International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 17, No. 2, June 2026, pp. 1265~1278
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v17.i2.pp1265-1278

A hybrid simulation and hardware approach for a regenerative braking system in an electric motorcycle

Faris Anwar Amir Faisal[1], Siti Fauziah Toha[1], Nurul Muthmainnah Mohd Noor[1], Ahmad Syahrin Idris[2], Mohamad Osman Tokhi[3]
[1]Department of Mechatronics, Kulliyyah of Engineering, International Islamic University Malaysia, Selangor, Malaysia
[2]Department of Electrical and Electronic Engineering, University of Southampton Malaysia, Iskandar Puteri, Malaysia
[3]Department of Electrical and Electronic Engineering, London South Bank University, London, United Kingdom

Article Info

Article history:

Received Sep 6, 2025
Revised Feb 23, 2026
Accepted Mar 6, 2026

Keywords:

Electric motorcycle
Energy efficiency
Energy recovery
MATLAB simulation
Regenerative braking

ABSTRACT

Conventional electric motorcycles mostly depend on mechanical braking systems that dissipate kinetic energy as heat, resulting in significant energy losses, frequent battery recharging, and reduced operational efficiency. To address these limitations, a regenerative braking system (RBS) is designed and developed to recover and store kinetic energy during braking phases. The proposed RBS integrates a brushless DC (BLDC) motor that serves as a propulsion and energy regenerative unit, a lithium-ion battery for energy storage, and an Arduino microcontroller for real-time control and seamless system integration. A hybrid methodology combining MATLAB/Simulink simulations and hardware prototyping was adopted to evaluate system performance under various operating conditions. The simulation results demonstrated effective braking torque generation and back electromotive force (EMF) recovery to validate the system's ability to convert kinetic energy into storable electrical energy. The proposed RBS achieved a theoretical energy recovery efficiency of approximately 70%, attributed to internal resistance and motor back EMF variations. These findings demonstrates the potential of regenerative braking in improving the energy efficiency of electric motorcycles, extending battery life, and reducing dependency on external charging. Furthermore, this study establishes a foundation for future RBS development incorporating lightweight materials, cost-effective components, and intelligent control strategies that can contribute to advancing sustainable and energy-efficient urban mobility solutions.

Corresponding Author:

Siti Fauziah Toha
Department of Mechatronics, Kulliyyah of Engineering, International Islamic University Malaysia
Gombak St., 53100 Kuala Lumpur, Selangor, Malaysia
Email: tsfauziah@iium.edu.my

1. INTRODUCTION

The increasing rate of urbanization and the combination with global efforts to reduce carbon dioxide emissions have positioned electric motorcycles as a viable replacement for traditional motorcycles. In Malaysia, the growing urban population further encourages the adoption of electric motorcycles, which are practical, cost-efficient, and environmentally friendly [1]. This mode of transportation is ideal for urban environments where traffic congestion, noise, and air pollution remain challenges. According to the Global EV Outlook 2025 report [2], the annual adoption of electric motorcycles is increasing, as illustrated in Figure 1.

The graph shows that the number of electric motorcycles increases year by year, emphasizing the importance of embracing sustainable mobility solutions to mitigate environmental impacts.

In general, electric vehicles are powered by batteries and use electric propulsion systems compared to internal combustion engines (ICEs), they have a greater priority on electric power quality, especially during energy conversion operations [3]. However, many electric motorcycles are still equipped with traditional braking systems that dissipate kinetic energy and turn it into thermal energy. The conventional braking system not only wastes energy but also increases the frequency of external battery charging [4]. Furthermore, some challenges like limited driving range, complex battery management, and the need for effective regenerative braking may be addressed in electric cars and other large electric vehicles (EVs), which provides an opportunity to introduce similar solutions in electric motorcycles [5].

A regenerative braking system (RBS) is introduced in an electric motorcycle to recover energy, extend the riding range, reduce the need for regular charging, and improve battery durability. The RBS enables the electric motor to function as a generator during deceleration, converting kinetic energy into electrical energy that is stored in the battery. This feature is particularly advantageous in urban areas with frequent stop-and-go traffic, where braking occurs often, as well as in conditions such as uphill riding [6]. However, implementing RBS in light electric vehicles introduces unique challenges compared to high-powered electric vehicles, due to differences in power capacity, load, and battery size. The system must be designed to maximize energy recovery while remaining lightweight and avoiding unnecessary complexity. Therefore, RBS can improve battery utilization to enhance charging efficiency, extend the overall driving range, and increase battery life. Beyond technical benefits, regenerative braking also supports environmental sustainability by reducing energy consumption.

This paper is divided into five sections, beginning with the introduction. Section 2 presents the theoretical background of regenerative braking for electric motorcycles. Meanwhile, section 3 outlines the research methodology for both hardware and software aspects, including the components used in the prototype of the regenerative braking system. Section 4 discusses the findings, particularly the relationship between RPM and voltage, as well as the initial results of the MATLAB simulation. Finally, section 5 concludes the paper by summarizing the outcomes and highlighting future research directions.

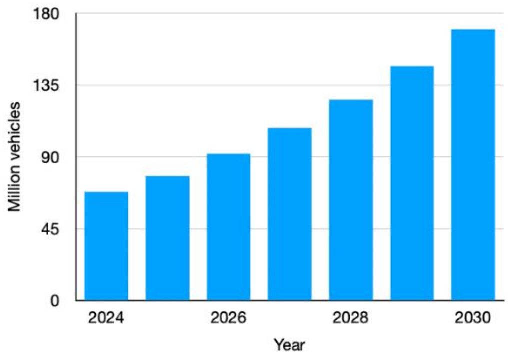


Figure 1. The projected number of global electric motorcycles between 2024 and 2030 [2]

2. REGENERATIVE BRAKING SYSTEM

In recent years, RBS has gained attention as a sustainable transportation option for a global priority. Unlike conventional braking systems, which dissipate kinetic energy as heat, RBS captures and stores the energy for reuse by reducing energy consumption and enhancing environmental sustainability. When applied to electric motorcycles, RBS can extend battery life, reduce the frequency of external charging, and improve braking performance.

Regenerative braking systems operate by converting kinetic energy into electrical energy during deceleration and storing it in the battery system. This concept is significant in removing fossil fuel dependency, as conventional braking dissipates energy in the form of heat [7]. In the context of electric motorcycles, regenerative braking presents a promising solution for extending range and improving energy efficiency [8]. These systems commonly use brushless DC (BLDC) or permanent magnet synchronous motors (PMSM) due to their favorable torque and speed characteristics [9]. Therefore, the implementation involves the digital processor to control the inverter switching cycle and enable effective energy recovery [10].

Previous studies have shown that regenerative braking systems can operate effectively within battery specifications, with current increasing proportionally to speed. This technology not only reduces energy loss but also has the potential to extend travel range [11]. Meanwhile, regenerative braking has also been successfully implemented in electric cars to enhance vehicle efficiency by capturing energy that would otherwise be dissipated as heat in conventional braking systems [12]. Consequently, regenerative braking is emerging as a cutting-edge technology, increasingly adopted in various modes of transportation, including hybrid buses, trains, and electric cars, to improve both the sustainability and efficiency of transport.

2.1. Concept of RBS

The concept of RBS begins with braking initiative, where the rider applies the brakes, and the system engages with the electric motor to act as a generator [13]. Figure 2 shows the block diagram of the regenerative braking system applied to an electric motorcycle. During energy conversion, the kinetic energy of the motorcycle is converted into electrical energy by the motor. This energy is then transferred through the transmission system to ensure efficient delivery to the storage unit. The generated electrical energy is stored in the battery for later use, thereby reducing the reliance on external charging. To ensure system effectiveness, efficiency monitoring tracks parameters such as recovered energy, braking performance, and battery charging status. Finally, the feedback loop communicates performance data back to the control system, enabling real-time adjustments that optimize braking response and energy recovery.

The regenerative braking system in electric motorcycles consists of three primary components: the motor (or generator), the energy storage unit, and the control system unit. The motor functions as a generator during deceleration, then converts mechanical energy into electrical energy. The energy storage unit, such as a lithium-ion battery or a supercapacitor, will produce energy to store. Supercapacitors are often preferred in electric motorcycles due to their high charge and discharge rates, making them highly efficient for rapid energy recovery [14]. Finally, the control system plays a main role in managing the distribution of braking force between regenerative and mechanical brakes to maximize energy recovery while ensuring rider safety. However, advanced control strategies also regulate the battery's SOC to extend battery life and improve overall system performance. Therefore, all components enhance energy density, reduce reliance on external charging, and establish RBS as a fundamental element in modern electric motorcycle architectures.

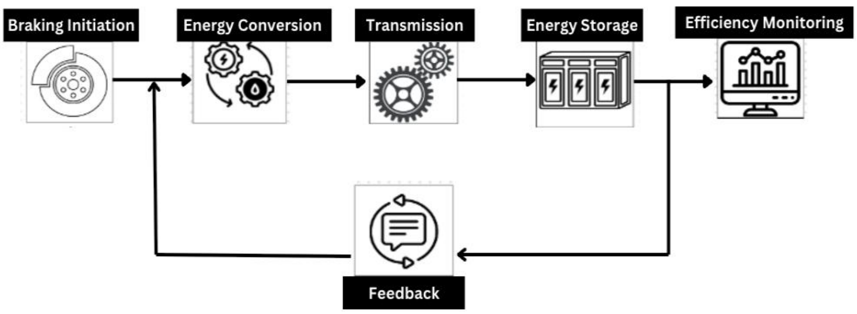


Figure 2. The block diagram of a regenerative braking system for an electric motorcycle

2.2. Control strategies in RBS

The RBS is also an advanced technology that enhances the energy efficiency and low-emission characteristics of electric vehicles. In addition, to improve driving performance, RBS requires effective control strategies to maximize energy recovery. Studies have shown that optimized regenerative braking can improve fuel economy in urban driving cycles by up to 37.8% [15]. To achieve this without compromising vehicle performance, various control methods such as fuzzy logic control (FLC), neural networks (NN), model predictive control (MPC), and adaptive controller modelling have been applied [16]-[18]. Furthermore, RBS can also be integrated with anti-lock braking systems (ABS) to enhance vehicle stability and braking safety. The combination of regenerative and friction braking, supported by a closed-loop wheel slip control strategy, enables maximum energy recovery while maintaining optimal wheel slip and braking distance, offering performance comparable to ABS-only systems [19].

Control techniques in RBS regulate energy recovery, braking performance, and rider safety in electric motorcycles. One common approach is the blended brake control strategy, which combines regenerative and friction braking to ensure effective deceleration during low-speed operation while maximizing energy capture at higher speeds. Torque control also helps to prevent wheel lock and instability by limiting the braking force applied by the motor. Similarly, speed-based control adjusts the level of regenerative braking according to the vehicle speed, prioritizing regenerative braking at higher speeds and mechanical braking at lower speeds for precise stopping. SOC control is also a fundamental item as it restricts regenerative braking when the battery is nearly full to prevent overcharging and extend battery life. Finally, a rider-adaptive control adjusts braking based on the rider's input, road conditions, and load for both safety and comfort. These control strategies enable optimal, reliable, and safe braking performance measured to the dynamic operating conditions of electric motorcycles.

Fuzzy logic control (FLC) is widely applied in RBS to regulate the distribution of braking force between regenerative and mechanical systems. FLC operates based on predefined parameters such as vehicle speed, SOC, and braking torque demand. The application of FLC enhances energy recovery while maintaining vehicle stability and safety [20], [21]. This makes FLC particularly suitable for electric motorcycles, where braking requirements can vary significantly depending on rider behavior and operating conditions. Meanwhile, neural networks (NN) apply machine learning techniques to manage the distribution of braking force in RBS. Unlike rule-based approaches such as FLC, NN-based controllers can learn from past data and adapt dynamically to changing conditions. This adaptability can predict the rider's actions and road conditions, to improve braking performance and energy recovery rates [22], [23]. By processing real-time inputs such as speed, SOC, and braking torque demand, NN-based controllers can optimize braking force distribution, making them highly effective for electric motorcycles where operating conditions and rider behavior can vary significantly. Another approach to optimize energy recovery in RBS is model predictive control (MPC). MPC offers significant advantages for managing RBS, as it operates in a real-time control strategy to predict future system states and adjust control actions accordingly. This predictive capability ensures that energy recovery is optimized while maintaining rider comfort and vehicle stability [24]. MPC is also suitable for electric motorcycles, where lightweight structures demand high efficiency and precise energy management. Unfortunately, every control strategy has its strengths and limitations as stated in Table 1.

Table 1. Some strengths and limitations of the control strategy in the regenerative braking system [25]

Control strategy	Strengths	Limitations
Fuzzy logic control (FLC)	Easy to understand and interpret for a non-expert control engineer	Fully reliant on human expertise and understanding
	Most cost-effective control techniques	Manual tuning is time-consuming for large-scale
Neural network (NN)	The training method and the output data can be produced without proper information	Need an acceptable network structure, skill, and trial and error
	The training method learns from identical events and makes a decision based on them	ANN requires processors with parallel processing capabilities
Model predictive control (MPC)	Able to handle multiple variables of inputs and outputs with single-input and output ones	Need a suitable model of the system
		Derivation of the control law is complex
	Use to regulate a variety of processes, such as non-minimum phase, long delay, and open-loop stability	
Sliding mode control (SMC)	Suitable for a non-linear system	Limited to a single-input system
	A robust technique that can be used to control systems with uncertainties	Chattering occurrence in an undesirable phenomenon
Adaptive control	Easy to apply and good stability	The required design for employment is enormous
	Can change parameters easily and respond quickly to the system	Need an appropriate model of the system

3. METHOD

The propulsion efficiency can be achieved up to 90%, and round-trip regenerative braking efficiency can reach to 70% [26]. Therefore, this study introduces the RBS that was designed for electric motorcycles by combining a BLDC motor, a lithium-ion battery, and an Arduino microcontroller within an integrated hardware and simulation setup. Through MATLAB/Simulink analysis and experimental validation, the system demonstrates improved energy efficiency, extended battery life, and enhanced sustainability for urban electric mobility applications.

In this project, a sub-model of RBS was developed for the electric motorcycle to recover and reuse the energy generated during braking. The system integrates with hardware and software to enable energy recovery and improve the overall energy efficiency of the electric motorcycle. The prototype used a 12-inch tyre driven by the BLDC motor controlled through a 40 A and powered by an 11.1 V LiPo battery. Three push buttons provide selectable speed levels (low, medium, and high), while an emergency stop switch provides operational safety. Meanwhile, braking was achieved by engaging a direct current (DC) motor, which functions as a generator to convert mechanical energy into electrical energy, feeding it back to the battery. Real-time measurements of voltage and RPM were displayed on an LED interface and logged into Excel using PLX-DAQ. Data acquisition and control were managed through an Arduino microcontroller, while MATLAB/Simulink was used to simulate the system and validate its performance.

The results in hardware were analyzed to assess the system's effectiveness and verify that the objectives were met. Figure 3 shows the flowchart of the proposed regenerative braking system. The process began with a comprehensive literature review of existing studies on the RBS, in which the current approach was identified, as well as research gaps, especially in control strategies. The parameters related to the RBS were determined, including motor type, controller, battery, and braking mechanism for both hardware and software. Before hardware implementation, a MATLAB/Simulink simulation was developed. This step involved evaluating system feasibility, testing control algorithms, and predicting overall performance. Once the simulation stage validates the concept, hardware development proceeds by integrating the BLDC motor, battery, braking mechanism, and controller. In parallel, software development was performed through designing control algorithms by using the Arduino platform. This algorithm was designed to regulate braking force distribution and energy recovery. Both hardware and software were then integrated into a prototype, forming a complete RBS setup. Then, the prototype undergoes testing under varying operating conditions. If the results are satisfactory, the test data is analyzed to evaluate performance, energy recovery efficiency, braking stability, and optimization opportunities. Finally, the model was refined and adjusted based on the findings to enhance efficiency, safety, and overall system stability, with improvements made at both the simulation and hardware levels.

3.1. MATLAB/Simulink simulation

In this part, the simulation was used to evaluate the performance of the back electromotive force (EMF) and the amount of torque produced during braking. This method helps to determine the most suitable parameters for the prototype by predicting braking torque response, back EMF generation, and the overall energy recovery capability of the RBS. Conducting simulation tests resolved potential issues in advance, ensuring a smoother transition during hardware implementation. which helped the process move smoothly during the hardware installation. To model the RBS for the electric motorcycle, the Simulink model was developed with the necessary components of the electrical and mechanical subsystems of the regenerative braking system. The main components of the system include the BLDC motor with dual function for propulsion during normal operation and power generation during braking, the battery for energy storage, the ideal torque source for providing resisting force, the inertia block to represent the mechanical load, and the voltage sensor for measuring energy captured, as shown in Figure 4.

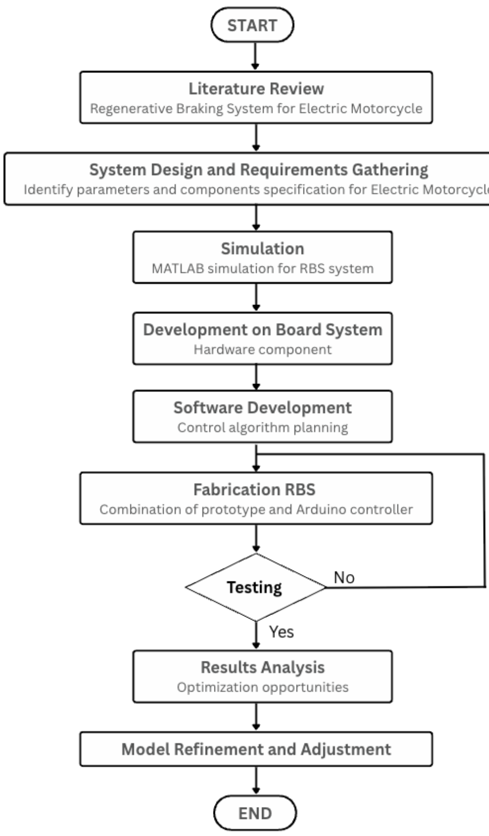


Figure 3. Proposed process flow of RBS

The BLDC motor was represented by an electromechanical block that converted electrical input into rotational motion during propulsion and generated electrical energy during braking. Meanwhile, the battery subsystem was modelled using a DC voltage source with an internal resistance that serves as the primary energy storage unit. It allows bidirectional energy flow. The power electronic converter regulates the current direction and voltage levels to ensure stable operation during both monitoring and regenerative modes. During braking, the vehicle operates in reverse as a generator, converting kinetic energy into electric energy. The generated voltage (V) is proportional to the motor's speed (ω) and its speed constant (K_v) as in (1).

$$V = \frac{\omega}{K_v} \tag{1}$$

Where K_v is the speed constant of the motor in RPM. For the A2212 motor, K_v is 1000 RPM. The model also incorporates a LiPo 3S battery rated at 11.1 V with a capacity of 2200 mAh.

The control logic that was implemented through switch and comparator blocks will monitor the braking signals and vehicle speed to determine the transition between drive and regenerative states. This operation allowed the kinetic energy from the motor shaft to be converted into electrical energy and directed back to the battery. The scope block was used to monitor the system variables such as current, voltage, and braking torque. From this simulation setup, it enables the analysis of back EMF, current flow during regenerative braking torque to validate theoretical energy recovery, which can reach to 70% under simulated urban braking conditions.

However, the mechanical subsystem consists of the inertia block, representing the combined wheel rotational inertia and rotor inertia of the motor, while the braking was simulated through the ideal torque source, which applied torque to the motor, reducing its angular velocity, ω, and generating electrical energy. In Simulink, the interactions were captured by connecting the motor's mechanical part to the inertia block and torque source, while electrical terminals were linked to the battery and voltage source.

The simulation was carried out to analyze the RBS in both normal and braking mode. Initially, electrical energy from the battery was used to power the DC motor, which drove the inertial mass to simulate normal riding conditions. At t = 2 s, the ideal braking torque of 0.3 Nm was applied, introducing the braking phase. This external torque slowed the motor and switched it into generator mode. The kinetic energy was converted into electrical energy (back EMF). The generated back EMF, based on a motor constant, K_e = 0.026, reflected the relationship between angular velocity and induced voltage. The voltage measured across the motor terminals indicated the recovered energy and demonstrated the regenerative capability of the system. Time-series data of motor speed, braking torque, and generated voltage were recorded for energy recovery performance, storage efficiency, and overall system behavior. This phase was essential in evaluating the energy recovery characteristics of the regenerative braking system.

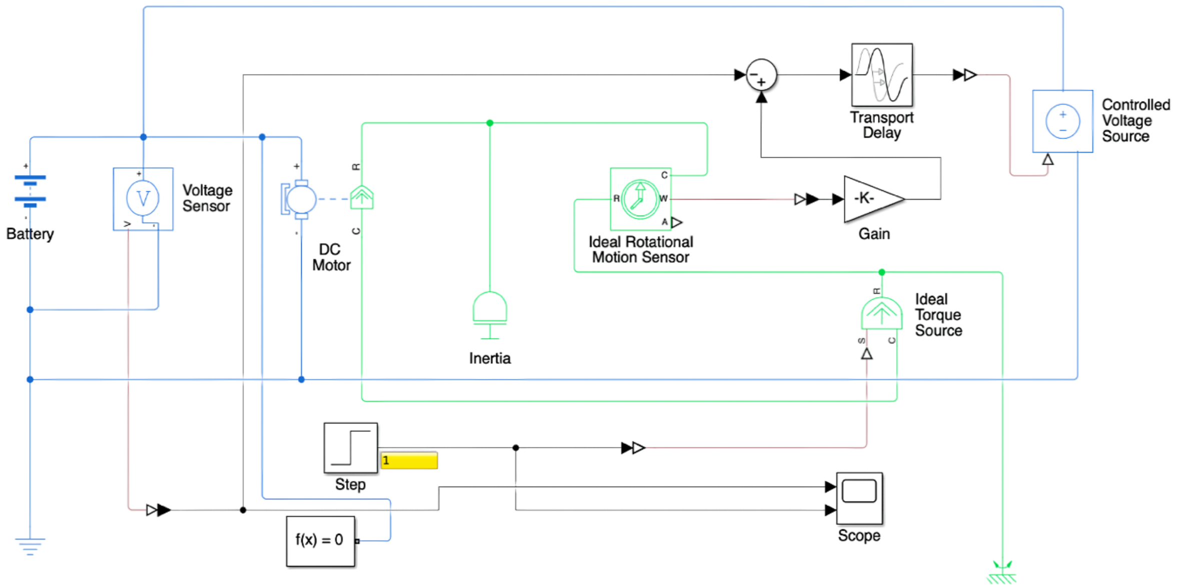


Figure 4. Simulink diagram for the RBS system

3.2. Hardware and software implementation

Figure 5 illustrates components used in the development of the regenerative braking systems for electric motorcycles. The braking was operated when the rider applied the brake lever, which sent a signal to the Arduino Uno microcontroller. The Arduino processed the signal and regulated the electric motor system, enabling it to operate in generator mode during braking. The motor was mechanically coupled to the pulley and belt drive, which transferred the braking torque to the tyre, thereby slowing down the vehicle. Simultaneously, the motor converted the vehicle's kinetic energy into electrical energy, which was redirected to charge the battery as an input source. To ensure effective monitoring and control, a sensor unit or feedback system continuously measures system parameters such as speed and braking force, sending real-time data back to Arduino for adjustment. This closed-loop structure ensures smooth braking performance, efficient energy recovery, and enhanced rider safety.

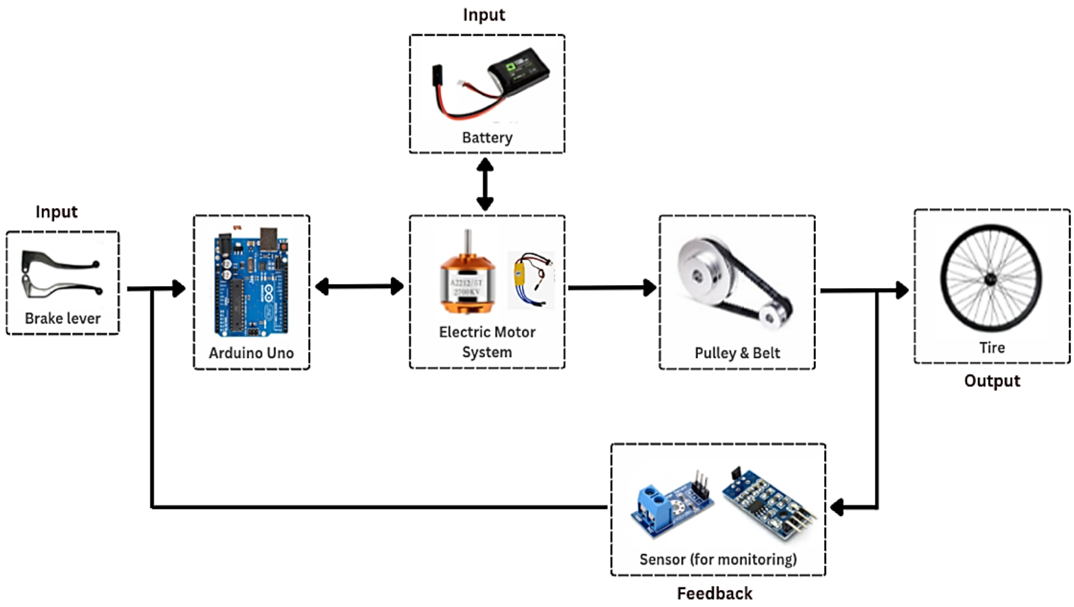


Figure 5. Block diagram of regenerative braking system components

The Arduino Uno managed both the motor and the braking system by processing signals from buttons, the emergency button, the brake lever, and sensors to adjust motor speed and braking response. The motorcycle's movement was driven by a BLDC motor, controlled by a 40A ESC motor speed controller that was connected to a 12-inch tyre through a 2GT pulley system, with speed adjustable via three buttons (low, medium, high). Braking was achieved through a manual lever that activates a DC motor, which pressed against the moving tyre to slow it down while converting kinetic energy into electricity. This energy was captured by a voltage sensor and displayed, with both the DC motor and lever linked to the Arduino for fast control. A hall effect sensor with a neodymium magnet was used to measure motor RPM, while the voltage sensor continuously monitors the generated power, and both parameters were displayed in real time on an LED screen, giving the user instant feedback. To support long-term monitoring and analysis, the PLX-DAQ system logged data such as motor speed and output voltage directly into an Excel spreadsheet for evaluating system performance.

In the control strategy, the control logic of the RBS was implemented through the Arduino microcontroller that programmed the monitor vehicle speed, throttle position, and brake activation signals. Under normal operation, the controller maintains the BLDC motor in monitoring mode to drive the wheel. When braking was detected, the controller adjusted the pulse-width modulation (PWM) signals to alter the current and make the motor operate in generating mode. The generated back EMF induced a current that flows toward the lithium-ion battery through the converter circuit to charge the battery. The algorithm was used to make a smooth transition between monitoring and braking modes while maintaining stability and avoiding wheel lock. Table 2 summarizes the main hardware components utilized in the development of the regenerative braking system for the prototype.

Table 2. Components of a regenerative braking system for an electric motorcycle

Component	Specification	Function
Arduino Uno	ATmega328P, 14 digital I/O pins	Acts as the main controller for signal processing and system integration.
BLDC electric motor	1000 KV, 12 V	Provides propulsion and generates back EMF during braking for energy recovery.
Electronic speed controller (ESC)	30 A, compatible with BLDC	Controls motor speed and braking response by regulating voltage/current.
LiPo battery	3S, 11.1 V, 2200 mAh	Stores recovered electrical energy and supplied power to the system.
Hall effect sensor	Digital, 5 V	Detects wheel or motor rotational speed for braking and energy recovery control.
Brake lever	Mechanical with a sensor switch	Triggers regenerative braking when pressed by the rider.
Neodymium magnet	N52 grade	Provides a magnetic field for the hall effect sensor operation in detecting speed or position.
Voltage sensor	0–25 V	Measures the voltage generated during braking for monitoring and control.
2GT pulley and belt	20T pulley with timing belt	Transfers rotational motion from the wheel to the generator motor.
Tire	12-inch	Provides road contact and rotational input for the RBS.

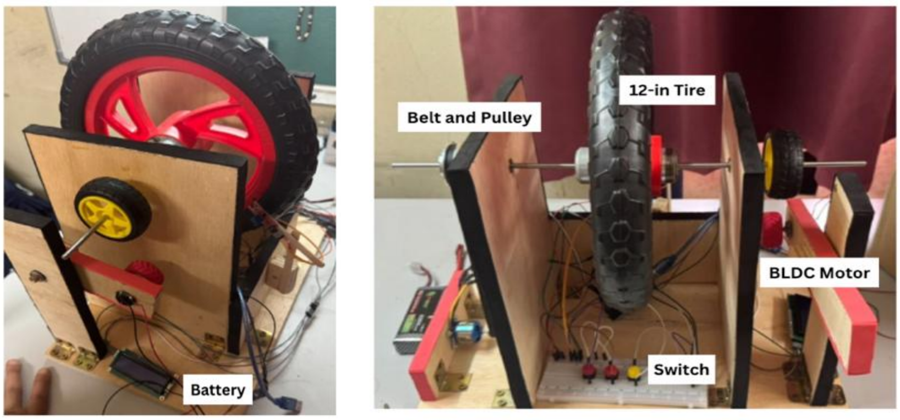
4. RESULTS AND DISCUSSION

This section discusses the results obtained from the study, with emphasis on RBS in the electric motorcycle as well as the MATLAB simulation. The simulation data generated in MATLAB/Simulink during the earlier setup was compared with real-time experiment results to validate the model and ensure consistency. The purpose of this evaluation is to examine the performance of the regenerative braking system in terms of energy recovery, voltage output, and braking torque. Furthermore, it also presents a detailed description of the developed prototype, thereby providing a comprehensive understanding of the RBS's functionality and effectiveness.

4.1. Prototype of regenerative braking system

A prototype of the RBS was developed to demonstrate the working principle of a regenerative braking system for the electric motorcycle. Figure 6 shows the experimental setup, which consists of the designed RBS components, including the 12- inch wheel mounted on a horizontal shaft, data acquisition, and safety circuitry. The motor functions in dual modes: as the drive motor during propulsion and as the generator during braking. When the brake lever was activated, the motor switched to generator mode, converting the wheel's kinetic energy into electrical energy.

The generated electricity was measured using a voltage sensor and displayed on the system's monitoring interface. The braking force was also applied through the motor's electromagnetic resistance, which simultaneously slows down the wheel and enables energy recovery. An auxiliary, smaller wheel was attached on the right side to simulate load dynamics and ensure realistic testing of braking responses. The system was controlled using the Arduino microcontroller, which manages operations such as speed control, braking activation, emergency stop, and real-time data logging. Finally, the prototype was equipped with push-button switches to regulate wheel speed at different PWM levels and an LED dashboard interface for output display. Data from the Arduino board was transmitted to the PLX-DAQ software, and motor speed, recovered voltage, and braking torque were recorded for analysis.



(a) (b)

Figure 6. The prototype of the regenerative braking system: (a) side view and (b) front view

4.2. Simulation and experimental results on RBS

The Simulink model of the regenerative braking system was used to evaluate its performance during braking. The simulation results showed that the system was able to recover energy effectively, with the back EMF reaching a peak of 1.25 V. This demonstrates that part of the wheel's kinetic energy can be converted into electrical energy during deceleration. The recovered energy was successfully stored in the battery, and the system performed consistently under various braking conditions. Figure 7 shows the graph of voltage obtained from a simulation based on a step input. The back EMF, regulated by a gain factor of 0.026, supported the energy recovery process by converting mechanical deceleration into electrical energy for battery charging. From t = 2 s, a braking torque of 0.3 Nm, from calculation was applied consistently, marking the start of the energy recovery phase. During the period, the system generated up to 1.25 V, which aligned with the expected performance of the model.

Once the simulation was done using MATLAB, the result was verified by experiment. In this part, the efficiency of energy recovery was evaluated at low, medium, and high speeds. At low speeds, the system recovered only a small amount of energy, reaching a peak voltage of 0.12 V. Meanwhile, at medium speeds, the performance improved, with the recovered voltage increasing to 0.27 V. At high speeds, the system achieved a peak of 0.71 V, confirming that higher braking forces and motor speeds enhance the effectiveness of energy recovery. During low speed, the electric motorcycle's kinetic energy is too small to allow significant regeneration due to the weaker braking force, so the low voltage output is produced, since the vehicle decelerates gradually. As a result, the conversion of kinetic energy into electric energy was not very efficient under these conditions.

However, at medium speed, the system achieved better energy recovery. This improvement can be linked to the faster wheel rotation and stronger braking force, which allowed more kinetic energy to be converted into electric energy. Meanwhile, at a higher speed, the kinetic energy is more compared to medium speed. However, even though the voltage at high speed was higher, the overall recovery energy remained relatively small, indicating that further improvements to the system are still needed. In addition, for the electric motorcycle, the mode of speed can be classified based on the percentage of the maximum speed, V_{max}. Table 3 presents the specifications used to classify the speed range into low, medium, and high modes according to the maximum achievable speed of the motorcycle.

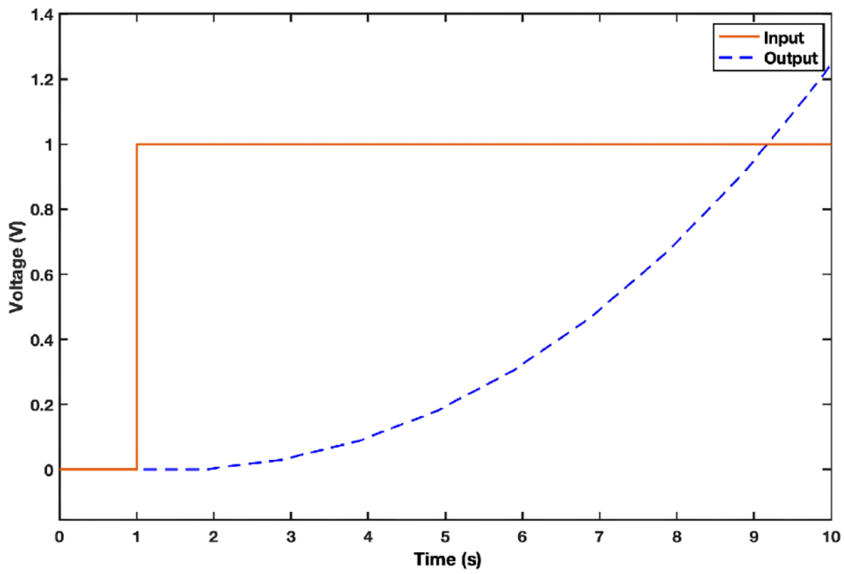


Figure 7. A voltage output from the step input is given

Table 3. The range of speed modes

Speed mode	Range of percentages of maximum speed (%)	Range of speed (km/h)
Low	0–30	0–24
Medium	30–60	25–48
High	60–100	49–80

Figures 8 to 10 illustrate the relationship between angular speed and the voltage produced by RBS across different speed modes. The results show that at low speed, the recovered energy was minimal, with a peak voltage of only 0.12 V. At medium speed, recovery improved, reaching 0.27 V, but at the maximum angular speed of 840 RPM, the system achieved its highest peak voltage of 0.71 V, indicating greater energy recovery due to the higher motor speed. Table 4 presents the average value for both angular speed and voltage, as well as peak voltage. By comparing the simulation and experimental results, it was found that the simulation predicted a higher voltage of 1.25 V, while the experiment showed a maximum voltage achieved of 0.71 V. This difference can be explained by real-world factors such as frictional losses, motor inefficiencies, and sensor inaccuracies, which are typically not considered in simulations. Nevertheless, the results show that the RBS is capable of recovering energy during braking, especially at higher speeds.

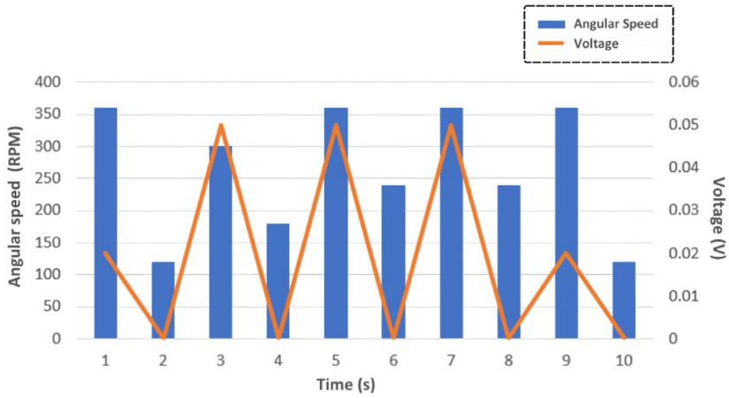


Figure 8. Relationship between speed in RPM and voltage produced at low-speed mode

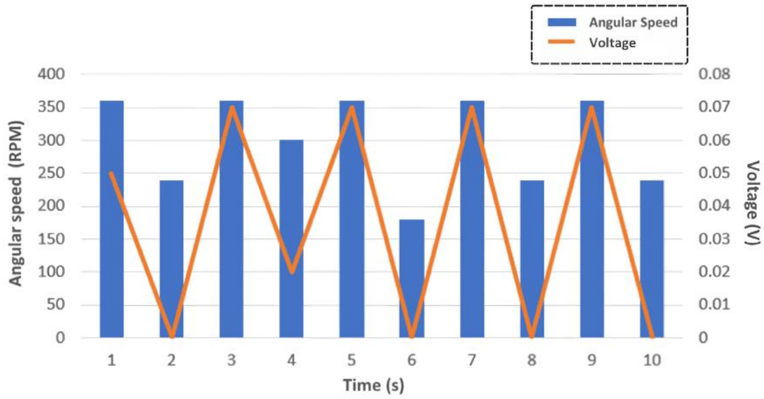


Figure 9. Relationship between speed in RPM and voltage produced at medium-speed mode

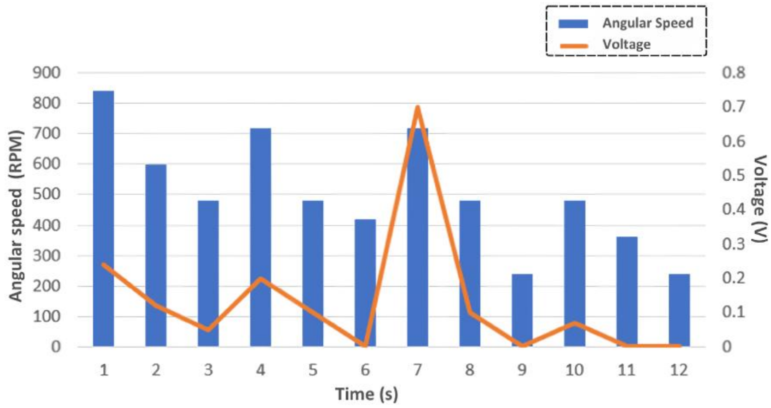


Figure 10. Relationship between speed in RPM and voltage produced at high-speed mode

To further improve performance, it is important to optimize the braking control, increase motor efficiency, and conduct more real-world tests to enhance energy recovery and the system's performance. Energy recovery in electric motorcycles significantly improves the system efficiency and extends the driving range. During braking or deceleration, some amount of the kinetic energy is normally lost as heat in conventional braking systems. However, with the regenerative braking technology, this energy can be captured and converted into usable electrical energy in the battery. This process not only reduces energy waste but also minimizes reliance on external charging to make the vehicle more energy efficient and environmentally friendly. Therefore, understanding and analyzing the amount of energy recovered is essential for evaluating system performance and optimizing the braking strategy.

The regenerative braking performance of the proposed system was evaluated using time domain data of angular speed obtained during braking. The corresponding energy recovery was calculated based on the change in kinetic energy at each time step. Table 5 summarizes the kinetic energy variations during deceleration periods and the corresponding recovered electrical energy, considering a regeneration efficiency of 70% for three riding speed modes: low, medium, and high. The findings show that higher angular speeds produce greater energy recovery due to increased wheel rotation and generator response during braking. In low-speed mode, an average speed of 263 RPM and the vehicle speed of 4.10 m/s, the system generated 5180.65 J of kinetic energy and successfully recovered 3626.45 J. In medium speed mode, the angular speed increased to 297 RPM with a corresponding speed of 4.74 m/s. Although the total kinetic energy decreased to 4220.18 J due to variability in braking profiles, the recovered energy reached 2954.13 J. The highest recovery was observed in high-speed mode, where the angular speed reached 516 RPM, and the vehicle speed increased to 8.23 m/s. In this mode, 5667.25 J of kinetic energy was generated and extracted as 3967.07 J through regenerative braking. These results demonstrate that energy recovery is more effective at higher speeds, as greater rotational energy can be captured and converted during braking. It highlights the potential of regenerative braking to enhance energy efficiency in electric motorcycles.

Table 4. Average speed, voltage, and peak voltage for each mode

Speed mode	Average angular speed (RPM)	Average voltage (V)	Peak voltage (V)
Low	263.0	0.03	0.12
Medium	297.0	0.05	0.27
High	516.0	0.10	0.71

Table 5. Total kinetic energy and energy recovered for each mode

Speed mode	Average angular speed (RPM)	Average speed (m/s)	Total kinetic energy (J)	Total energy recovered	
				in Joule (J)	in Watt (Wh)
Low	263.0	4.20	5180.65	3626.45	1.01
Medium	297.0	4.74	4220.18	2954.13	0.82
High	516.0	8.23	5667.25	3967.07	1.10

5. CONCLUSION

In conclusion, this study has presented the simulation and prototyping of the regenerative braking system for electric motorcycles that utilizes the BLDC motor for propulsion and the DC motor for energy recovery, the Arduino-based control interface, and the lithium-ion battery, successfully demonstrating the feasibility of recovering braking energy. The MATLAB/Simulink simulation predicted the energy recovery efficiency of up to 70 %, while the experimental test, although showing lower recovery due to real-world factors such as frictional losses and motor inefficiencies, validated the capability of the system to generate usable electrical energy, particularly at higher speeds. Overall, the results show that regenerative braking can enhance the energy efficiency and sustainability of electric motorcycles. Future improvements will focus on advanced energy storage, such as hybrid use of lithium-ion batteries, optimized control strategies using intelligent algorithms such as fuzzy logic or model predictive control, and refined hardware design to maximize recovery. In addition, reducing system weight and cost with lightweight materials, coupled with the internet of things (IoT) and artificial intelligence (AI). Based monitoring for predictive control will further improve practicality and performance. These advancements will contribute to making regenerative braking a more effective and scalable solution for sustainable urban transportation.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Ministry of Higher Education Malaysia for supporting this research. The authors also extend their appreciation to the Department of Mechatronics, Kulliyyah of Engineering, International Islamic University Malaysia, for their invaluable support in completing this research project.

FUNDING INFORMATION

This work was supported by the Ministry of Higher Education Malaysia for a research grant FRGS/1/2023/TK03/UIAM/01/1.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Faris Anwar Amir Faisal	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Siti Fauziah Toha	✓	✓					✓	✓	✓	✓	✓	✓	✓	✓
Nurul Muthmainnah Mohd Noor	✓			✓	✓					✓	✓			
Ahmad Syahrin Idris					✓		✓			✓		✓	✓	✓
Mohamad Osman Tokhi					✓		✓			✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest either in financial interests or personal relationships.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] N. A. Q. Muzir, M. R. H. Mojumder, M. Hasanuzzaman, and J. Selvaraj, "Challenges of electric vehicles and their prospects in Malaysia: A comprehensive review," *Sustainability*, vol. 14, no. 14, p. 8320, Jul. 2022, doi: 10.3390/su14148320.

[2] I. Energy Agency, "Global EV Outlook 2025 Expanding sales in diverse markets," 2025, [Online]. Available: www.iea.org

[3] F. Alanazi, "Electric vehicles: benefits, challenges, and potential solutions for widespread adaptation," *Applied Sciences*, vol. 13, no. 10, p. 6016, May 2023, doi: 10.3390/app13106016.

[4] R. K. Chidambaram *et al.*, "Effect of regenerative braking on battery life," *Energies*, vol. 16, no. 14, p. 5303, Jul. 2023, doi: 10.3390/en16145303.

[5] E. M. Szumska, "Regenerative braking systems in electric vehicles: a comprehensive review of design, control strategies, and efficiency challenges," *Energies*, vol. 18, no. 10, p. 2422, May 2025, doi: 10.3390/en18102422.

[6] I. Oyeyemi Olayode, E. Jamei, and F. Justice Alex, "Integration of e-bikes in public transportation based on their impact, importance, and challenges: A systematic review," *Multimodal Transportation*, vol. 4, no. 1, 2025, doi: 10.1016/j.multra.2024.100182.

[7] A. Teasdale, L. Ishaku, C. V. Amaechi, I. Adelusi, and A. Abdelazim, "A study on an energy-regenerative braking model using supercapacitors and DC motors," *World Electric Vehicle Journal*, vol. 15, no. 7, p. 326, Jul. 2024, doi: 10.3390/wevj15070326.

[8] T. Sutikno, N. S. Widodo, B. Santosa, R. A. Aprilianto, T. Wahono, and A. Pamungkas, "Design of an electrical regenerative braking system for e-bike applications," in *2023 10th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, Sep. 2023, pp. 428–432. doi: 10.1109/EECSI59885.2023.10295635.

[9] M. Gupta, "Evaluation of regenerative braking and its functionality in electric vehicles," in *2020 International Conference for Emerging Technology (INCET)*, Jun. 2020, pp. 1–6. doi: 10.1109/INCET49848.2020.9154047.

[10] C. Contò and N. Bianchi, "E-Bike motor drive: a review of configurations and capabilities," *Energies*, vol. 16, no. 1, p. 160, Dec. 2022, doi: 10.3390/en16010160.

[11] H. Guozhong, L. Wenzhao, G. Xuehong, X. Lingyun, W. Yan, and D. Honglei, "Advancing the regenerative braking systems of new energy vehicles: a comprehensive state-of-the-art review," *International Journal of Energy Research*, vol. 2025, no. 1, Jan. 2025, doi: 10.1155/er/3460776.

[12] M. S. Sharma, A. N. Singh, and R. Y. | A. J. | K. V. | M. Fahim, "Regenerative braking system," *International Journal of Trend in Scientific Research and Development*, vol. Volume-3, no. Issue-4, pp. 298–300, 2019, doi: 10.31142/ijtsrd23546.

[13] C. Yang, T. Sun, W. Wang, Y. Li, Y. Zhang, and M. Zha, "Regenerative braking system development and perspectives for electric vehicles: An overview," *Renewable and Sustainable Energy Reviews*, vol. 198, p. 114389, Jul. 2024, doi: 10.1016/j.rser.2024.114389.

[14] N. M. Jamadar and H. T. Jadhav, "Effectiveness of supercapacitor during braking operation of electric vehicle," *Materials Today: Proceedings*, vol. 56, pp. 314–319, 2022, doi: 10.1016/j.matpr.2022.01.168.
[15] H. Faghihian, M. Sarkar, and A. Sargolzaei, "A novel energy-efficient regenerative braking system for electric vehicles," in *SoutheastCon 2024*, Mar. 2024, pp. 1300–1305. doi: 10.1109/SoutheastCon52093.2024.10500159.
[16] B. Ashok *et al.*, "Model-based integrated control strategy for effective brake energy recovery to extend battery longevity in electric two wheelers," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 238, no. 9, pp. 2843–2864, Aug. 2024, doi: 10.1177/09544070231167616.
[17] Y. Yang, C. Wang, S. Yang, and X. Tang, "Study on top hierarchy control strategy of AEBS over regenerative brake and hydraulic brake for hub motor drive BEVs," *Energies*, vol. 15, no. 22, p. 8382, Nov. 2022, doi: 10.3390/en15228382.
[18] V. Vodovozov, Z. Raud, and E. Petlenkov, "Review on braking energy management in electric vehicles," *Energies*, vol. 14, no. 15, p. 4477, Jul. 2021, doi: 10.3390/en14154477.
[19] Y. Yao, Y. Zhao, and M. Yamazaki, "Integrated regenerative braking system and anti-lock braking system for hybrid electric vehicles & battery electric vehicles," *SAE International Journal of Advances and Current Practices in Mobility*, vol. 02, no. 3, pp. 2020-01–0846, Apr. 2020, doi: 10.4271/2020-01-0846.
[20] H. Liu, Y. Lei, Y. Fu, and X. Li, "Multi-objective optimization study of regenerative braking control strategy for range-extended electric vehicle," *Applied Sciences*, vol. 10, no. 5, p. 1789, Mar. 2020, doi: 10.3390/app10051789.
[21] Suyanto, P. A. Darwito, R. A. Wahyuono, M. S. Arifin, and B. Sudarmanta, "Design of regenerative braking system for electric motorcycle based on supercapacitor with fuzzy PID," *International Journal of Automotive Technology*, vol. 24, no. 1, pp. 187–194, Feb. 2023, doi: 10.1007/s12239-023-0017-6.
[22] K. K. Ramakrishna Pandian, T. Q. Dinh, and J. Marco, "Modelling and brake blending control for multi-drive mode electric two-wheelers," in *2021 24th International Conference on Mechatronics Technology (ICMT)*, Dec. 2021, pp. 1–6. doi: 10.1109/ICMT53429.2021.9687134.
[23] M. H. Hwang *et al.*, "Regenerative braking control strategy based on AI algorithm to improve driving comfort of autonomous vehicles," *Applied Sciences*, vol. 13, no. 2, p. 946, Jan. 2023, doi: 10.3390/app13020946.
[24] J. D. Valladolid and J. Macas, "A proposed strategy for the optimal control of regenerative braking in electric vehicle based on driving style," in *2023 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Oct. 2023, pp. 1–5. doi: 10.1109/VPPC60535.2023.10403205.
[25] P. Saiteja, B. Ashok, A. S. Wagh, and M. E. Farrag, "Critical review on optimal regenerative braking control system architecture, calibration parameters and development challenges for EVs," *International Journal of Energy Research*, vol. 46, no. 14, pp. 20146–20179, Nov. 2022, doi: 10.1002/er.8306.
[26] A. Boretti, "Analysis of the regenerative braking efficiency of a latest electric vehicle," in *8th SAEINDIA International Mobility Conference & Exposition and Commercial Vehicle Engineering Congress 2013 (SIMCOMVEC)*, Nov. 2013. doi: 10.4271/2013-01-2872.

BIOGRAPHIES OF AUTHORS

Faris Anwar Amir Faisal received the degree of Bachelor of Engineering in Mechatronics (B.Eng.) from the International Islamic University Malaysia (IIUM) in 2025. His final year project focused on the development of a Regenerative Braking System (RBS) for an E-bike, where he designed the sub-model and simulated an energy recovery system using MATLAB Simulink to improve energy efficiency by storing recovered braking energy in a secondary Li-Po battery. He completed his industrial internship with Malaysian Refining Company in 2024, where he contributed to equipment reliability strategy, SAP maintenance optimization, and automation of large-scale asset data validation using Excel VBA. His academic and independent projects include gesture-controlled applications, real-time object detection using YOLOv8 on Jetson Orin Nano, CycleGAN-based image style transfer, and a cyberbullying detection chatbot with BERT. His research interests include artificial intelligence, machine learning, computer vision, automation systems, and intelligent energy management in electric mobility. He can be contacted at email: frsanwr2002@gmail.com.

Siti Fauziah Toha is currently a professor in artificial intelligence at the Department of Mechatronics Engineering, International Islamic University Malaysia (IIUM). She received B.Eng. (Hons) in Electrical and Electronics Engineering from University Technology Petronas and received M.Sc. from Universiti Sains Malaysia in electrical engineering. She then completed her Ph.D. in Automatic Control and Systems Engineering from the University of Sheffield, UK. She specializes in modelling and analysis of complex systems (MACS), control algorithms and artificial intelligence optimization, assistive devices and bio-inspired robotics, electric vehicles and green renewable energy. She is currently appointed and serves on the Engineering Accreditation Council Panel by the Board of Engineers Malaysia (BEM) within her capacity as a professional engineer. She is also a Chartered Engineer (C.Eng.) registered by the Engineering Council with the Institution of Engineering and Technology (IET), UK. She is appointed as a visiting professor at London South Bank University, UK, and the University Tun Hussein Onn, Malaysia. She has also shown her strong capability in research and is extensively involved in 45 projects handling a total of RM 3.5 million grants as principal researcher as well as co-researcher spanning over national, international, industrial, and societal related grants with more than 100 paper publications with 16 H-Index (Scopus). As the recipient of the IIUM Most Promising Academic Award 2019, she also won various gold medals and special awards for prestigious innovation in MTE, PECIPTA, and IMDC, with 7 patents filed. She is crowned winner of the 3rd KANS Scientific Competition 2022, in the Field category of ICT and AI. She is currently the vice president of PERINTIS Malaysia, which is a registered Scientist organization in Malaysia. She has also been actively involved with the Young Scientist Network (YSN-ASM) and appointed as the secretariat for the Academy of Sciences Malaysia (ASM) Energy Committee and the ASM MyNet Zero Task Force, comprising a synergy of activists advocating Energy Sustainability and working toward Net Zero RESET (Net Zero Emission for a Resilient Society by 2050) as a solution to climate resilience. Before that, she was involved in review and formulation for Malaysia's National Policy of Science, Technology, and Innovation (NPSTI) 2021-2030. She can be contacted at email: tsfauziah@iium.edu.my.

Nurul Muthmainnah Mohd Noor received the degree of Bachelor of Engineering in Mechatronics (B.Eng) from the International Islamic University Malaysia (IIUM) in 2007 and the Master of Science (M.Sc.) from the same university in 2013 in Mechatronics. She is currently pursuing a Ph.D. degree with the Department of Mechatronics Engineering, IIUM. However, she has been a lecturer at Universiti Teknologi MARA Cawangan, Pulau Pinang, under the Mechanical Faculty since 2013. During the lecturer, she got a few research grants from the Minister of Higher Education, Malaysia. She also supervised almost 30 students under the Final Year Project at UiTM. Most projects related to the rehabilitation projects, for example, modelling the wheelchair using EOG, and the latest project related to an autonomous project. Her research interests include signal processing, control systems, bioengineering for rehabilitation purposes, and autonomous robots. She can be contacted at email: nurul.muth@gmail.com.

Ahmad Syahrin Idris received the B.Eng. degree (Hons.) in electrical and electronics engineering from University Technology PETRONAS, Malaysia, in 2003, the M.Phil. degree in electronic and electrical engineering from The University of Sheffield, UK, in 2011, and the Ph.D. degree in opto-electronics from Kyushu University, Japan, in 2018. After the B.Eng. degree, he joined Intel as a Product Development Engineer, specializing in developing design-for-test solutions for Intel chipset products. While in the UK, he was a researcher with the University of Sheffield, specializing in the fabrication and characterization of III-V semiconductors for APD and PIN photodetectors. After the M.Phil. degree, he joined Freescale Semiconductor as a senior test development engineer, developing test solutions for automotive and industrial microcontrollers. He is currently an Assistant Professor and the Deputy Head of the School of Electrical and Electronic Engineering, University of Southampton Malaysia (UoSM). He is also a professional engineer with the Board of Engineers Malaysia and the Institute of Engineers, Malaysia. His current research interests include the fabrication and characterization of opto-electronic devices and developing design-for-test solutions for microelectronic circuits. He can be contacted at email: a.s.idris@soton.ac.uk.

Mohamad Osman Tokhi obtained his B.Sc. (electrical engineering) from Kabul University (Afghanistan) in 1978 and Ph.D. from Heriot-Watt University (UK) in 1988. He also is a Chartered Engineer, Fellow of IET (Institution of Engineering and Technology), Senior Member of IEEE (Institute of Electronic and Electrical Engineering), and Member of IIAV (International Institute of Acoustics and Vibration) and of CLAWAR (Climbing and Walking Robots) Association. He has worked in various academic positions and in the industry. He is currently Professor of Robotics in the School of Engineering, London South Bank University (UK). His main research interests include active control of noise and vibration, adaptive/intelligent control, assistive robotics, soft computing techniques for modelling and control of dynamic systems, and high-performance real-time computing. He has published extensively and has executed numerous research projects to successful completion in these areas. He can be contacted at email: tokhim@lsbu.ac.uk.