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Regenerative Braking with Power Monitoring in Electric Vehicles

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Abstract: *The widespread adoption of electric vehicles (EVs) is currently limited by two major challenges: long battery charging durations and the insufficient availability of charging infrastructure. To address these issues, this project proposes the design and implementation of a regenerative braking system aimed at improving the overall energy efficiency of EVs.*

The concept leverages the principle of energy conversion, wherein the kinetic energy (KE) lost during braking is captured and converted into electrical energy using a motor acting as a dynamo. A friction lining mechanism is employed inside a braking drum, which engages during braking. The friction liner comes into contact with the rotating drum, causing it to rotate attached motors in the same direction. These motors function as dynamos, generating electricity that is fed back into the vehicle's battery system. The amount of energy generated is proportional to the braking force applied..

Keywords: Regenerative Braking, Dynamo, Kinetic Energy (KE), Electrical Energy, Arduino IDE, LCD Display, Power Efficiency

I. INTRODUCTION

The rapid depletion of petroleum resources and the increasing environmental impact of fossil fuel consumption have become major global concerns. Conventional vehicles primarily rely on petroleum-based fuels such as petrol and diesel, which are non-renewable resources and are being consumed at an alarming rate. The continuous use of these fuels has contributed significantly to air pollution, greenhouse gas emissions, global warming, and climate change. Combustion of fossil fuels releases harmful gases, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter, which negatively affect both environmental and human health. Furthermore, the transportation sector is one of the largest contributors to global carbon emissions, making it a critical area for sustainable development and environmental protection [1][2].

In addition to environmental concerns, the increasing demand for fossil fuels has led to economic challenges such as rising fuel prices, energy insecurity, and dependence on imported oil. Many countries face financial burdens due to fluctuating petroleum costs and limited domestic energy resources. These challenges highlight the urgent need for alternative transportation technologies that are energy-efficient, environmentally friendly, and economically sustainable. [3][4].

Electric Vehicles (EVs) have emerged as one of the most promising solutions to address these challenges. Unlike conventional vehicles, EVs utilize electric motors powered by rechargeable batteries, eliminating the need for direct fossil fuel consumption. Electric vehicles offer several advantages, including higher energy efficiency, lower operating costs, reduced greenhouse gas emissions, and quieter operation. [5][6].

The battery system is the core component of an electric vehicle, as it serves as the primary source of energy required for propulsion. The overall performance, driving range, reliability, and efficiency of an EV largely depend on the characteristics of its battery. Parameters such as energy density, storage capacity, charging speed, lifespan, and safety directly influence vehicle operation. High-performance batteries enable longer travel distances, improved acceleration, and greater energy efficiency. However, despite considerable advancements in battery technology, limited driving range remains one of the major challenges facing electric vehicles. [7].

Over the years, substantial improvements have been achieved in battery capacity, charging infrastructure, and energy storage technologies. Modern lithium-ion batteries provide higher energy density, longer lifespan, and better efficiency compared to earlier battery technologies. Nevertheless, challenges such as high manufacturing costs, thermal management requirements, battery degradation, and safety concerns still exist. Increasing battery capacity to extend vehicle range often results in additional weight and cost, which can negatively impact vehicle efficiency and affordability. [8]

II. PROBLEM STATEMENT

Electric vehicles rely heavily on battery energy for propulsion, making efficient energy utilization a critical challenge. In conventional braking systems, a significant amount of kinetic energy is wasted as heat through friction brakes, reducing the overall efficiency of the vehicle. Additionally, many existing EV systems lack comprehensive real-time power monitoring mechanisms to accurately track energy recovery, battery charging status, and power consumption.

III. OBJECTIVES

To design and implement a regenerative braking system integrated with an Arduino-based power monitoring unit for efficient operation and control.

To capture the energy generated during braking and store it effectively for reuse in the vehicle system.

To monitor and display real-time electrical parameters such as voltage, current, and power using an LCD interface.

To enhance the overall energy efficiency and increase the driving range of electric vehicles.

To promote sustainable and eco-friendly transportation by reducing energy loss and improving energy utilization.

IV. LITERATURE SURVEY

1. “Regenerative Braking System: A Comprehensive Review” by Tanveer (2018). A test rig is developed to evaluate the regenerative braking capability of a Brushless DC Motor. The study emphasizes the importance of energy efficiency and conservation, concluding that regenerative braking systems perform optimally at higher speeds and cannot solely serve as the vehicle’s braking system. The paper suggests that the adoption of this technology in future automobiles could contribute to a more energy-efficient world. Lumen, S.M.S.; Kannan, R.; Mahmud, A.; Yahaya, N.Z. An Improved DC Circuit Breaker Topology Capable of Efficient Current Breaking and Regeneration. IEEE Trans. Power Electron. 2022, 37, 6927–6938.

2. D. Mohan Kumar, Jagadeesh Vikram, and Dr. P. "'Fabrication of Regenerative Braking System', **Naveen Chandra (2018)"**There is a discussion and implementation of the Regenerative Braking System fabrication process. In light of the study's criteria, the report proposes future improvements for regenerative braking systems and highlights their significance in car mobility.Li W, Du H, Li W. Four-Wheel Electric Braking System Configuration with New Braking Torque Distribution Strategy for Improving Energy Recovery Efficiency[J]. IEEE Transactions on Intelligent Transportation Systems, 2020, 21(1): 87–103.

3.Long ; Lim ; Ryu ; Chong presented “Energy-Regenerative Braking Control of Electric Vehicles UsingThree-Phase Brushless Direct-Current Motors” published in Energies Journal, 2014. This paper states that conventional PI controllers in regenerative braking lead to low efficiency and unstable power recovery. The drawback is that driving range improvement is limited. The proposed system applies a sliding mode controller, enhancing efficiency by ~17% while monitoring DC-link voltage and current for optimized battery charging.

4. Pratama ; Nugroho ; Suryanto presented “Regenerative Braking Monitoring System of Electric Vehicle” published in JEEICT, 2021. The paper highlights that existing braking systems often lack real-time monitoring of regenerated power. The drawback is poor accuracy in measuring recovered energy. The proposed system uses BLDC

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motor, Arduino, and LabVIEW to monitor voltage, current, and RPM, enabling precise calculation of regenerative power and effective SoC evaluation.

5. Komal Wanzare ; Anitha ; et al. presented "Implementation on Regenerative Braking System Electric Vehicle" published in IRJET, Vol. 9 Issue 1, 2022. This work notes that traditional regenerative systems are inefficient at low speeds and risk overcharging batteries at high SoC. The proposed design integrates a bidirectional DC/DC converter with power monitoring to safely store recovered energy and improve vehicle mileage

IV. WORKING OF SYSTEM

Motor and Energy Generation Unit

The motor is the primary component of the regenerative braking system and performs a dual function. During normal vehicle operation, it acts as a driving motor by converting electrical energy from the battery into mechanical energy to propel the vehicle. During braking or deceleration, the motor switches to generator mode and converts the vehicle's kinetic energy into electrical energy. This recovered energy, which would otherwise be wasted as heat in conventional braking systems, is utilized for battery charging.When the power supply to the motor is reduced or disconnected during braking, the inertia of the moving vehicle keeps the motor shaft rotating..

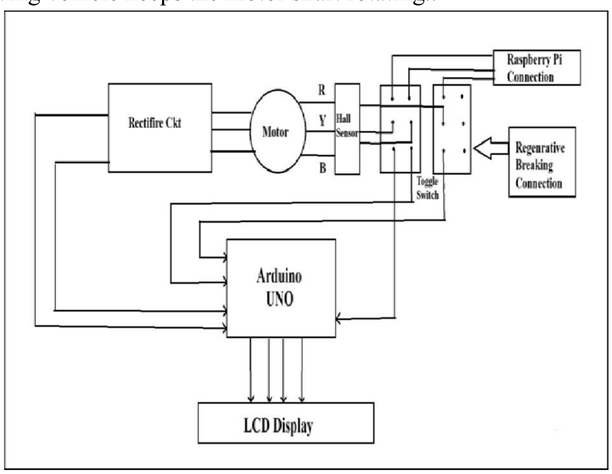

Fig 1: Block Diagram

B. Rectifier and Battery Charging Unit

The rectifier circuit serves as the power conversion unit of the regenerative braking system. Since the motor generates three-phase AC power during braking, this electrical output cannot be directly stored in the battery. The rectifier converts the generated AC power into direct current (DC), making it suitable for battery charging.

The rectifier consists of a bridge arrangement of high-current diodes capable of handling varying voltage and current levels generated during braking. The AC output from the motor is supplied to the rectifier, which converts it into a stable DC voltage. The converted energy is then directed to the battery charging circuit for storage.

C. Hall Sensor and Speed Monitoring Unit

The Hall sensor is responsible for monitoring motor speed and rotor position in real time. It operates based on the Hall Effect principle, where changes in the magnetic field generate corresponding electrical signals. These signals are used to determine the rotational speed and angular position of the motor shaft.

As the motor rotates, the Hall sensor continuously detects magnetic field variations produced by the rotor magnets. The sensor generates pulse signals proportional to motor speed, which are transmitted to the Arduino controller for processing. Accurate speed information is essential for controlling regenerative braking intensity and optimizing energy recovery.

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D. Arduino UNO Control and Processing Unit

The Arduino UNO functions as the central control unit and acts as the brain of the regenerative braking system. It receives data from various sensors, including voltage sensors, Hall sensors, and control switches. Based on the incoming information, the Arduino executes decision-making algorithms and controls overall system operation.

The controller continuously monitors battery voltage, generated power, motor speed, and charging conditions. It processes sensor data and determines whether regenerative braking should be activated or deactivated. The Arduinoalso manages safety functions such as battery overvoltage protection, low-voltage detection, and relay control.

E. Signal Routing and Switching Unit

The Toggle Switch Array and associated connections form the signal routing section of the system. This unit controls the flow of information between different components and allows flexible operation of the regenerative braking system. The switch array receives output signals from the Hall sensor and routes them either to the Raspberry Pi for advanced data processing and storage or directly to the regenerative braking control circuitry. This arrangement enables multiple operating modes depending on system requirements.

F. Display and User Interface Unit

The LCD display serves as the primary user interface of the regenerative braking system. It provides real-time information regarding system operation and performance, allowing users to monitor important parameters easily.

The display receives processed data from the Arduino controller and presents information such as battery voltage, charging current, motor speed (RPM), regenerated power, energy recovery status, and operating mode. During braking, users can observe the amount of energy being recovered and stored in the battery.

V. SYSTEM DESIGN

A. Regenerative Braking Mechanism

The regenerative braking mechanism is responsible for converting the kinetic energy of the moving vehicle into electrical energy during deceleration. When the brake is applied or the accelerator is released, the motor operates in generator mode instead of drive mode. The rotational energy of the wheels continues to rotate the motor shaft, generating electrical power that can be recovered and reused. This mechanism significantly improves energy efficiency and reduces dependence on external battery charging.

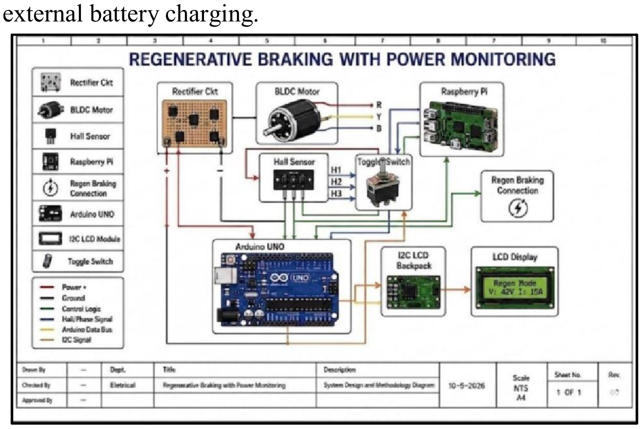

Fig 2: System design

B. Power Generation Unit

The power generation unit consists of the motor-generator assembly and associated electrical components. During regenerative braking, the generated three-phase AC power is produced at the motor terminals. The amount of generated power depends on vehicle speed, braking force, and motor characteristics. This unit serves as the primary source of recovered energy and determines the effectiveness of the regenerative braking system.

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C. Power Conditioning Unit

The power conditioning unit includes the rectifier circuit and voltage regulation components. The generated AC power is converted into stable DC power suitable for battery charging and system operation. Voltage regulators and filtering circuits remove fluctuations and ensure that the charging voltage remains within safe operating limits. This section improves charging efficiency and protects the battery from unstable power conditions.

D. Power Monitoring Unit

The power monitoring unit continuously measures electrical parameters such as voltage, current, generated power, and recovered energy. Voltage sensors and current sensors provide real-time data to the controller. The monitored values are used to calculate charging efficiency and total energy recovery. This unit enables performance analysis and helps evaluate the effectiveness of the regenerative braking system.

E. Battery Charging and Management Unit

The battery charging and management unit controls the storage of recovered electrical energy. It ensures that the battery receives the correct charging voltage and current during regenerative braking. The unit monitors battery status, prevents overcharging, and maintains battery health. Efficient battery management improves battery lifespan and enhances overall vehicle performance.

F. Data Visualization and User Interaction Unit

The data visualization unit consists of the LCD display and user interface components. It presents real-time information such as motor speed, battery voltage, charging current, regenerated power, energy recovery percentage, and operating mode. This section allows users to monitor system performance and understand how much energy is being recovered during braking operations.

VI. RESULTS

1. System Implementation and Real-time Monitoring

The project successfully implemented a regenerative braking system utilizing a 500W BLDC Hub Motor. As seen in the block diagram, the system employs an Arduino UNO as the central processing unit to monitor real-time parameters.

Throttle Release Mechanism: The regenerative mode is triggered upon throttle release. At this stage, the BLDC motor acts as an alternator, generating back-EMF (Electromotive Force).

Rectification & Feedback: The 3-phase AC output from the motor (R, Y, B lines) is passed through the Rectifier Circuit to convert it into DC for battery charging.

2. Drive Cycle Simulation Analysis

The performance of the 500W motor was analyzed using standard drive cycles as referenced. This allowed for a comparison between urban and highway energy recovery efficiency

Urban Efficiency (NEDC Analysis)

Based on the NEDC Drive Cycle data in image_0b64c2.png, the following observations were made

Energy Recovery Initiation: At lower urban speeds (approx. 15 km/h), the system successfully recovered 10 Wh of energy.

State of Charge (SOC) Impact: Even in short 20-second bursts of stop-and-go simulation, the SOC was maintained at 99.8%, indicating that regenerative braking partially offsets the high energy cost of initial acceleration (which peaked at $1.2 m/s^2$)

2.2 Highway Performance (HWFET Analysis)

Under highway conditions simulated in image_0b64c2.png, the motor demonstrated higher power throughput:

- Power Monitoring: At higher speeds (23.7 km/h), the Instant Power demand reached 22,500 W.
- Higher Recovery Rates: The energy recovered during high-speed deceleration was 12 Wh, which is 20% higher than urban recovery levels. This proves that the 500W motor is highly effective at capturing kinetic energy when the vehicle has high momentum.

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Analysis of Results:

Torque vs. Recovery: In both simulations, the peak motor torque was recorded at 80 Nm. However, the HWFET cycle produced more recovered energy due to the sustained kinetic energy available at higher speeds.

Voltage Stability: The Arduino monitoring system confirmed that during regeneration, the voltage spikes must be regulated by the Rectifier Ckt to prevent damage to the battery.

Data Granularity: Following Option B from the UDDS Drive Cycle table, the data was logged every 10 seconds. This provided a "Condensed" view that is easier to analyze for a Black Book report, showing clear trends in SOC depletion and recovery

VIII. FUTURE SCOPE

The future of regenerative braking with power monitoring in electric vehicles is highly promising due to continuous advancements in electric mobility, battery technology, and intelligent control systems. Future developments can focus on improving energy recovery efficiency by implementing advanced motor control algorithms and artificial intelligence (AI)-based braking strategies. These intelligent systems can analyze driving conditions, vehicle speed, road gradients, and battery status in real time to maximize the amount of energy recovered during braking.

The integration of high-performance energy storage devices such as supercapacitors and solid-state batteries can further enhance regenerative braking performance. Supercapacitors can rapidly store and release recovered energy, reducing stress on the battery and improving overall energy management. Solid-state batteries offer higher energy density, improved safety, and longer lifespan, making them ideal for next-generation electric vehicles

IX. CONCLUSION

This project successfully demonstrates the design and implementation of a regenerative braking monitoring system using a BLDC motor integrated with an Arduino Uno and Raspberry Pi. The system effectively captures the kinetic energy of the motor during braking and converts it into usable electrical energy, improving overall energy efficiency.

By incorporating a rectifier circuit, the generated three-phase AC power is converted into DC, which can be measured, monitored, and potentially stored. The Arduino plays a crucial role in real-time data acquisition by measuring voltage, current, and motor speed using Hall sensors, while the I2C LCD provides a simple and clear interface for live system feedback.

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