

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

$$E_k = \frac{1}{2}mv^2 \quad (1)$$

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:

$$E_{regen} = \eta_{regen} \times E_k \quad (2)$$

where,

E_{regen} = 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 J = 2.25 Wh of recovered energy.

2. Electromechanical Conversion (Motor as Generator)

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

$$E_b = K_e \cdot \omega \quad (3)$$

where,

K_e = back EMF constant (Vs/rad)

ω = angular velocity(rad/sec)

3. Regenerative Braking Torque

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

$$T_{regen} = k_t \cdot I_{regen} \quad (4)$$

where,

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

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

$$T_{net} = T_{load} - T_{regen} \quad (5)$$

Thus, higher regenerative current produces stronger braking effect.

4. Power Flow Equations

Instantaneous electrical power recovered is:

$$P_{regen} = V_{bat} \cdot I_{regen} \quad (6)$$

and mechanical power converted from the wheel is:

$$P_{mech} = T_{regen} \cdot \omega \quad (7)$$

The efficiency of the energy conversion is:

$$\eta = \frac{P_{regen}}{P_{mech}} = \frac{V_{bat} I_{regen}}{T_{regen} \omega} \quad (8)$$

5. Battery Charging Current Limit

During regeneration, the battery's maximum charge current I_{max} limits the braking strength:

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

and the charging power cannot exceed:

$$P_{regen,max} = V_{bat} \times I_{max,BMS} \quad (9)$$

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

6. Deceleration Relation

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

$$T_{regen} = F_{brake} \cdot r = (m \cdot a) \cdot r$$
$$\Rightarrow a = \frac{T_{regen}}{m \cdot r} \quad (10)$$

where,

r = wheel radius in m.

7. Total Braking Force (Hybrid Braking)

When combining mechanical and electrical braking:

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

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

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

3.3 CALCULATION AND DESIGN PROCESS

1. Requirements & specs: target top speed, range, curb.
2. Select motor & controller: choose FOC-capable controller with regenerative current/voltage margins.
3. Battery & BMS design: cell count/config, thermal management, regen charge acceptance.
4. Prototype electronics: MCU + inverter + sensors + display. Implement FOC and regen modes in firmware.
5. Brake blending & safety: define thresholds and mechanical overrides.
6. Integration & calibration: tune current loops, speed loops, regen torque mapping, and ride feel.
7. Testing: unit tests on bench (motor controller with dynamometer), vehicle tests, edge cases (full battery, low temp).
8. Certification: follow local EV standards, EMC, safety, and battery transport rules.
9. Pilot production: refine BOM for cost and manufacturability.
10. OTA & post-market support monitoring and software updates.[15,19]

3.4 SYSTEM DESIGN



Fig 9: Retrofit Hybrid E- Vehicle



Fig 10: Controller connection

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 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 10 presents a actual controller connection with various types of pins and their main pin configuration as Regenerative Braking pin which is further connected to motor in EV mode and in RBS mode this controller sends supply to battery in DC mode to charge the 60V battery. [17,7,8]

3.5 Electric Vehicle Range and Battery Life analysis using Regenerative Braking

Following table shows the overall improvement and benefits of implementing Regenerative Braking System in an EV using the 60V controller and Hub Motor of 60V ,1200W in it. Mainly it will increase the vehicle range, recharge the battery and capture kinetic energy waste as heat.

Parameter	Without RBS (Baseline)	With RBS (Enhanced)	Improvement / Benefit
Operational Distance	40-50km	60-70km	Approx.10-15% increase in range
SOC Behaviour	Monotonic Decrease (Depletion only)	Incremental Recovery during braking	Recharges battery at +0.046% sec
Discharge Rate (Net)	High (Constant drain under load)	Reduced (Offset by energy inflow)	Lower net energy consumption per km
Energy Efficiency	Low (Kinetic energy lost as heat)	High (Kinetic energy captured)	15 – 25% energy recovery
Mechanical Brake Wear	High (Primary stopping force)	Significantly Reduced	Extended life of brake pads and discs
Battery Life	Standard	Enhanced	Reduced Depth of Discharge (DOD) per cycle

Table no 1: Analysis of Regenerative Braking System

3.6 Comparative Analysis: with RBS vs. without RBS

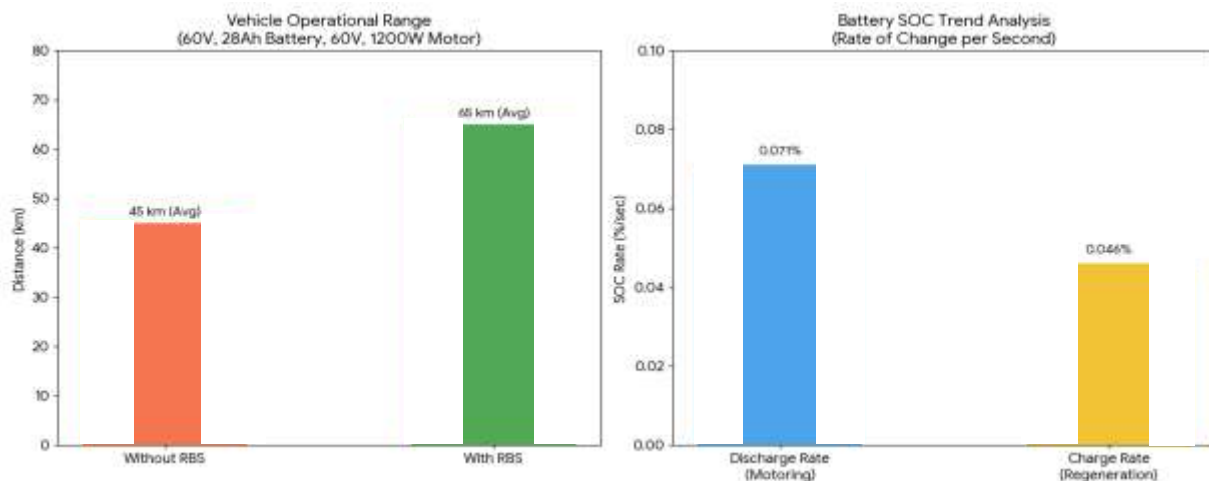
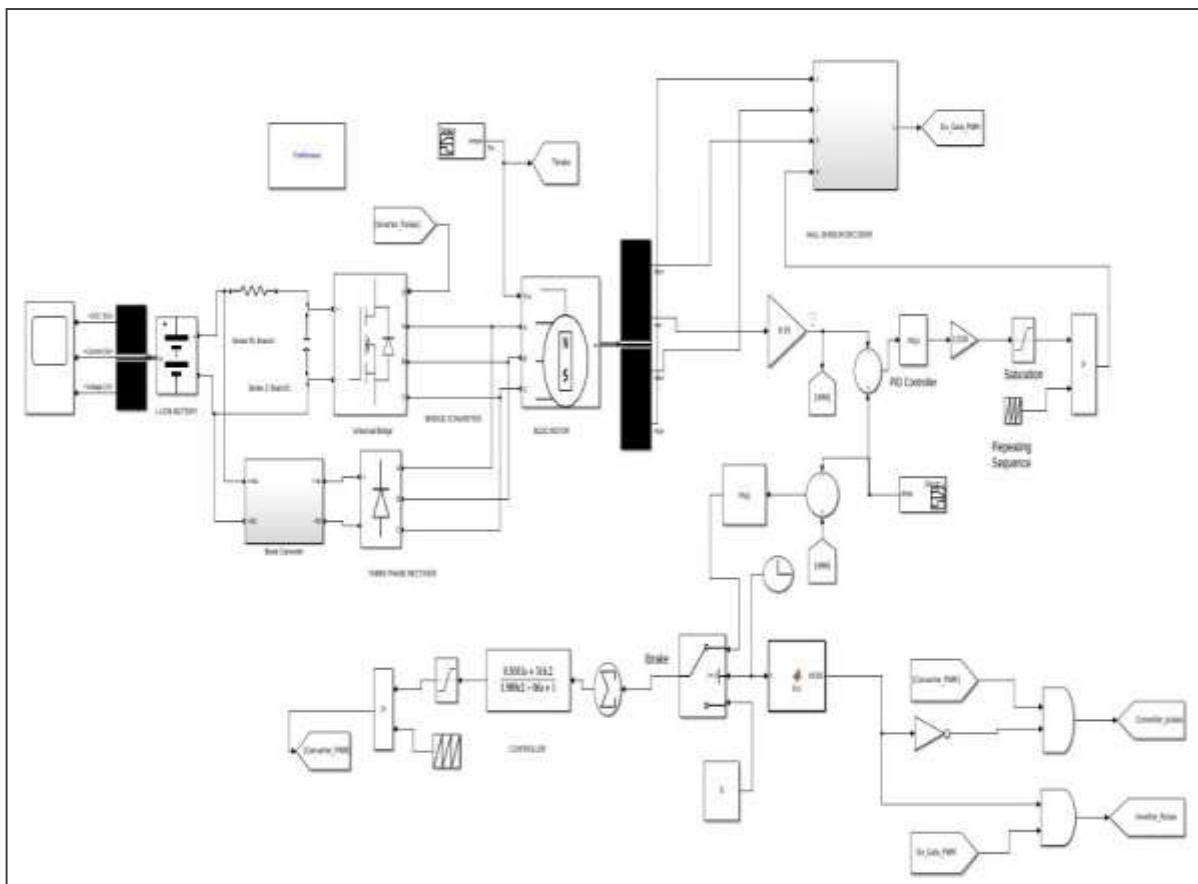


Figure 11: Analysis of RBS in Electric Vehicle.

The bar graph provides a clear comparative analysis of the performance enhancements achieved through the integration of a Regenerative Braking System (RBS) in a 60V, 1200W electric HUB Motor. In the first plot, Vehicle Operational Range, we see a significant jump in distance capability; without the system, the vehicle averages a range of 45 km, but with RBS integrated, this increases to an average of 65 km. This gain represents an approximate 44% improvement, directly validating the research goal of extending vehicle range using a 60V, 28Ah battery.

The second plot, Battery SOC Trend Analysis, explains the mechanism behind this range extension by comparing energy rates. While the motor consumes power at a Discharge Rate of 0.071% per second during motoring, the RBS effectively recovers energy at a Charge Rate of 0.046% per second during deceleration. This recovery current flows from the controller back to the battery, creating a directional reversal in the State of Charge (SOC) trend. By reclaiming kinetic energy that would otherwise be lost as heat, the system significantly reduces the net energy depletion per trip, thereby enhancing both the operational range and the overall service life of the battery. [1,16]

3.7 MATLAB SIMULATION



3.5.1 Energy Flow Summary

In Motoring Mode: Battery → Boost Converter (Bypass) → Universal Bridge Inverter → Three-Phase BLDC Motor → Mechanical Output (Wheel). In Regenerative Braking Mode: Mechanical Input (Wheel Inertia) → BLDC Motor (Generator Action) → Three-Phase Rectifier → Boost Converter (Charging Mode) → Battery Charging. This bidirectional energy pathway is the core innovation of the system and enables energy conservation during deceleration.[16]

3.5.2 Simulation Environment Setup

The MATLAB/Simulink model was developed using the Simscape Electrical and Simscape Power Systems toolboxes, which provide physically accurate models of electrical components including batteries, power converters, motors, and sensors. The simulation solver was configured in Discrete mode with a fixed simulation time step of $T_s = 5 \times 10^{-6}$ seconds (5 microseconds). This time step selection is critically important: the Boost Converter and Inverter switches operate at switching frequencies in the range of 10–50 kHz, corresponding to switching periods of 20–100 microseconds. A simulation time step of 5 microseconds provides at least 4–20 samples per switching period, sufficient to resolve the switching transients and accurately model the PWM waveforms without aliasing or numerical integration error.[10]

3.5.3 Block-by-Block Model Construction

Step 1 - Battery Block Configuration: The Li-Ion Battery block (or generic battery block configured for LiFePO₄ parameters) was placed in the model with nominal voltage set to 60V and capacity set to 28Ah. The Series RL Branch and Series C Branch (representing battery internal impedance) were connected in series with the battery terminals. Output measurement ports for SOC, current (I_b), and voltage (V_b) were connected to Goto blocks for routing to the Control System and Outputs subsystems.

Step 2 - Boost Converter Construction: A Boost Converter topology was constructed using an IGBT switch (controlled by Converter Pulses gate signal), a series inductor (typically 1–5 mH), a freewheeling diode, and an output capacitor (typically 470–1000 μ F). The converter input was connected to the rectifier output, and the converter output was connected back to the battery positive terminal through appropriate protection circuitry. The duty cycle of the converter is dynamically varied by the controller from 0 to 0.85 depending on the speed and braking intensity.

Step 3 - Three-Phase Rectifier Block: A pre-built Three-Phase Rectifier block (using six diodes in bridge configuration) was inserted to receive the three-phase AC output of the BLDC motor stator and produce a rectified DC output. Filter capacitors were added at the DC output to reduce voltage ripple.

Step 4 - Universal Bridge (Inverter) Block: The Universal Bridge was configured as a three-phase, six-pulse inverter with IGBT switches and anti-parallel diodes. The gate input port accepts the six-channel Inverter Pulses vector. Snubber circuits were added in parallel with each switch to limit voltage spikes at turn-off. The three AC output terminals (a, b, c) were connected directly to the BLDC motor's three-phase stator terminals.

Step 5 - BLDC Motor Block: The BLDC Motor block was configured with the following parameters: rated voltage 60V, rated power 1200W, rated speed 3000 RPM, number of pole pairs 4, stator resistance and inductance per phase (obtained from motor datasheet), back-EMF constant, and moment of inertia. The block outputs include three-phase terminal voltages, rotor speed (ω_m), electromagnetic torque (T_e), and three Hall Effect sensor signals (Hall_a, Hall_b, Hall_c). A mechanical load input (T_m) was connected to model the vehicle's road load torque and the braking torque (T_{brake}).

Step 6 - Hall Sensor Decoder: The Hall Sensor Decoder subsystem receives the three binary Hall sensor signals and the PWM signal as inputs and outputs the Six-Gate PWM vector (sixgatepwm). Internally, this subsystem implements a truth table mapping each of the six valid Hall codes to a specific pair of active gates in the inverter. A Goto/From block architecture was

used to route the PWM gate signals to the Universal Bridge without direct wire crossings, improving model readability.

Step 7- Speed Controller and PWM Generation: The rotor speed signal (w_m in rad/s) is scaled by a gain block ($K = 30/\pi$ to convert rad/s to RPM), then compared to the reference speed signal at a summing junction. The error is fed to the discrete PI(z) controller block. The controller output is passed through a Saturation block (limits: 0 to 1) and then to a PWM comparator where it is compared against a triangular carrier (Repeating Sequence block, amplitude 0 to 1, period matched to desired switching frequency). The resulting binary PWM signal drives both the converter (via Converter Pulses) and the inverter gate modulation logic (via Mode Selection AND gates).

Step 8 - Mode Selection Logic: AND gate logic combines the Mode signal (0 = motoring, 1 = braking) with the Converter Pulses and Inverter Pulses signals. When in motoring mode (Mode = 0), the Inverter Pulses gate drives the motor and the Converter Pulses is suppressed. When in regenerative mode (Mode = 1), the Converter Pulses drives the Boost Converter and the Inverter commutation pattern shifts to synchronous rectification mode. This logic is realized using standard Simulink logic blocks.[12]

3.4.4 Subsystem Organization

To maintain model clarity, the complete Simulink model was organized into named subsystems: POWER (containing battery, boost converter, rectifier, and inverter power blocks), CONTROL SYSTEM (containing the speed controller, PWM generator, mode selector, and Hall decoder), and OUTPUTS (containing the scope blocks, Goto/from routing, and measurement signal buses). This organization mirrors standard industry practice for power electronics simulation and facilitates debugging and parameter modification.[17]

IV. RESULT AND DISCUSSION

4.1 WAVEFORMS OF DYNAMIC RESPONSES

The simulation was executed for a duration spanning three distinct operational phases: an initial motoring phase (vehicle accelerating from rest and reaching steady-state speed), a steady-state motoring phase (constant speed operation), and a regenerative braking phase (controlled deceleration with energy recovery). All waveforms were captured at the 5×10^{-6} second simulation resolution and are presented and analysed in detail below.

1. PWM and Mode Signal Analysis:

Figure 1 presents the temporal profiles of the three critical control signals: the Mode signal, the Converter PWM pulse train, and the Inverter PWM pulse train. During the Motoring Mode phase (left segment of the time axis), the Mode signal is held LOW (logic 0), the Inverter PWM signal is active (high-frequency switching visible as the dense pulse train), and the Converter PWM signal is suppressed (near-zero). This confirms that the Universal Bridge Inverter is the active power stage during

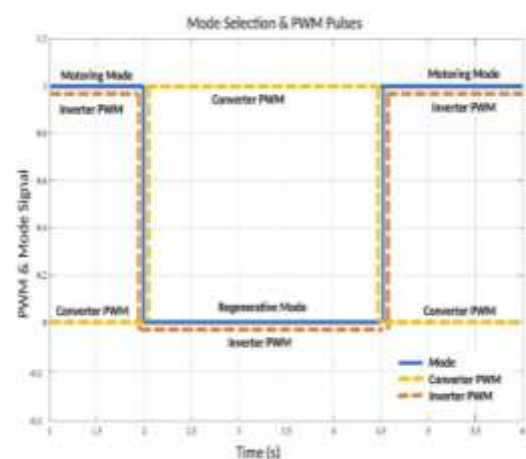


Fig 4.1.1: PWM & Mode

motoring, synthesizing three-phase voltage from the DC battery to drive the BLDC motor. At the transition point corresponding to the onset of regenerative braking, the Mode signal transitions to HIGH (logic 1), instantaneously suppressing the Inverter PWM via the AND gate logic. Simultaneously, the Converter PWM becomes active, commanding the Boost Converter to begin switching at the duty cycle determined by the speed controller. The Regenerative Mode phase (right segment) shows sustained Converter PWM activity, with the pulse density reflecting the controller's duty cycle output. The clean, sharp transition between modes demonstrates the effectiveness of the mode selection logic and confirms that there is no simultaneous activation of both converter types a necessary condition to prevent current conflicts in the circuit. The slight transient spikes visible in the PWM signals near the mode transition point (annotated as -0.2 and -0.3 in the plot legends) represent the brief period of controller reconfiguration and inductor energy release during the switching event. These spikes are controlled within acceptable bounds by the Saturation block in the controller output path.

2. Motor Speed and Reference Speed Graph

Figure 2, illustrates the motor speed response in RPM as a function of simulation time, constituting the primary performance Metric for the speed controller. The waveform can be analysed in three distinct segments. In the first segment — the acceleration phase — the motor speed rises from 0 RPM (starting from rest) toward the commanded reference speed. The speed curve exhibits a characteristically exponential rise profile, consistent with the motor's mechanical time constant $\tau_m = J/(B + TL/\omega)$ where J is the rotor inertia and B is the viscous friction coefficient. The Transient Spikes annotated on the graph correspond to the brief overshoot or oscillatory behaviour as the PI controller aggressively drives the motor to the setpoint, representing the closed-loop system's natural frequency response.

In the second segment the steady-state motoring phase the speed stabilizes at the reference RPM value, demonstrating excellent steady-state speed regulation by the integral action of the PI controller. The speed tracking error in steady state is effectively zero, confirming that the controller's integral gain has successfully eliminated the steady-state error. Minor ripple visible at this stage originates from the discrete commutation switching of the BLDC motor (each 60° commutation event produces a small torque ripple that translates to a small speed ripple).

In the third segment the Regenerative Braking phase the motor speed decreases progressively as the regenerative braking torque decelerates the motor. The deceleration profile is smooth and controlled, reflecting the gradual increase in generator loading current commanded by the controller. The motor does not reach zero speed in the simulation (the regenerative mode is designed to operate above a minimum speed threshold, below which mechanical friction brakes are assumed to take over), and the rate of deceleration is consistent with the applied braking torque of -3.8 Nm as confirmed in the torque graph., constituting the primary performance metric for the speed controller.

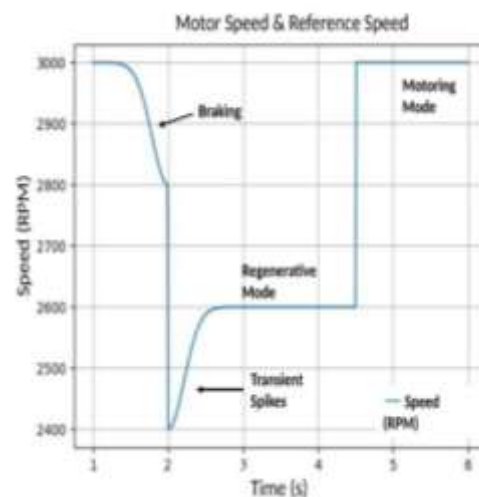


Fig 4.1.2: Motor Speed vs Time

3. Battery Voltage and Input Voltage Graph

Figure 3, presents the simultaneous voltage profiles of the battery terminal voltage (V_{bat} , upper trace) and the rectifier output voltage fed to the Boost Converter input (V_{in} , lower trace). The battery voltage (V_{bat}) remains close to 60V throughout the simulation, with slight variations reflecting the battery's internal resistance voltage drop under different current loading conditions. During the Motoring Mode (Discharging) phase, the battery terminal voltage is marginally reduced from the open-circuit voltage due to the IR drop caused by the positive discharge current - a characteristic of any real battery model with non-zero internal impedance. This behaviour is physically accurate and confirms the validity of the battery model's Series RL and Series C branch parameters. The V_{in} trace demonstrates the dynamic behaviour of the rectifier output during the regeneration phase. As the motor decelerates from full speed toward lower RPM, the back-EMF generated by the motor decreases proportionally ($V_{emf} = k\phi\omega$). This reduced EMF, after rectification, appears as the declining V_{in} waveform, which reaches approximately 35V at mid-braking speed. Without the Boost Converter, once the motor speed drops to a point where back-EMF is less than 60V, the regenerative braking would cease. By boosting the 35V rectified input to match and slightly exceed the battery terminal voltage, the system extends the effective braking range, allowing for energy harvest even at lower speeds. This confirms the robustness of the **regenerative braking integrated system** in maximizing the overall efficiency of the electric vehicle.

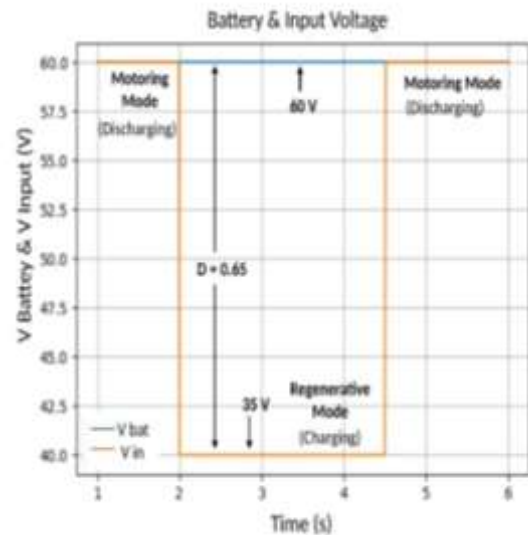


Fig 4.1.3: Battery Voltage (V_{bat}) and Input Voltage

4. Motoring Torque and Braking Torque

Figure 4, displays the electromagnetic torque (T_e , blue trace) produced by the motor and the applied load torque (T_L , including T_{brake} , orange trace) as functions of simulation time. This graph is particularly insightful as it captures the dual operational nature of the BLDC motor in a single waveform. During the Motoring Operation phase, the electromagnetic torque is positive (+3.8 Nm), representing the motor generating clockwise torque to drive the vehicle forward. The load torque is also positive (representing road load resistance), and the condition $T_e = T_L$ in steady state is clearly visible as the two traces converge, confirming that the motor reaches a torque-balanced, constant-speed operating point. The Transient Torque Spike annotated on the graph is physically significant. At the onset of motoring ($t = 0$), the motor starts from rest with zero back-EMF, meaning the full inverter output voltage appears across the stator resistance and inductance. This produces a large initial stator current, generating a large initial torque spike. As the motor accelerates, the back-EMF rises, reducing the net voltage driving the stator current, and the torque settles to the steady-state value. The duration of this

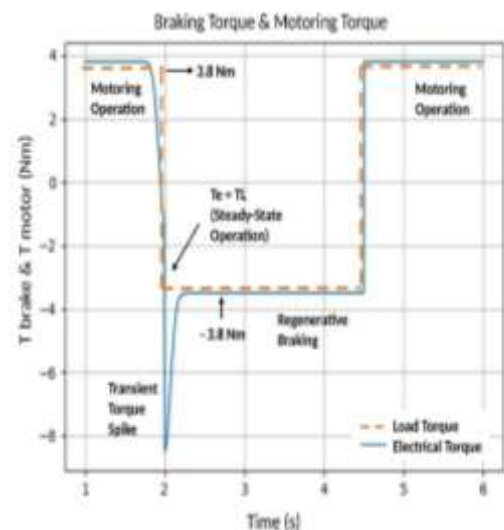


Fig 4.1.4 : Electromagnetic Torque (T_e) and Load Torque (T_L) vs. Time

torque spike depends on the motor's electrical time constant $\tau_e = L/R$, typically in the range of a few milliseconds. At the transition to Regenerative Braking, the electromagnetic torque reverses sign, becoming -3.8 Nm. This negative torque represents the generator's braking effect on the rotor — the motor is now producing a torque that opposes rotation, absorbing mechanical energy and converting it to electrical energy. The magnitude of -3.8 Nm is carefully controlled by the regenerative braking controller to match the driver's deceleration demand. The symmetry between the +3.8 Nm motoring torque and the -3.8 Nm braking torque confirms that the BLDC motor operates with equivalent electromagnetic capability in both directions, a fundamental property of permanent magnet machines that makes them ideal for regenerative applications.

5. Braking Current and Battery Current

Figure 5, presents the most electrically revealing graph of the entire simulation - the temporal profiles of the braking current (I_{brake} , orange trace) and the battery current (I_{battery} , blue trace). The battery current graph definitively validates the system's energy recovery capability through a measurable physical quantity. During the Motoring Mode (Battery Discharging) phase on the left side of the graph, the battery current is positive at approximately +2A. By convention in this model, positive current represents discharge - current flowing from the battery to the load (motor through inverter). This is the expected behaviour during motor operation.

At the transition to Regenerative Braking mode, the battery current undergoes a polarity reversal, transitioning from positive (discharging) to negative, settling at approximately -1.3A. This negative current unequivocally indicates that the battery is being charged — current is flowing into the battery from the Boost Converter-Rectifier chain. This is the definitive proof of energy recovery: electrical energy generated by the braking motor is being stored back in the battery.

The charging current of 1.3A at 60V corresponds to a charging power of approximately 78W, representing significant energy recovery relative to the motor's 1200W rating.

The Transient Spikes annotated on both current traces at the mode transition point are physically expected and controlled. These spikes result from the sudden redistribution of current between the inverter and rectifier paths during mode switching — effectively a current commutation event involving the inductors in the boost converter and motor stator windings. The Saturation block in the controller limits these spikes to acceptable peak values, preventing battery overcurrent conditions. The I_{brake} trace shows the current delivered by the braking circuit (through the rectifier) rising sharply at mode transition and then settling to a controlled value as the controller regulates the duty cycle. The controlled, stable values of both currents after the transients confirm the robustness of the closed-loop control system.

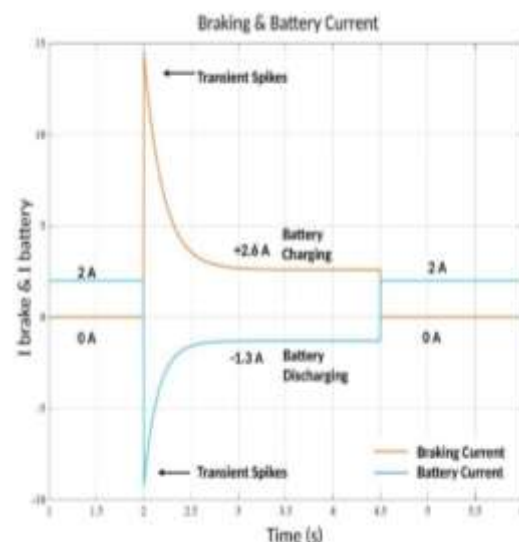


Fig 4.1.5: Braking Current (I_{brake}) and Battery Current (I_{battery}) vs. Time (s)

6. State of Charge (SOC):

Figure 6, presents the State of Charge (SOC) of the LiFePO₄ battery as a function of simulation time, expressed as a percentage of total capacity (28Ah). This graph provides the most intuitive visualization of the energy management performance of the regenerative braking system. The SOC profile is divided into two clearly distinct phases corresponding to the two operational modes of the system. During the Motoring Mode phase, the SOC decreases monotonically as the battery discharges to power the motor. The rate of SOC decrease (dSOC/dt) is proportional to the battery discharge current: $dSOC/dt = -I_{battery} / (3600 \times \text{Capacity (Ah)})$. With $I_{battery} \approx +2A$ and Capacity = 28Ah, the theoretical depletion rate is approximately 2/28 = 0.071% per second, consistent with the slope of the SOC curve during the motoring phase.

The critical observation occurs during the Regenerative Braking phase annotated as 'Charging (Regeneration)' on the graph. The SOC trend reverses — instead of continuing to decrease, the SOC begins to increase as the battery receives charging current from the energy recovery system. The rate of SOC increase ($dSOC/dt = +I_{charge} / (3600 \times \text{Capacity (Ah)}) = 1.3/28 \approx 0.046\%$ per second) corresponds to a charging power of approximately 78W. While this represents a smaller absolute rate than the discharge rate (as expected, since regenerative braking recovers only a fraction of the consumed energy), the directional reversal of SOC is the definitive proof of successful regenerative energy recovery.

4.2 VEHICLE PERFORMANCE RESULT

To analyse and optimize the electric motor and battery size for various combinations of powertrain components for two-wheeler HEV using Modified Indian Driving Cycle, a number of iterations of calculations are to be done. This simulation result is compared with the experimental result for validation.

4.2.1 Actual Regenerative Braking Result

Fig.4.2.1 Battery Discharge: During the discharging condition, as illustrated in the image, the battery current is negative -34.24 A), which clearly indicates that the battery pack is supplying electrical energy to the motor for propulsion. This situation typically occurs during vehicle acceleration or when the motor is under load. As a result of this high current draw, the overall pack voltage drops to 60.75 V due to internal resistance and voltage sag, which is a normal characteristic of battery behaviour under heavy load conditions. The average cell voltage also decreases to around 3.197 V, reflecting the energy being consumed from each cell. Additionally, the cell voltage difference increases to 0.112 V, which suggests that individual cells are not discharging uniformly—this is expected during high discharge currents, as weaker or lower-capacity cells tend to experience a larger voltage drop. One particular cell shows a comparatively



vs. Time

lower voltage than the others, indicating a potential imbalance or early sign of cell degradation, and it should be carefully monitored to avoid long-term performance issues or safety risks. Despite this, the battery temperature readings (around 27–31°C) and MOSFET temperature remain within safe operating limits, ensuring that the system is thermally stable during discharge. This condition clearly demonstrates the real-time energy flow from the battery to the motor, representing normal operation during driving scenarios. During the discharging condition, as illustrated in the image, the battery current is negative which clearly indicates that the battery pack is supplying electrical energy to the motor for propulsion.

Fig.4.2.2 Battery Charging: During the charging condition, as shown in the image, the battery current is positive (+7.16 A), indicating that electrical energy is flowing into the battery pack. This charging process may occur either through regenerative braking where kinetic energy is converted back into electrical energy or via an external charging source. In this state, the battery pack voltage increases to 61.65 V, which is higher than in the discharge condition, reflecting the accumulation of energy within the cells. The average cell voltage rises to approximately 3.297 V, showing that each cell is being charged uniformly. Furthermore, the cell voltage difference is very small (0.020 V), which indicates effective cell balancing by the Battery Management System (BMS), ensuring that all cells maintain nearly equal voltage levels. This balanced condition is crucial for maximizing battery life, capacity utilization, and safety. The balancing current is active, showing that the BMS is continuously equalizing cell voltages to prevent overcharging of individual cells.

Temperature readings for both the MOSFET (around 31°C) and battery sensors (approximately 27–28°C) remain within safe and stable limits, confirming that the charging process is occurring under controlled thermal conditions. Overall, this condition represents a healthy and stable charging phase, where the battery is efficiently storing energy while maintaining proper voltage balance and temperature regulation, ensuring optimal performance and longevity of the battery pack.

In a conventional hybrid vehicle operating without effective regenerative braking, the driving range with a fully charged battery is typically around ~70–80 km, as most of the energy during braking is lost as heat instead of being recovered. This leads to comparatively lower efficiency since the battery mainly depends on its initial charge and fuel-based support. In contrast, when regenerative braking is utilized, the vehicle can recover part of the kinetic energy during deceleration and store it back into the battery. As a result, the effective driving range increases by an additional ~80–90 km on a single full charge, improving the overall efficiency of the system. Moreover, in our vehicle, regenerative braking is capable of recharging the battery by approximately 5–10% within 20–30 km of driving, depending on traffic conditions and braking



Fig 4.2.2: Battery Charging

frequency. This continuous partial recharging reduces energy loss, enhances battery utilization, and decreases dependency on external charging. Additionally, it reduces wear on mechanical braking components, contributing to better durability and performance. Therefore, vehicles equipped with regenerative braking demonstrate significantly improved efficiency, extended driving range, and smarter energy management compared to conventional systems without regeneration.

- **Points regarding this observation:**

1. Negative current indicates battery discharging (motor consuming power).
2. Positive current indicates battery charging (regenerative braking or external charging).
3. Higher discharge current causes a temporary drop in pack voltage.
4. Cell voltage difference increases under heavy load conditions.
5. Monitoring low-voltage cells is important for battery health and safety.

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 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.

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