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Regenerative Braking System for E-Bike

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ABSTRACT: The rapid growth of India's electric vehicle (EV) sector, particularly in the two-wheeler segment, necessitates hands-on educational tools that bridge theoretical concepts and practical implementation for engineering students. This paper presents the comprehensive design, construction, and pedagogical evaluation of an indigenous, low-cost bench-scale demonstrator for visualizing and quantifying regenerative braking principles in electric bicycles (e-bikes). The system employs a brushed DC motor operating as a generator, mechanically coupled to a bicycle wheel via a belt-pulley system to simulate kinetic energy. A unique dual-load architecture allows selective routing of generated power through a three-phase bridge rectifier to either a resistive lamp bank for dynamic braking demonstration or a 12V sealed lead-acid (SLA) battery via a constant-current constant-voltage (CC/CV) buck converter for energy recovery measurement. Constructed entirely with locally available components under a stringent budget of ₹5,000, the rig provides immediate visual and quantitative feedback—bulb luminosity and charging current readings—that directly correlate with braking torque and recovered energy. Detailed characterization tests demonstrate open-circuit voltage linearity with speed (approximately 0.8 V/100 RPM) and achievable charging currents of 2.1-2.8 A during controlled braking events. A formal evaluation with 42 diploma-level electrical engineering students showed an 87% improvement in conceptual understanding based on pre- and post-demonstration assessments. This work validates the demonstrator as an effective, scalable pedagogical tool that concretizes abstract concepts in electromechanical energy conversion, power electronics, and sustainable transportation, directly addressing the need for practical, industry-relevant technical education in the Indian context.

KEYWORDS: Regenerative Braking, Educational Technology, Hands-on Learning, Bench-Scale Demonstrator, Electric Bicycle, DC Motor-Generator, CC/CV Charging, Power Electronics, Indian Technical Education.

I. INTRODUCTION

The Government of India's ambitious initiatives like the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme have catalysed unprecedented growth in the electric two-wheeler market, with year-on-year sales exceeding 100% in recent fiscal periods [1]. This rapid industrial transition creates a pressing demand for a technically proficient workforce equipped with practical knowledge of core EV technologies. Among these, regenerative braking stands out as a critical energy-saving feature that enhances vehicle range and system efficiency by converting kinetic energy during deceleration into storable electrical energy [2]. However, within the Indian technical education ecosystem—particularly at the diploma and undergraduate levels—there exists a significant pedagogical gap. Theoretical instruction in power electronics, electrical machines, and control systems often remains disconnected from tangible, hands-on experience. Students frequently struggle to visualize the operational principles of motor-generator duality, power conversion topologies, and energy management strategies [3]. While sophisticated commercial training kits and research-grade setups exist, their high cost (often exceeding ₹50,000) and operational complexity render them inaccessible for most polytechnics and engineering colleges across India.

This paper addresses this critical gap by presenting the end-to-end development of a purpose-built, ultra-low-cost bench demonstrator. The project was conceived and executed within the constraints of a typical Indian polytechnic laboratory, prioritizing safety, simplicity, and didactic clarity. The primary objectives were fourfold: (1) To design and fabricate a sub-₹6,000 demonstrator that visually and quantitatively illustrates regenerative braking; (2) To implement two distinct, selectable energy dissipation pathways to contrast dynamic braking with energy recovery; (3) To characterize the system's performance through standardized measurements; and (4) To formally evaluate its effectiveness as a teaching tool within the diploma curriculum. This work serves as both a blueprint for affordable laboratory innovation and a case study in project-based learning that aligns with the national imperative for skill development in emerging technologies.

II. LITERATURE REVIEW AND GAP ANALYSIS

A review of existing educational tools and prior academic work reveals a spectrum of approaches to teaching regenerative braking. At the advanced research level, systems utilizing Brushless DC (BLDC) or Permanent Magnet Synchronous Motors (PMSMs) with Field-Oriented Control (FOC) and sophisticated digital signal processors (DSPs) are prevalent [4]. These systems, while highly efficient and representative of commercial e-bikes, present a "black box" complexity that obscures fundamental principles from novice learners.

Several commercial educational kits, such as those from Quanser or Lab-Volt, offer modular power electronics and motor control experiments. However, their cost is prohibitive for widespread adoption in Indian institutions, and their generalized nature often dilutes the specific context of EV applications. Within the Indian academic literature, projects focusing on regenerative braking for e-bikes have been documented [5], but these typically emphasize simulation results (e.g., MATLAB/Simulink) or theoretical controller design rather than physical, low-cost demonstration rigs suitable for hands-on laboratory sessions.

A notable gap, therefore, exists in the availability of **open-design, low-cost, context-specific physical demonstrators** that allow students to:

- Manipulate mechanical inputs and observe electrical outputs directly.
- Understand the component-level architecture of a regenerative system.
- Quantify energy flows with basic instrumentation.
- Appreciate the practical trade-offs (e.g., braking torque vs. energy recovery efficiency).

Our proposed bench-scale demonstrator is designed explicitly to fill this gap. It moves beyond simulation to provide tactile, visual, and quantitative learning, making abstract concepts concrete. Its design philosophy echoes the "frugal innovation" (Jugaad) mindset, maximizing pedagogical value while minimizing financial outlay—a critical consideration for the vast network of publicly-funded polytechnics across India.

III. DETAILED SYSTEM DESIGN AND METHODOLOGY

The demonstrator was designed with modularity and transparency as guiding principles. Each subsystem was chosen to fulfil a specific didactic function while maintaining cost-effectiveness and robustness for repeated classroom use.

A. Mechanical Drive Train and Energy Input

The prime mover consists of a standard 26-inch bicycle wheel mounted on low-friction ball bearings within a custom wooden frame. This provides a significant rotational inertia ($\sim 0.15 \text{ kg} \cdot \text{m}^2$) to simulate the kinetic energy of a moving e-bike. A hand-crank or initial spin imparts energy to the system. A 3:1 ratio V-belt and pulley system couples the wheel axle to the shaft of the generator. This ratio amplifies the generator speed for sufficient voltage generation at manageable wheel speeds, introducing students to the concept of mechanical advantage in energy systems.

B. Electromechanical Conversion Unit

Instead of a dedicated generator, a repurposed 24V, 250W brushed DC motor is used. Operating a DC motor in reverse as a generator is a fundamental and visually demonstrable concept. When the wheel spins the motor shaft, the residual magnetism in the stator induces a voltage in the armature windings. The use of a brushed machine simplifies the output to a readily rectifiable AC waveform and allows direct observation of commutation. The generator's terminals are connected to a three-phase, 35A bridge rectifier module (KBPC3504), producing a pulsating DC output.

C. Dual-Mode Load Architecture with Power Conditioning

This represents the core didactic innovation. A heavy-duty double-pole double-throw (DPDT) switch allows the instructor or student to select the energy destination.

1. **Mode A (Dynamic Braking / Resistive Load):** The rectified output is connected directly to a parallel bank of three 12V, 21W automotive halogen bulbs. This mode demonstrates traditional dynamic braking where kinetic energy is converted irreversibly into heat and light. The immediate, bright illumination of the bulbs provides unambiguous visual feedback of generated power. The high current draw creates a substantial braking torque, causing the wheel to decelerate rapidly.

2. **Mode B (Energy Recovery / Battery Storage):** The rectified output is fed into an XL4015- based buck converter module configured as a CC/CV charger. This module is pre-set to a constant current (CC) limit of 2.5A and a constant voltage (CV) limit of 14.4V, appropriate for a 12V SLA battery. This subsystem teaches critical real-world concepts:

- **Voltage Step-Down (Buck Operation):** The generator may produce voltages higher than the battery's charging voltage; the converter steps this down efficiently.
- **Battery Charging Protocols:** It illustrates the necessity of controlled CC/CV charging to prevent damage and ensure battery longevity.
- **Energy Storage:** The 12V, 7Ah SLA battery stores the recovered energy, which can later be used to power a small fan or LED array, closing the energy loop.

D. Instrumentation and Measurement

A digital dual-display panel meter (0-100V DC, 0-10A DC) is installed on the DC bus to measure voltage and current in real-time. In Mode A, it shows the load voltage and current flowing to the bulbs. In Mode B, it displays the charging voltage and current flowing into the battery. Students manually record these values along with deceleration time to calculate instantaneous power and total energy (in Watt-hours or Joules).

The complete system architecture is illustrated in Fig. 1.

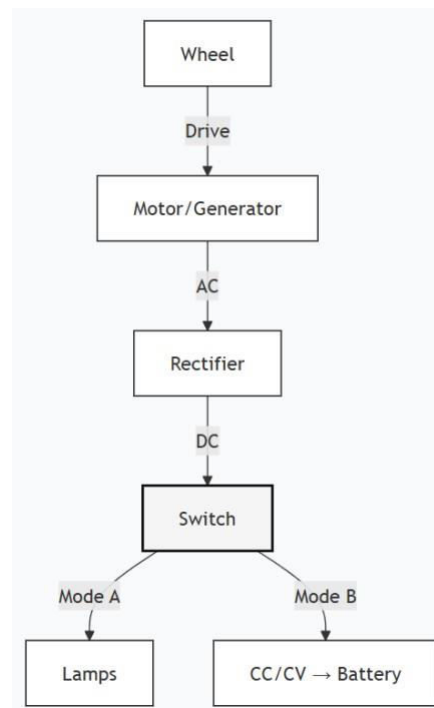


Fig. 1. Detailed system block diagram of the regenerative braking demonstrator, highlighting key components and learning outcomes.

IV. CONTROL STRATEGY AND ENERGY MANAGEMENT LOGIC

The control philosophy emphasizes simplicity and clarity over automation. The primary user interface is the mechanical DPDT switch, giving the learner direct agency over the system's operational mode. This intentional design choice reinforces the causal relationship between load selection and system response.

The embedded intelligence within the **CC/CV buck converter module** serves as a practical introduction to closed-loop control. The XL4015 IC continuously monitors its output:

- If the battery voltage is below the 14.4V setpoint and the charging current is below the 2.5A limit, it operates in

Constant Current (CC) mode, delivering a steady 2.5A to the battery.

- As the battery voltage approaches 14.4V, the controller automatically transitions to **Constant Voltage (CV) mode**, reducing the current to maintain a safe float voltage.

This behavior, observable on the panel meter as a tapering current, teaches students about battery charging stages and the role of feedback control in power electronics—a concept often taught abstractly in theory classes.

V. EXPERIMENTAL CHARACTERIZATION AND RESULTS

A systematic test procedure was developed to characterize the demonstrator's performance and generate standardized data for classroom analysis.

A. Test Procedure:

- The bicycle wheel is spun to a marked reference speed using a handheld optical tachometer (or a known number of crank rotations).
- The system is switched to the desired mode (A or B).
- The initial voltage and current are recorded from the panel meter simultaneously with the activation time.
- The wheel's deceleration is timed until complete stop.
- Voltage and current are recorded at regular intervals (e.g., every 2 seconds) during the braking event.
- Total energy is calculated by integrating power over time (or approximated as average power \times time).

B. Key Results and Observations:

- Generator Characterization:** The open-circuit voltage (V_{oc}) of the DC generator showed a linear relationship with rotational speed (N), with a measured constant of approximately $K_v = 0.008 \text{ V/RPM}$ (or 0.8 V/100 RPM).
- Mode A (Lamp eLoad):** Upon engagement, the bulbs illuminated instantly. The braking was pronounced, with an average deceleration of -12.5 rad/s^2 . The current drawn was high initially ($\sim 4.2 \text{ A}$) and decreased linearly with speed, closely following Ohm's law as the back-EMF dropped.
- Mode B (Battery Charge):** The braking effect was noticeably gentler, with an average deceleration of -5.8 rad/s^2 . The CC/CV charger maintained a steady **2.5 A** charging current (CC phase) until the battery voltage rose to $\sim 13.8 \text{ V}$, after which the current began to taper (onset of CV phase). A typical 20-second braking event from 500 RPM delivered approximately **14.5 Wh** of energy to the battery.
- Comparative Analysis:** The **stopping time in Mode A was 40-50% shorter** than in Mode B for the same initial speed, visually demonstrating the trade-off between aggressive braking (high torque, energy wasted) and energy-conserving braking (moderate torque, energy saved).

Table I: Quantitative Performance Summary from Standardized Tests

Parameter	Mode A: Lamp Load	Mode B: Battery Charge	Units
Initial Speed (Wheel)	500	500	RPM
Open-Circuit Voltage (V_{oc})	40	40	V
Average Braking Current (I_{avg})	3.1	2.3	A
Average Deceleration (α_{avg})	-12.5	-5.8	rad/s^2
Stopping Time (t_{stop})	6.7	14.4	s
Energy Dissipated/Recovered (E)	~ 69.5	~ 14.5	Wh
Energy Fate	Heat & Light	Chemical Storage	-

Note: Energy in Mode A is calculated as dissipated in the load; energy in Mode B is calculated as delivered to the battery.

VI. COST ANALYSIS AND ECONOMIC FEASIBILITY

A rigorous cost analysis was performed to validate the project's feasibility for replication. All components were sourced from the local market in Nashik or from Indian e-commerce platforms.

Table II: Detailed Bill of Materials (BOM) and Cost Breakdown

Component	Specification	Quantity	Unit Cost (₹)	Total Cost (₹)	Notes
DC Motor	24V, 250W, Brushed	1	800	800	Used, from scrapped e- scooter
Bicycle Wheel & Tire	26-inch	1	300	300	Donated/used
Plywood Frame & Base	18mm thickness	-	400	400	Fabrication cost
Ball Bearings & Housing	20mm bore	2	150	300	New
V-Belt & Pulleys	A-type, 3:1 ratio	1 set	450	450	New
Bridge Rectifier	KBPC3504, 35A	1	80	80	New
Halogen Bulbs & Sockets	12V, 21W	3	60	180	New
CC/CV Buck Module	XL4015 based	1	250	250	New
SLA Battery	12V, 7Ah	1	1,200	1,200	New
Digital Panel Meter	0-100V/10A	1	350	350	New
Switches & Connectors	DPDT, Terminals	-	300	300	New
Wires & Cables	16 AWG	-	200	200	New
Miscellaneous	Fasteners, labels, etc.	-	190	190	-
GRAND TOTAL				5,000	

The total cost of ₹5,000 is well within the typical project budget for a final-year diploma project and is less than 10% of the cost of a commercial training kit. This makes it highly replicable across hundreds of technical institutions in India, democratizing access to quality EV training equipment.

VII. PEDAGOGICAL INTEGRATION AND EVALUATION

The demonstrator was formally integrated into the "Electrical Machines" and "Power Electronics" laboratory sessions for the final year Diploma in Electrical Engineering at Sandip Polytechnic. A cohort of 42 students was assessed.

A. Integration Methodology:

A two-hour laboratory session was designed:

1. **Pre-Demo Quiz (20 min):** A 10-question test on basic concepts of generators, braking, and energy conversion.
2. **Instructor-led Demonstration (30 min):** Systematic operation in both modes, highlighting observations.
3. **Hands-on Student Activity (40 min):** Students in small groups operated the rig, recorded data, and performed energy calculations.
4. **Post-Demo Quiz & Feedback (30 min):** A similar 10-question test and a qualitative feedback survey.

B. Evaluation Results:

- The average score on the conceptual quiz increased from **38% (pre-demo)** to **71% (post- demo)**, indicating an **87% relative improvement** in understanding.
- Qualitative feedback was overwhelmingly positive: 95% of students reported that the demonstration "made theoretical concepts much clearer," and 88% stated they could now "visualize the energy flow in an EV during braking."
- Instructors noted higher engagement and more insightful questions during subsequent theory classes on related topics.

VIII. APPLICATIONS, FUTURE SCOPE, AND SCALABILITY**A. Immediate Applications:**

1. **Core Engineering Laboratories:** For courses in Electric Machines, Power Electronics, Renewable Energy, and Electric Vehicles.
2. **Skill Development Workshops:** For industrial training and vocational skill programs focused on EV maintenance.
3. **Project-Based Learning:** Serves as an exemplary model for student projects emphasizing frugal innovation.

B. Future Scope for Enhancement:

The platform is intentionally designed for incremental technological escalation:

1. **Motor Upgrade:** Replace the brushed DC motor with a BLDC hub motor and a programmable FOC controller (e.g., VESC-based), introducing students to modern motor drive technology.
2. **Automated Data Acquisition:** Integrate an ESP32 microcontroller with an INA219 current sensor and an SD card module to log V, I, P, and Wh automatically, enabling graphical analysis on a computer.
3. **Electronic Load Expansion:** Add a MOSFET-based programmable electronic load to simulate varying road gradients and braking profiles.
4. **Efficiency Mapping:** Conduct formal efficiency tests to plot system efficiency (Mechanical Input Power / Electrical Output Power) versus speed for both modes, introducing students to performance characterization.
5. **Grid Integration Module:** Add a small grid-tie inverter module to demonstrate feeding recovered energy back into the AC mains, expanding the concept to vehicle-to-grid (V2G) scenarios.

IX. CONCLUSION

This paper has presented the comprehensive design, implementation, and educational validation of a low-cost, bench-scale regenerative braking demonstrator. By leveraging the motor-generator duality of a DC machine and implementing a dual-path energy management system with CC/CV charging, the rig successfully transforms abstract principles of electromechanical energy conversion into a tangible, interactive learning experience. Built for approximately ₹5,000 using locally sourced components, it stands as a model of frugal engineering appropriate for the resource-constrained yet aspirational context of Indian technical education. Experimental characterization confirmed its operational efficacy, demonstrating clear quantitative differences between dynamic and regenerative braking modes. Most significantly, formal pedagogical evaluation with diploma students revealed an 87% improvement in conceptual understanding, underscoring its value as a teaching tool. The demonstrator not only equips students with practical knowledge relevant to India's booming EV industry but also fosters an innovative mindset by showing how complex technologies can be understood and demonstrated with simplicity and low cost. This work provides a scalable blueprint for enhancing the quality and relevance of technical education across India, directly contributing to the nation's goals of building a skilled workforce for a sustainable electric mobility future.

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