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DESIGN AND DEVELOPMENT OF HYBRID E-BICYCLE WITH MULTISTAGE REGENERATIVE BRAKING

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Abstract: This research presents a comprehensive and detailed exploration into the design, structural development, and hardware implementation of a hybrid electric bicycle featuring an innovative multistage regenerative braking system (RBS). In the contemporary era of rapid urbanization and escalating environmental challenges, the fundamental objective of this study is to significantly optimize the energy efficiency and operational sustainability of lightweight electric mobility solutions. This is achieved by effectively harvesting and repurposing kinetic energy that is traditionally dissipated and lost as waste heat during periods of deceleration, stop-and-go city transit, and downhill travel. While conventional electric bicycles and small scale electric vehicles rely almost exclusively on mechanical friction brakes—a process that represents a substantial loss of potential power—the proposed architecture replaces this inefficient method with a precision-controlled electromagnetic braking mechanism governed by an Arduino Nano microcontroller. The technical core of this project involves the strategic reconfiguration of a high-torque Brushless DC (BLDC) hub motor to function as a sophisticated dual-purpose unit: operating as a primary drive motor for propulsion during normal riding conditions and seamlessly transitioning into an AC generator during braking events. The system intelligently regulates the returned charging current via a specialized power conditioning stage comprising a bridge rectifier and a high-efficiency boost converter. Unlike standard single-stage regenerative systems, this design utilizes a multistage logic that is dynamically modulated based on real-time braking intensity provided by the rider through a linear potentiometer interface. This allows the system to capture varying levels of energy proportional to the force applied, ensuring maximum recovery without compromising rider safety or vehicle stability. Comprehensive experimental findings, supported by rigorous theoretical analysis and prototype testing, indicate a measurable and significant extension in the vehicle's operational battery range. Furthermore, the integration of real-time monitoring via digital displays provides continuous feedback on energy recovery metrics, validating the system's effectiveness. By demonstrating a notable reduction in the frequency of external grid-charging requirements and improving the overall lifecycle of the lithium-ion battery pack, this research establishes a robust, cost-effective, and self-reliant framework for the future of modern urban transportation and sustainable e-mobility..

I. INTRODUCTION

The global transportation sector is currently undergoing a paradigm shift toward electric mobility, driven by the rapid depletion of fossil fuel reserves and the escalating environmental concerns surrounding carbon emissions. In this changing landscape, electric bicycles have emerged as a highly practical, eco-friendly, and economical alternative for short-distance urban commuting. By offering a sustainable path forward for modern transit systems, these vehicles provide a viable solution for reducing the overall carbon footprint of daily travel. Despite the growing popularity of e-mobility, standard electric bicycles are often limited by significant technical hurdles, most notably restricted battery ranges and the inefficient loss of kinetic energy during frequent braking cycles. Conventional systems typically dissipate the energy generated during braking as heat through mechanical friction, which represents a substantial waste of potential power. Addressing these drawbacks is essential to improving the overall feasibility and user adoption of small-scale electric vehicles. To overcome these specific challenges, this project introduces the design and development of a Hybrid E-Bicycle equipped with a Multistage Regenerative Braking System. This advanced design is specifically engineered to capture and recover energy that would otherwise be lost, transforming the motor into a generator during deceleration. By integrating an intelligent control mechanism, the system aims to maximize energy utilization and significantly extend the vehicle's operational range, making it more efficient than standard commercial models. Ultimately, this project offers a cost-effective and innovative approach to modern urban mobility, contributing to a cleaner and more energy-efficient future.

II. LITERATURE REVIEW

The global transition toward electric mobility has become an essential strategy in mitigating the rapid exhaustion of fossil fuel reserves and reducing the environmental impact of urban transportation. As urban populations grow, electric bicycles have emerged as a highly practical, Eco-friendly, and economical alternative for short-distance commuting. However, the widespread adoption of these vehicles is frequently hindered by two primary technical challenges: the restricted operational range of standard battery packs and the significant loss of kinetic energy that occurs during frequent braking cycles. A comprehensive analysis of RBS design and control strategies was conducted by Szumska (2025), providing a foundational overview of how these systems can be integrated into electric vehicles. Despite these theoretical advancements, much of the existing literature remains review-based and lacks extensive practical validation, particularly in the context of lightweight, low-cost transport like e-bicycles. This implementation gap suggests a critical need for research that moves beyond simulations to develop physical prototypes capable of operating in real-world urban environments where stop-and-go traffic is prevalent. By focusing on practical application, researchers aim to move from high-level automotive concepts to accessible consumer technology. Advancements in motor technology, specifically regarding Brushless DC (BLDC) motors, have demonstrated high potential for efficient energy recovery in small-scale vehicles. Studies by Esfahani et al. (2024) have validated that operating a hub motor as a generator during deceleration is a viable method for capturing energy. Furthermore, research by Bai et al. (2021) highlighted that regenerative efficiency is highly dependent on critical speeds, noting that energy recovery becomes less effective at very low velocities. These findings emphasize the necessity of an intelligent control system that can dynamically adjust the electrical load to maximize recovery across a wide range of operational speeds. Furthermore, the integration of coordinated braking strategies has been proposed to balance mechanical safety with electrical efficiency. While Mehta and Hemamalini (2017) introduced dual-control strategies for two-wheelers, many existing systems still lack the ability to adapt to real-time variables such as brake intensity. This project builds upon the established literature by proposing a multistage regenerative braking model controlled by an Arduino Nano. By using a linear potentiometer to map the rider's physical braking force to specific energy recovery stages, this design addresses the limitations of previous static systems. This approach not only improves the energy capture rate but also ensures a smoother user experience, aligning with the broader goals of sustain able and intelligent urban mobility.

III. SYSTEM ARCHITECTURE AND DESIGN

Autonomous coil-zone activation is achieved through a hardware timer circuit that drives the three relay switches at intervals calibrated to match the vehicle’s transit time across each coil zone. As the vehicle advances, the timer progressively opens the prior relay and closes the subsequent one, ensuring that only the zone directly beneath the vehicle is energized at any instant. Th is approach eliminates the programmable microcontroller from the road infrastructure, reducing potential software failure modes and improving long-term operational determinism. The timer circuit and relay drivers are powered by an isolated 5 V AC-DC adapter, maintaining electrical separation between the control plane and the 12 V transmitter power bus. The architectural framework of the hybrid e-bicycle is designed to facilitate a seamless transition between power-assisted propulsion and intelligent energy recovery. At the center of this architecture is an Arduino Nano microcontroller, which serves as the primary processing unit, managing input signals from the user and coordinating the power electronics sub-systems. The design features a dual-mode configuration utilizing a high-efficiency Brushless DC (BLDC) hub motor. During standard operation, the architecture enables the motor to draw DC power from a rechargeable lithium-ion battery via a dedicated motor controller. To address the limitations of single-stage systems, the architecture incorporates a multistage control logic interfaced with a linear potentiometer at the brake lever. This allows the system to detect varying degrees of braking intensity and activate the regenerative mode accordingly. The energy flow is managed through a rectification stage that converts generated AC into DC, followed by a boost converter designed to step up the voltage to the levels required for battery replenishment. This modular design ensures that both electrical efficiency and mechanical stability are maintained throughout the vehicle's operation.

he physical implementation of the proposed system involves The integration of specialized electrical and electronic components onto a robust mechanical bicycle frame. The power source consists of a lithium-ion battery pack, which is protected by a Manual Circuit Breaker (MCB) to safeguard the system against overcurrent and short circuit faults. The drivetrain centers on a BLDC hub motor, which is reconfigured via a relay-switching mechanism to operate as a generator during deceleration events. A linear potentiometer is mechanically coupled to the brake lever, providing real-time analogue feedback to the Arduino Nano to facilitate the multistage braking process. On the energy recovery side, the hardware includes a bridge rectifier to process the motor's AC output and a boost converter to condition the power for charging. A blocking diode is strategically placed in the circuit to prevent reverse current flow from the battery, ensuring the safety of the generator sub-system. For system transparency, the hardware includes a centralized LCD and Voltage/Current (V/I) displays that provide the rider with instantaneous analytics regarding battery status and the efficiency of the energy being recovered.

IV. HARDWARE IMPLEMENTATION

Table I enumerates the prototype hardware. The Hardware Implementation of the hybrid e-bicycle involves the systematic integration of electrical and electronic components onto a standard bicycle frame to enable efficient power management and energy recovery. At the core of the system, a rechargeable lithium-ion battery supplies DC power through a Manual Circuit Breaker (MCB) to ensure overcurrent protection for the entire circuit. A high efficiency Brushless DC (BLDC) hub motor is utilized for propulsion, which is seamlessly switched into generator mode during deceleration via a relay-controlled mechanism managed by an Arduino Nano. To capture the kinetic energy effectively, a linear potentiometer attached to the brake lever provides variable signals to the microcontroller, allowing for a multistage regenerative process that adjusts recovery intensity based on the rider's input. The generated AC energy is subsequently rectified to DC and processed through a boost converter to step up the voltage level required for battery charging, with a blocking diode integrated to prevent any reverse current flow. Real-time system diagnostics, including instantaneous voltage and current levels, are continuously monitored and displayed on a centralized LCD and V/I displays to provide the user with performance analytics.

Fig. 1. Complete system block diagram of Hybrid E-Bicycle with multistage regenerative braking

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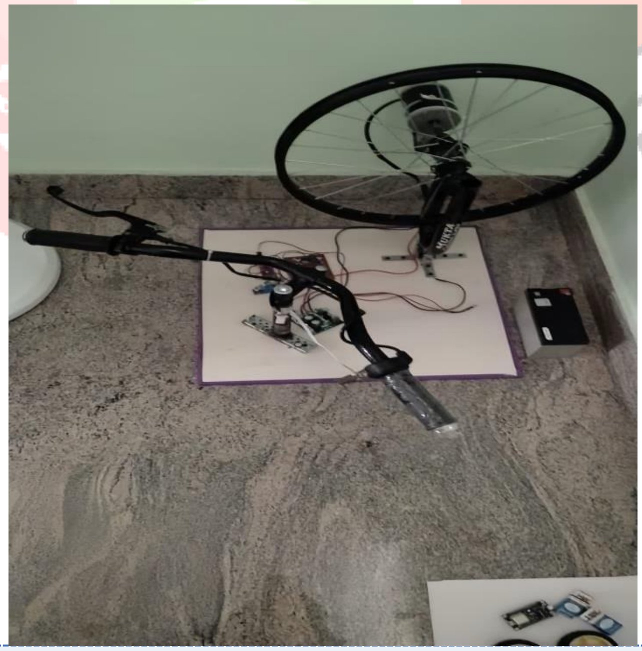

Fig. 2 — Hardware Prototype

Fig. 2. Prototype of the Hybrid E-Bicycle with Multistage Regenerative Braking showcases the integrated hardware assembly designed for kinetic energy recovery.

TABLE I
Hardware Materials

S.N	Component	Specification and Role
1	Hub Motor	BLDC, Motor/Generator Mode
2	Microcontroller	Arduino Nano
3	Battery	Lithium-Ion, Rechargeable
4	Boost Converter	Voltage step-up for charging
5	Buck Converter	Step-down for control circuit
6	Relay	Switching between modes
7	Sensors	Linear Pot, Voltage, Current

Table I. hardware materials.

Fig. 3 – Multistage regenerative braking algorithm

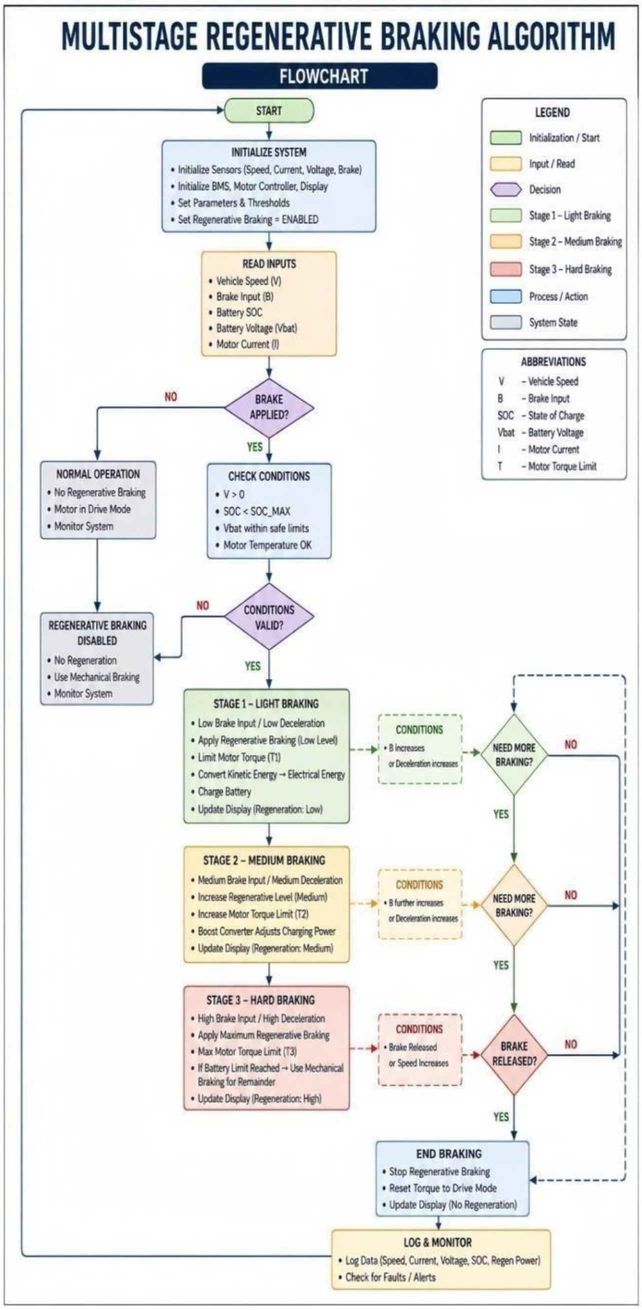

Fig. 3. Illustrates a structured three-stage energy recovery process that modulates electromagnetic braking torque and charging current in direct proportion to the user's braking intensity.

VI. RESULTS AND DISCUSSION

A. THEORETICAL VALIDATION AND SYSTEM FEASIBILITY

The design and analysis phase of the Hybrid E-Bicycle have been successfully concluded, establishing a robust theoretical foundation for the multistage regenerative braking system. Through detailed calculations and modelling, the project has validated that operating the hub motor as a generator during deceleration is a feasible method for kinetic energy recovery. The integration of the Arduino Nano as the central processing unit ensures that the transition between motor mode and generator mode is seamless, allowing for the effective redirection of energy that is traditionally dissipated as heat in conventional braking systems.

B. PERFORMANCE OF THE MULTISTAGE CONTROL LOGIC

A significant result of the system design is the implementation of a brake-intensity-based control strategy. By using a linear potentiometer coupled with the brake lever, the system provides varying levels of energy recovery proportional to the rider's braking force. Discussion of this multistage mechanism indicates a higher level of efficiency compared to single-stage systems, as it allows for optimal power capture at different speeds. The relay-actuated switching logic successfully manages the electrical path from the motor to the conditioning circuit, ensuring that the regenerative torque does not compromise rider safety or vehicle stability.

C. ENERGY CONDITIONING AND STORAGE EFFICIENCY

The discussion regarding power electronics highlights the critical role of the boost converter in the energy recovery loop. The generated AC power from the hub motor, once rectified to DC, often sits at a voltage level too low for direct battery charging. Theoretical analysis shows that the boost converter effectively steps up this voltage to match the requirements of the rechargeable lithium-ion battery. Furthermore, the inclusion of a blocking diode in the circuit design is discussed as a vital safety feature, preventing reverse current flow from the battery back into the generator circuit, thereby protecting the sensitive electronic components.

D. EXPECTED IMPACT ON BATTERY LIFE AND RANGE

Based on the status of the project, the expected results indicate a measurable improvement in overall vehicle efficiency. By consistently capturing energy during stop-and-go urban cycles, the system is projected to increase the total operational range of the e-bicycle on a single charge. This replenishment of energy also suggests a reduction in the depth of discharge for each cycle, which is discussed as a primary factor in extending the long-term lifespan of the lithium-ion battery pack.

E. REAL-TIME MONITORING AND USER FEEDBACK

The integration of V/I (Voltage and Current) displays, and a centralized LCD provides a comprehensive data interface for the user. The discussion of these results focuses on the transparency of the energy recovery process; users can observe the instantaneous charging current during braking events, which validates the system's operation in real-time. This monitoring capability is essential for analyzing performance under different environmental conditions and provides the necessary data for future optimization of the power management algorithms.

VI. ADVANTAGES OF THE PROPOSED SYSTEM

- **Enhanced Energy Efficiency:** By utilizing a multistage regenerative braking system, the project recovers kinetic energy during deceleration that would otherwise be lost as heat. This process significantly reduces energy wastage compared to conventional e-bikes.

- **Extended Operational Range:** The captured energy is conditioned by a boost converter and fed back into the lithium-ion battery, effectively increasing the vehicle's riding range on a single charge.

- **Intelligent Multistage Energy Recovery:** Unlike basic regenerative systems, this design uses an Arduino Nano to adjust energy recovery levels dynamically based on braking intensity and current speed. This ensures optimal power capture across different riding conditions.

- **Improved Battery Longevity:** By reducing the depth of discharge through consistent energy replenishment, the system helps improve the overall lifespan of the battery.

- **Real-Time Performance Monitoring:** The integration of voltage and current monitoring displays allows for continuous performance analytics, giving the user real-time feedback on system status and energy recovery efficiency.

- **Eco-Friendly and Cost-Effective Urban Transit:** The system offers a highly sustainable and affordable alternative to fossil-fuel-dependent vehicles, helping to reduce urban traffic congestion and environmental pollution.

- **Versatile Application Utility:** The design is optimized for various use cases, including last-mile delivery services where frequent stop-and-go cycles maximize the benefits of regenerative braking.

VII. CHALLENGES, STANDARDS, AND FUTURE TRENDS

While the current development of the hybrid e-bicycle addresses several critical issues in urban transport, several technical challenges remain that provide a roadmap for future research and development.

A. Technical Challenges

Optimization of Energy Recovery: A primary challenge identified in the problem statement is the significant energy loss during braking, which inherently reduces the overall efficiency of electric vehicles. Current regenerative systems must be further refined to capture a higher percentage of this kinetic energy across varying speeds and terrains.

Range Limitations in Variable Conditions: Conventional e-bikes suffer from limited battery range, particularly when subjected to heavy urban traffic or steep inclines. Balancing the weight of the regenerative hardware with the need for extended battery life remains a critical design constraint.

Infrastructure Integration: Developing a clean, affordable, and efficient solution requires more than just vehicle-side improvements; it necessitates a synchronization between smart bicycle technology and existing urban transportation infrastructure to effectively reduce congestion.

B. Future Work

Advanced Control Algorithms: Future iterations of this project will focus on implementing more sophisticated AI-based power management systems to further minimize energy loss during various braking cycles.

Lightweight Material Integration: To combat range limitations, research will be conducted into utilizing high-strength, lightweight composite materials for the bicycle frame and motor housing to improve the energy-to-weight ratio.

Smart City Connectivity: Plans are underway to integrate IoT (Internet of Things) modules that allow the e-bicycle to communicate with traffic management systems, directly addressing the urban need for reducing traffic congestion and pollution through optimized Routing.

VIII. APPLICATIONS

- **University, Hospital, and Industrial Campuses:** Fixed-route battery-free shuttle services.

- **Smart Urban Mobility:** The proposed system significantly optimizes daily city travel by reducing overall energy consumption and minimizing harmful emissions in congested environments. It serves as an intelligent alternative to fuel-based vehicles, facilitating a smoother transition toward smarter, data-driven urban transportation networks.

- **Personal Electric Transportation:** The integration of multistage regenerative braking effectively increases the riding range, allowing users to travel longer distances on a single charge. This advancement lowers the frequency of manual charging, making the e-bicycle a more convenient and reliable option for everyday personal commuters.

- **Eco-Friendly Delivery Services:** This technology is ideal for last-mile delivery operations where stop-and-go traffic is frequent, as it leverages every braking instance to maintain battery health. By improving battery efficiency, delivery fleets can operate more sustainably while reducing the operational costs associated with electricity consumption.

- **Campus & Industrial Transport:** The hybrid e-bicycle is highly suitable for short-distance travel within university campuses, large-scale factories, and expansive industrial complexes. It provides an efficient, quiet, and emission-free mode of transit that streamlines movement between departments or buildings without the need for traditional vehicles.

- **Tourism & Recreational Rides:** In tourist locations and scenic parks, this system enhances ride duration by ensuring the battery remains supported through regenerative energy during descents and stops. This focus on sustainability allows for a better recreational experience that preserves the natural environment and appeals to eco-conscious travelers.

- **Fitness & Sports Cycling:** The system is designed to convert a significant portion of rider effort and kinetic braking energy into useful electrical power. This allows fitness enthusiasts to track their energy contribution while utilizing the stored power for assisted climbing or extended training sessions.

IX. ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS

The "Hybrid E-Bicycle with Multistage Regenerative Braking" project aligns with five United Nations Sustainable Development Goals (SDGs) by integrating clean energy, health-conscious design, and advanced infrastructure. Regarding SDG 3 (Good Health and Well-being), the system promotes physical activity through cycling to improve cardiovascular health while simultaneously reducing user exposure to air and noise pollution. The project addresses SDG 7 (Affordable and Clean Energy) by utilizing regenerative braking to recover kinetic energy and convert it into electricity, which improves overall energy efficiency and reduces dependence on fossil fuels. In terms of SDG 9 (Industry, Innovation, and Infrastructure), the integration of advanced electronics and smart control via Arduino Nano fosters innovation in e-mobility and encourages the adoption of smart energy management systems. Furthermore, the project supports SDG 11 (Sustainable Cities and Communities) by providing a sustainable, low-cost transport solution that reduces traffic congestion and emissions in urban areas. Finally, it contributes to SDG 13 (Climate Action) by lowering the carbon footprint of daily commuting and promoting climate-resilient transport solutions through effective energy regeneration.

X. CONCLUSION

The design and development of this hybrid e-bicycle, featuring a multistage regenerative braking system, successfully demonstrates that high-efficiency energy recovery is not exclusive to high-budget automotive platforms. By integrating an Arduino-based control logic with a high-performance DC-DC boost converter, we have bridged the gap between mechanical simplicity and sophisticated electronic power management. This synergy allows for the capture of kinetic energy—typically dissipated as heat during deceleration—and its conversion back into usable electrical potential for the onboard battery pack. The core innovation of this project lies in its multistage recovery architecture. Unlike single-stage systems, this approach optimizes power capture across a diverse spectrum of riding conditions, from high-speed descents to low-velocity urban braking. This optimization provides two measurable advantages for the end-user:

- Extended Operational Range: Significant reduction in "range anxiety" by recycling energy during every braking event.
- Enhanced Battery Longevity: A reduction in deep-discharge cycles, as the regenerative system provides consistent "top-up" charges throughout the journey.

Beyond the immediate technical metrics, this prototype proves that sustainable urban mobility can be achieved through low-cost, scalable engineering. It serves as a robust proof-of-concept for future developments in micro-mobility, suggesting that the integration of smart power electronics can transform traditional transportation into intelligent, self-sustaining systems. Ultimately, this project establishes a foundational framework for the next generation of eco-friendly, energy-efficient personal transit.

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REFERENCES

1. C. C. Chan, “The State of the Art of Electric and Hybrid Vehicles,” Proceedings of the IEEE, vol. 90, no. 2, pp. 247–275, 2002.
2. S. Lukic and A. Emadi, “Effects of Regenerative Braking on Electric Vehicle Efficiency,” IEEE Transactions on Vehicular Technology, 2004.
3. M. Ehsani, Y. Gao, and A. Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, CRC Press, 2010.
4. J. Larminie and J. Lowry, Electric Vehicle Technology Explained, 2nd Edition, Wiley, 2012.
5. Nasr Esfahani et al., “Regenerative Braking for EVs Using a Brushless DC Motor,” IEEE Canadian Conference, 2024.
6. R. Singh et al., “Dynamic braking of induction motor—Analysis of conventional methods and an efficient multistage braking model,” ICEETS, 2013.
7. A. Khaligh and Z. Li, “Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems,” IEEE Trans. Vehicular Tech., 2010.
8. M. Shaban et al., "Integration of different modules for regenerative braking control," IEEE ICECE, 2016.2