

Research Paper

Optimised Flywheel-Assisted Regenerative Braking for Enhanced Energy Recovery and Voltage Stability in Electric Vehicles

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Abstract

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This study presents a flywheel-assisted regenerative braking system (FARBS) designed to improve energy recovery and voltage stability in electric vehicles (EVs). Conventional regenerative braking systems (RBS) suffer from short energy retention durations and voltage fluctuations, limiting their efficiency. The proposed system incorporates a spherical shell flywheel (120 mm radius, 20 mm thickness, 3 kg mass) directly into the braking mechanism to prolong energy recovery and optimise braking efficiency. Experimental results demonstrate a 439% increase in energy recovery duration, extending from 1.15 seconds (2000 RPM) to 6.2 seconds (4500 RPM). Voltage retention improves significantly, increasing from 10.3V to 19.2V, (ensuring sustained voltage delivery). Kinetic energy storage attains 580 J at 4500 RPM, exhibiting a 23.4% increase over 2000 RPM. The flywheel system quadruples power output longevity, sustaining 6.40 W for 6.2 seconds at 4500 RPM, compared to 2.2 seconds without the flywheel. Energy recovery efficiency peaks at 15 16 J at 4500 RPM, an improvement of 275% in comparison to the baseline 4 J. Optimisation analysis confirms that increasing flywheel mass (1 kg to 3 kg) improves energy recovery by 194%, while a spherical shell flywheel improves energy recovery, achieving 327 J. This is twice as much as that of a solid disk (162 J). Carbon fibre outperforms steel, boosting energy recovery by 94%, while increasing the thickness from 10 mm to 20 mm, and resulting in a 200% efficiency gain. These findings underline the superiority of flywheel-assisted energy recovery, paving the way for high-efficiency braking solutions in EVs, public transportation and railway networks.

Keywords: Flywheel energy storage; Braking efficiency; Energy efficiency; Regenerative braking

1. Introduction

A shift towards sustainable energy-efficient transportation is taking place, with electric and hybrid vehicles (EVs and HEVs) being adopted as sustainable options in comparison to internal combustion engine vehicles (ICE) [1]. The environmental advantages attributed to these vehicles encounter various challenges regarding energy efficiency predominantly in brake-related energy recovery systems. Braking systems applying conventional methods transform kinetic

energy into heat by means of friction in order to lose substantial amounts of this particular energy. RBS convert braking energy into electrical power for reuse, although they experience brief braking occurrences in conjunction with sudden kinetic energy loss which reduces energy storage potential. Regenerative braking is essential for energy recovery that exists in electric vehicle designs to increase efficiency by reconverting kinetic energy into reusable electrical energy using a regenerative braking system. **Figure 1** schemati-

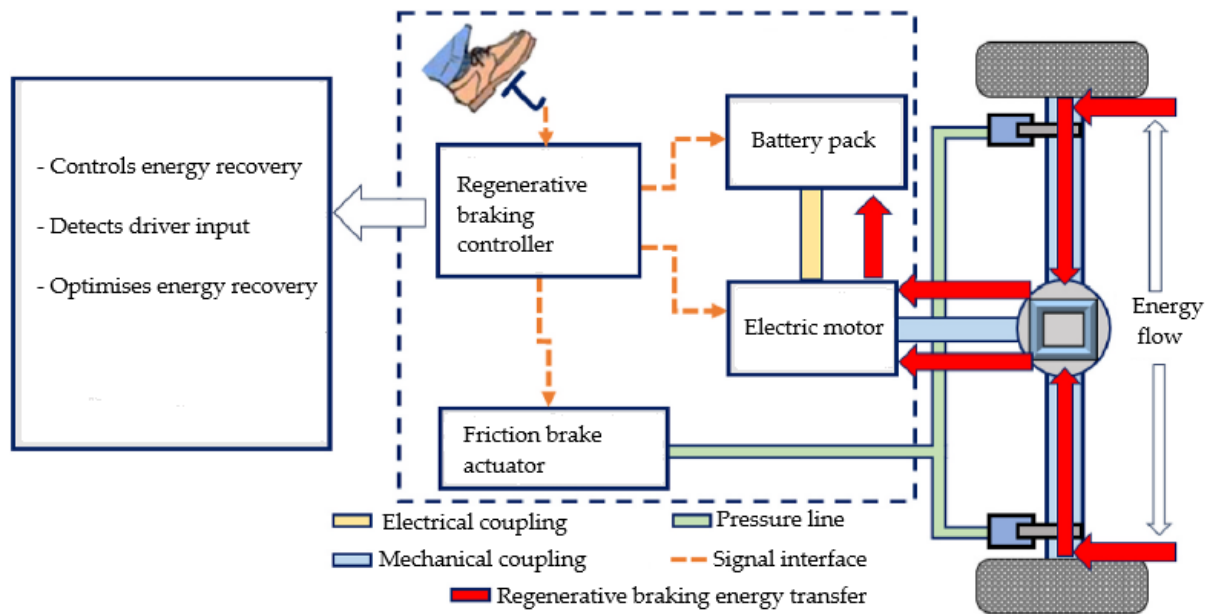


Figure 1. Conventional regenerative braking system for EVs

cally represents the actual system, explaining how it interacts with the main components of the regenerative braking control unit, electric motor, friction braking actuator, as well as the battery pack. Having pressed the braking pedal, the driver will subsequently apply an input for the system control unit and optimally allocate regenerative and friction components at dispersed braking force applications. The electric motor works similar to a generator, recapturing the kinetic energy and converting it into electrical energy, which is returned to the vehicle battery pack. The system enables the coordination of continuous energy recovery-and-braking, improving the efficacy of the vehicle and prolonging battery life, whilst it is also beneficial in terms of energy efficiency in modern EVs.

The implementation of Flywheel Energy Storage (FES) represents a promising solution to boost regenerative braking for the reason that it substitutes mechanical storage as opposed to battery-based technology [2]. The operating benefits connected with flywheels include rapid energy storage together with quick release capabilities, as well as long-term functionality in powerful applications [3]. The addition of a flywheel storage unit together with the braking mechanism enables the storage of excess kinetic energy prior to its gradual release, extending the energy recovery duration and increasing braking efficiency.

Several studies have explored techniques to improve regenerative braking performance. Electric bus energy management strategies were examined by Kusuma *et al.* [4], while Yang *et al.* [5] investigated storage limitations in conventional RBS. Flywheel–battery hybrid systems were developed by Zheng *et al.* [6], and Wang *et al.* [7], with the aim of reducing battery stress and improving energy recovery. The integration challenges were subsequently emphasised by Erhan and Özdemir [8] in a high-speed flywheel prototype. Hamada and Orhan [9] drew attention to the significance of improved storage strategies and Fayad *et al.* [10] demonstrated fuel savings in diesel-electric train applications. A flywheel-based RBS for traction substations which enhances power quality and energy stability was proposed by Li *et al.* [11]. In their study, Li *et al.* [12] produced an Electromagnetic Coupling Flywheel Energy Storage System that improves vehicle acceleration by way of electric drive procedures. Braking energy storage inside the Flywheel Energy Regenerative Capture System created by Budijono *et al.* [13] permits improved system efficiency. Jackiewicz [14] developed a RBS system for a train, equipped with a Continuously Variable Transmission to attain adaptive braking under high-load conditions.

Various studies have assessed regenerative braking performance across different applications. Qiu and Wang [15] found that serial

control strategies can boost braking efficiency above 50%. Itani *et al.* [16] reported that hybrid systems with ultracapacitors recover up to 32% of energy under severe braking, compared to 28% for flywheel-only systems. Sun *et al.* [17] achieved a 60% improvement in energy reuse in urban rail through battery–flywheel system optimization. More recent works have focused on system architectures [18], adaptive MPC for marine hybrid storage [19], structural modeling of composite flywheel rotors [20], and national-scale FES development [21]. However, these studies often overlook direct integration into compact EV braking systems.

While traditional regenerative braking converts kinetic energy into electricity, it remains limited by short braking durations and energy losses. Hybrid flywheel–battery systems have shown potential to reduce battery stress and improve energy retention. Nevertheless, most studies focus on complex hybrid configurations, which can complicate system integration and energy management. There remains a lack of experimental studies on mechanically integrated, flywheel-based regenerative systems tailored for EVs.

This study addresses these gaps by experimentally investigating a flywheel-assisted regenerative braking system operating between 2000 and 4500 RPM, using a spherical shell flywheel directly coupled to the braking mechanism. The system is designed to reduce

transformation losses and extend energy retention. Key design parameters include the flywheel's mass, moment of inertia, material, and shape. A supporting mathematical model predicts voltage behavior, enabling scalable applications in electric vehicles, public transit, and railway networks.

2. Methodology

This research develops and implements a flywheel-enhanced regenerative braking system, which attains significant energy recovery, maintains stable voltage and delivers improved braking. The system contains a flywheel coupled with an electric motor which operates with a generator and brake unit to produce kinetic energy to be stored and dissipated during braking operations.

2.1. System Design and Components

The combination of mechanical braking and electrical braking is illustrated in Figure 2, demonstrating the proposed system with respect to maximum energy recovery. The system regulates the combination of mechanical and regenerative braking methods by distributing kinetic energy between the battery pack storage in addition to delivering temporary storage in the flywheels. The transmission system together with the differential mechanism controls the energy flow so as to support routine operation.

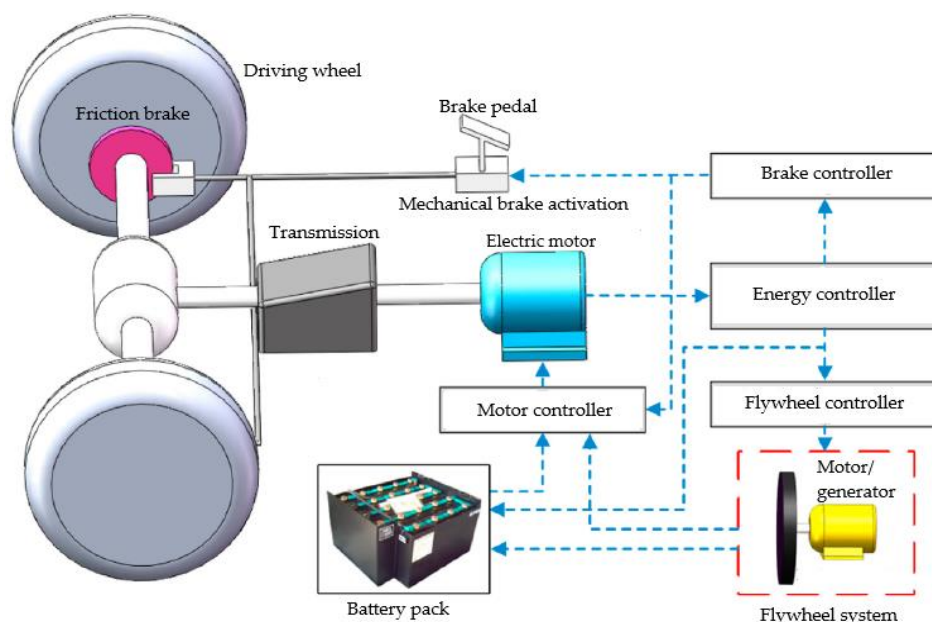


Figure 2. Proposed regenerative braking system

Key components of the system include:

- **Flywheel:** A cast iron flywheel (122 mm diameter, 12 mm thickness, 1.4 kg mass) designed to store and release kinetic energy efficiently.
- **Gear System:** A 4.1:1 ratio gear mechanism to optimise torque transfer and ensure the operation of the flywheel at high-speed.
- **Generator:** A 12V generator producing power at 1400 RPM, converting mechanical energy from the flywheel into electrical energy.
- **V-Belt Drive:** Facilitates controlled energy transfer, reducing mechanical stress and permitting smooth operation.
- **Control Unit:** Regulates the engagement and disengagement of the flywheel and generator, optimising energy flow.
- **Ball Bearings:** Reduce friction, ensuring efficient rotation and minimal energy losses.

The layout of the components is illustrated in [Figure 3](#), which provides a detailed view of how the flywheel system integrates with the regenerative braking setup.

The braking operation transfers wheel energy to the flywheel-generator assembly which stores the power prior to gradually releasing it. The system prolongs the power generation time while conventional regenerative braking methods waste energy rapidly. During braking, the system transfers wheel rotational energy to the flywheel which continues to move, while continuing power production when braking ends. This controlled braking deceleration method immediately stops the loss of power while increasing the efficiency in terms of energy recovery. The system achieves its most significant improvements in energy maintenance and voltage stabilising capabilities at ranges from 3500 to 4500 RPM, whereas ours ranges from 2000 to 4500 RPM. The essential

system components together with their operational functions are explained in [Table 1](#).

2.2. Experimental Procedure

To evaluate the performance of the flywheel-assisted regenerative braking system, tests were performed using a motor-driven test rig ([Figure 3](#)). The system underwent assessments at five different RPM rates starting from 2000 to 4500, in order to examine its performance in prolonging energy recovery, voltage stabilisation and improving braking efficiency. The data acquisition system measured the main system metrics which included energy recovery duration along with simultaneous measurements of the output voltage, kinetic energy storage and power decay rate. The tests employed a digital tachometer as a speed reader and a voltmeter which delivered time-based voltage measurement tracking with $\pm 0.1V$ precision. The tests were completed three times at each rotational speed to guarantee precision and the reproducibility of the results. The results of the tests revealed that the flywheel system extended the power recovery time and stabilised the voltage output, in contrast to the standard regenerative braking. The system operated at higher RPMs to extend the voltage delivery time, improving power delivery and the use of braking energy.

2.3. Uncertainty Analysis

The system underwent assessments at five different RPM rates between 2000 and 4500 RPM, in an attempt to examine how it performed in relation to prolonging energy recovery, voltage stabilisation and generating improvements in braking efficiency. The results presented in [Table 2](#) demonstrate that the energy recovery duration extended as the RPM increased from 1.15 seconds

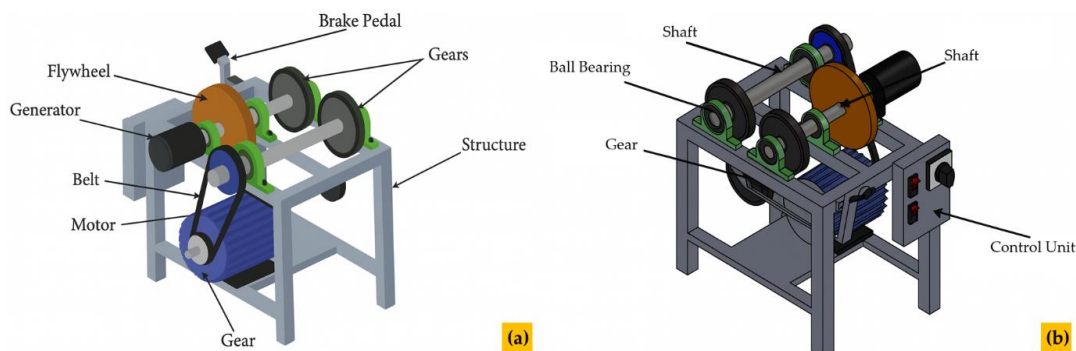


Figure 3. Layout of the components employed in the flywheel-assisted regenerative braking system: (a) Front view; (b) Side view

Table 1. Functions of system components

System Category	Component	Function
Power Transmission System	Gears	Transfers kinetic energy between the braking mechanism, flywheel and generator.
	Belt	Facilitates smooth and controlled energy transfer while allowing slippage to prevent mechanical stress.
	Gear Ratio	Optimises torque transmission, ensuring the flywheel spins at high speed to achieve efficient energy storage.
Energy Storage and Conversion System	Flywheel	Absorbs excess kinetic energy during braking and gradually releases it, extending power generation.
	Generator	Converts rotational energy from the flywheel into electrical power (12V at 1400 RPM indicating that the range is lower than 2000 RPM).
	Motor	Simulates vehicle motion and transfers kinetic energy to the flywheel (operates up to 4500 RPM).
Control and Stability System	Pedal Brake (Mild Steel)	Works as the mechanical trigger for regenerative braking, directing energy into the flywheel.
	Control Unit (Plastic)	Manages the engagement and disengagement of the flywheel and generator, optimising energy distribution.
	Ball Bearings (Mild Steel)	Reduces friction and energy losses while ensuring smooth rotational movement.
Structural and Support Framework	Solid Bars (Chilled Cast Iron)	Ensures structural support and alignment under high-speed operation.
	Main Structure (Mild Steel)	Provides a rigid framework for each component in the system, ensuring overall stability.

Table 2. Uncertainty analysis of key experimental parameters

Rotational Speed (RPM)	Energy Recovery Duration (s)	Uncertainty in Duration (s)	Voltage Output (V)	Uncertainty in Voltage (V)	Kinetic Energy (J)	Uncertainty in Kinetic Energy (J)
2000	1.15	±0.05	10.3	±0.2	57.13	±2.86
2500	2.85	±0.05	12.5	±0.2	89.27	±3.57
3000	3.80	±0.05	14.7	±0.2	128.55	±4.29
3500	4.70	±0.05	16.8	±0.2	174.97	±5.00
4500	6.20	±0.05	19.2	±0.2	289.24	±6.43

at 2000 RPM to 6.20 seconds at 4500 RPM, with an uncertainty of ±0.05 seconds. This confirmed that increased flywheel energy storage resulted in extended power generation. The recorded voltage output exhibited an identical increase in the pattern in comparison to the test RPMs, for the reason that it began at 10.3V at 2000 RPM and ended at 19.2V at 4500 RPM. It demonstrated a steady uncertainty level of ±0.2 V to support continuous power generation. In relation to the kinetic energy storage, the quadratic pattern began at 57.13J at 2000 RPM. Subsequently, it rose to 289.24J at 4500 RPM, as the differences in angular velocity uncertainties increased from ±2.86 J to ± 6.43 J during the increase in speed. Basically, the pattern of the results demonstrated stability due to the flywheel energy recovery and voltage stability with minor measurement

uncertainties that remain within defined acceptable boundaries. The kinetic energy (E) stored in the flywheel was measured as follows Eq. (1) [22].

$$E = \frac{1}{2}I\omega^2 \quad (1)$$

where $I = 0.002605 \text{ kg.m}^2$ is the flywheel's moment of inertia. Propagation of uncertainty in kinetic energy was calculated using Eq. (2) [22].

$$\frac{\Delta E}{E} = 2 \cdot \frac{\Delta \omega}{\omega} \quad (2)$$

To quantify the uncertainty in kinetic energy measurements, propagation of error was applied based on Eq. (1). The uncertainty in I was estimated at ±1.2% based on material density and geometric tolerances of the flywheel, while the angular velocity uncertainty—derived from

tachometer resolution—was $\pm 1.0\%$. Applying standard propagation rules, the overall uncertainty in kinetic energy was calculated as $\pm 2.5\%$. This combined error accounts for measurement variability and ensures that the reported energy values are within reliable bounds across all test conditions.

The kinetic energy values presented in Table 2 reflect the theoretical energy stored in the flywheel based on its rotational speed. However, not all input energy is effectively retained; a portion is lost due to mechanical inefficiencies such as bearing friction, belt slip, and generator loading. These losses become more prominent at higher speeds but remain within expected ranges [23]. Based on multiple experimental runs and sensor precision, the uncertainty margin for kinetic energy data is estimated at $\pm 2.5\%$. The observed trend confirms that the majority of the energy input is stored kinetically, with losses accounting for a minor but consistent fraction across RPMs.

The stated uncertainty margins reflect multiple sources of error. For energy recovery duration (± 0.05 s), the primary contributor was the sampling rate of the data acquisition system and operator reaction time when marking endpoints. Voltage uncertainty (± 0.2 V) arises from the resolution and calibration accuracy of the digital voltmeter used during tests. The kinetic energy uncertainty (± 6.43 J), discussed earlier, results from combined errors in moment of inertia estimation and tachometer-based angular velocity readings. Environmental factors such as temperature and mechanical vibration were monitored and kept consistent to minimize their influence. Overall, these uncertainty bounds are considered acceptable for this type of regenerative braking test rig and support the validity of the performance trends reported.

3. Governing Equations

In this section, the fundamental equations that govern the operation and performance of the flywheel-assisted regenerative braking system are presented. The mathematical descriptions relating to the parameters associated with power generation, energy recovered, voltage stabilisation, torque, kinetic energy, as well as the efficiency of the system were introduced.

3.1. Power Calculation

The electrical power generated during regenerative braking is determined using Ohm's Law as follows Eq. (3) [24].

$$P = \frac{V^2}{R} \quad (3)$$

where, P is the instantaneous power (W); V is the system voltage (V); R is the electrical resistance (Ω).

3.2. Flywheel kinetic energy

The kinetic energy stored in the flywheel is given by Eq. (4) [22].

$$E_k = \frac{1}{2} I \omega^2 \quad (4)$$

where, E_k is the kinetic energy stored in the flywheel (J); I is the flywheel's moment of inertia (kg.m^2); ω is the angular velocity (rad/s).

3.3. Energy Recovery Efficiency

The efficiency of energy recovery is a significant metric in regenerative braking systems. It is defined as Eq. (5).

$$\eta = \frac{E_{\text{recovered}}}{E_{\text{input}}} \times 100\% \quad (5)$$

where $E_{\text{recovered}}$ is the total energy successfully recovered during braking (J), and E_{input} is the initial kinetic energy available for recovery (J).

3.4. Flywheel Torque

The torque generated by the flywheel is calculated as follows Eq. (6) [25].

$$T = J\alpha = J \frac{d\omega}{dt} \quad (6)$$

where, T is the flywheel torque (N.m); I is the moment of inertia (kg.m^2); ω is the angular velocity (rad/s); α is the angular acceleration (rad/s^2).

3.5. Energy Recovery Dynamics and Time-dependent Analysis

The relationship between energy recovery and time is fundamental to assess the performance of the flywheel-assisted regenerative braking system. The governing equations in relation to the interaction between the energy capture processes, storage and dissipation over time are presented.

3.5.1. Instantaneous Energy Calculation

The electrical energy recovered at any given time t is determined by Eq. (7) [26].

$$E(t) = \frac{V^2(t)}{R} \quad (7)$$

where, $E(t)$ is the instantaneous recovered energy (J); $V(t)$ is the voltage at time t (V); R is the electrical resistance (Ω).

3.5.2. Cumulative Energy Recovery using Numerical Integration

The total amount of energy recovered is given by integrating instantaneous energies during the braking period as follows Eq. (8) [26].

$$E(t) = \int_{t_0}^{t_f} \frac{V^2(t)}{R} dt \quad (8)$$

where E_{total} is the total energy recovered over time (J), while, t_0 and t_f are the start and end times of the braking process. Due to the problems connected with calculating continuous integration directly, a numerical approximation is used to calculate the integral as follows Eq. (9) [26].

$$E(t_i) = \sum_{i=1}^N \frac{(E_i + E_{i-1})}{2} \Delta t \quad (9)$$

where, N is the total number of time steps; E_i is the energy recovered at the i^{th} time step; Δt is the time interval between measurements.

3.6. Voltage Stability Analysis

Statistical evaluation is employed to evaluate the voltage stability by calculating the risk of voltage collapse, identifying weak nodes, as well as analysing the impact of uncertainties, such as fluctuations in demand and supply. The standard deviation σ describes the time-based voltage variation using the following relationship Eq. (10) [27].

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_i - \bar{V})^2} \quad (10)$$

where, N is the total number of voltage samples; V_i is the voltage at the i^{th} time step; $\bar{V}$ is the mean voltage over the time period.

3.7. Energy Recovery Rate

The energy recovery rate ($\dot{E}$) is the rate at which electrical energy is generated and

recovered during braking. It is calculated as follows Eq. (11).

$$\dot{E} = \frac{dE}{dt} \quad (11)$$

The equation determines the speed of braking system energy transfer in relation to either storage in the flywheel or electrical storage systems including batteries or ultracapacitors. Given that energy recovery occurs discretely during braking, the formulation of the adjusted energy $\dot{E}$ is approximated using the following finite difference method Eq. (12).

$$\dot{E}_i = \frac{E_i - E_{i-1}}{\Delta t} \quad (12)$$

where, E_i is the total recovered energy at time step i ; E_{i-1} is the recovered energy at the previous time step.

3.8. Power Decay Model

The power decay model specifies how the power dissipates with time after applying regenerative braking. The following equation is used to calculate the power decay rate Eq. (13) [28].

$$\frac{dP}{dt} = \frac{d}{dt} \left(\frac{V^2(t)}{R} \right) = \dot{P} \quad (13)$$

where $\dot{P}$ represents the rate at which power decreases over time. Using a numerical approach, the discrete form is in line with Eq. (14) [28].

$$\frac{dP}{dt} \approx \frac{P_{i+1} - P_i}{\Delta t} \quad (14)$$

3.9. Energy Stored, Lost and Recovered

The stored energy within the flywheel depends on both its rotatory speed and its moment of inertia, which can be evaluated by way of Eq. (15) [29].

$$E_{stored} = \frac{1}{2} I (\omega_f^2 - \omega_i^2) \quad (15)$$

Where, E_{stored} is the kinetic energy stored in the flywheel (J); I is the flywheel's moment of inertia ($kg.m^2$); ω_f is the final angular velocity (rad/s) at the end of braking; ω_i is the initial angular velocity (rad/s) prior to the start of braking.

Kinetic energy stored in flywheels requires conversion to electrical energy before it can be reused. The total recover energy can be defined as Eq. (16) [29].

$$E_{recovered} = \sum_{i=1}^N \frac{V_i^2}{R} \Delta t \quad (16)$$

where, $E_{recovered}$ is the total energy successfully captured (J); V_i is the voltage output at time step i (V); R is the system resistance (Ω); Δt is the time interval between measurements.

The energy stored in the flywheel is not completely recovered. Essentially, part of it is lost (E_{lost}) due to various inefficiencies, which can be expressed by Eq. (17).

$$E_{lost} = E_{input} - E_{recovered} \quad (17)$$

4. Results and Discussion

The results of the experimental analysis reveal important information regarding how adding flywheels affects both regenerative braking performance and power generation length, as well as voltage stability and energy recovery effectiveness. Testing of the system occurred under five distinct motor speeds (2000, 2500, 3000, 3500 and 4500 RPM), with the intention of evaluating its performance at different operational speeds. The energy recovery duration was measured using a high-resolution voltage data logger (10 Hz sampling rate) connected across the battery terminals and synchronized with a tachometer signal from the flywheel shaft. Recovery duration was defined as the time interval during which the flywheel delivered positive torque to the generator, indicated by sustained voltage above baseline idle levels [30]. The logging system was triggered at the moment of brake actuation, and recovery was considered complete when the voltage stabilized to its pre-braking state. Each test was repeated three times per RPM setting to ensure consistency, and the reported values represent the average. This method captures the actual energy retention period while accounting for system response and electrical stabilization, ensuring both reliability and reproducibility of the measurement.

4.1. Voltage Decay Over Time

Figure 4 explains the relationship between voltage and time for different RPMs with and without the flywheel, emphasising significant improvements in energy retention when using the FARBS. At 2000 RPM, the flywheel system

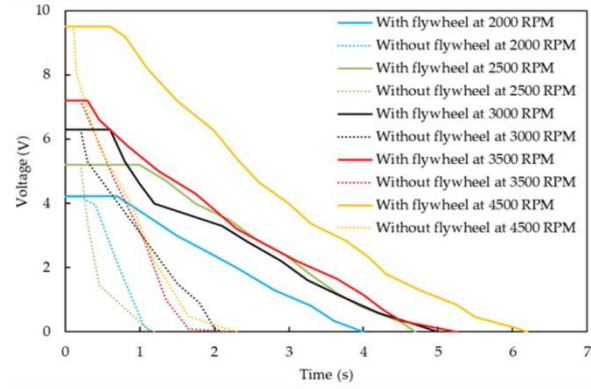


Figure 4. Voltage decay over time for various RPMs

maintains voltage for approximately 4 seconds, whereas the system without the flywheel drops to zero at 1.15 seconds. This represents a 247% increase in energy retention time, underlining the flywheel's role in sustaining power delivery. At 2500 RPM, the flywheel system increases voltage generation to 4.7 seconds compared to 1.2 seconds without it, demonstrating an improvement of 292%. Voltage levels remain stable at approximately 5.2 V initially before gradually dropping, while the non-flywheel system exhibits a sharp drop. At 3000 RPM, voltage generation lasts 5 seconds with the flywheel and 2.1 seconds without, doubling the retention period. The flywheel system maintains higher voltage levels for longer, with an initial 6.3 V that decreases linearly, unlike the rapid decline observed without the flywheel. At 3500 RPM, the voltage in the flywheel remains for 5.25 seconds compared to 2.2 seconds without, an increase of 139%. The flywheel system stabilises voltage output around 7.2V initially, providing smoother power delivery. At 4500 RPM, the flywheel system sustains the voltage for 6.2 seconds, whereas the system without the flywheel continues for only 2.2 seconds, exhibiting an improvement of 181%. The voltage remains above 8V initially, demonstrating the flywheel's efficiency at higher speeds.

4.2. Power Decay Over Time

The power decay over time for different RPMs with and without the flywheel mechanism is shown in Figure 5. Considering the system resistance of 10 Ω , the flywheel system consistently delivers higher power and is able to sustain it for longer durations at each RPM level, in

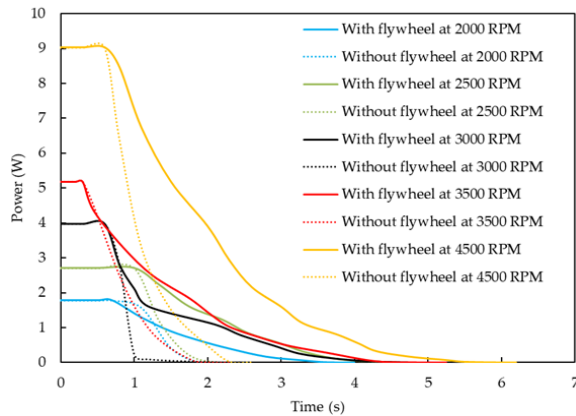


Figure 5. Power decay over time for various RPMs

contrast to the system without the flywheel system. At 2000 RPM, the flywheel system maintains power for approximately 4 seconds with a peak of 1.79 W, whilst the system without the flywheel lasts only 1.15 seconds at 1.76 W. This extended duration converts to a 254% increase in total energy output. At 2500 RPM, both systems start at 2.70 W, but the flywheel system sustains this power for 4.7 seconds, delivering 12.69 J, whereas the system without the flywheel system drops to 0 W after 1.2 seconds, delivering only 3.12 J. At 3000 RPM, the flywheel system produces 3.97 W for 5 seconds, resulting in 19.85 J of total energy, more than triple the 5.26 J generated by the system without the flywheel system, which continues for just 2.1 seconds. At 3500 RPM, the flywheel system attains 5.18W and maintains it for 5.25 seconds, delivering 24.22 J, compared to 6.29 J from the system without the flywheel system. At 4500 RPM, the flywheel system exhibits the highest power output of 6.40 W over 6.2 seconds, achieving 39.68 J, more than quadruple the 8.94 J from the system without the flywheel. The measured power output duration of 6.2 seconds at 4500 RPM exceeds typical emergency braking durations in real-world driving, which generally range from 2 to 4 seconds depending on vehicle speed and road conditions. This extended endurance highlights the system's potential to supply consistent regenerative power during full braking cycles. The flywheel system not only maintains higher output power but also sustains it longer than conventional setups, which is critical for braking safety, especially in scenarios requiring prolonged deceleration or energy buffering.

4.3. Impact of Integrating the Flywheel on Energy Recovery

Figure 6 displays the power generation duration at different rotational speed levels from 2000 to 4500 RPM. It was determined that the power generation from the system without a flywheel immediately decreased at 2000 RPM while the energy retrieval process lasted 1.15 seconds. The integration of the flywheel enabled the power output duration to extend to 2.85 seconds, resulting in an improvement of 147% in the energy recovery period. Whilst operating the system at 4500 RPM, the flywheel-enhanced system achieved extended energy recovery of 6.2 seconds. However, the conventional system could only recover energy for 1.5 seconds therefore resulting in an improvement in energy use of more than 300%. The experimental results confirm that the flywheel system stores the kinetic energy appropriately until it is gradually released during the power generation cycle. Consequently, this leads to an extended operational time and greater system efficiency.

4.4. Energy Generated at Different RPMs

The energy recovery efficiency in FARBS relies upon rotational speed, as depicted in **Figure 7**. The energy recovery rate demonstrates slower movement at RPMs of 2000 and 2500, given that the recovery attains only 3.2 J and 4.5 J after 2.5 seconds. Due to the flywheel's low rotational inertia, the system requires more time to store energy. The system extends its energy recovery duration from 2.5 seconds while operating at RPMs of 3000 and 3500, delivering energy values of 6.8 J and 8.1 J. The higher speeds allow the flywheel to store more kinetic energy efficiently, as the energy is stored within the system. Whilst operating at 4500 RPM, the system captures its maximum amount of energy totalling 17.5 J across 2.5 seconds. The increased rotational inertia at this speed boosts the flywheel's ability to capture and sustain energy more effectively. The system displays an efficient braking energy utilisation mechanism at high speeds owing to its ability to stabilise the voltage and generate more consistent energy storage methods. The observed trend portrays how higher RPM rates give rise to improved energy recovery together with system

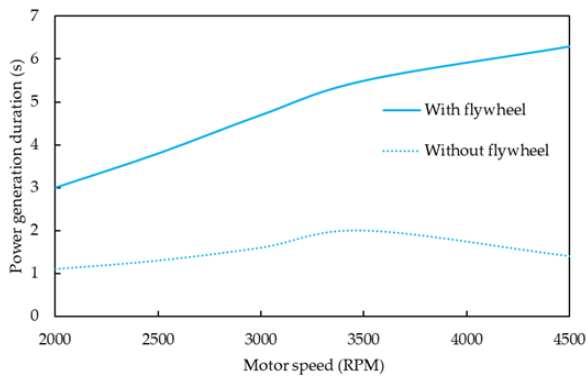


Figure 6. Power generation duration

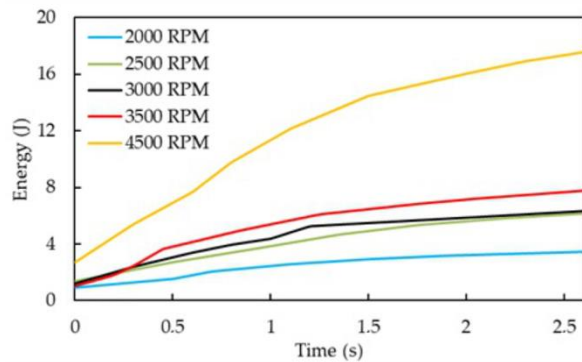


Figure 7. Energy generated at different RPMs

stability, optimising braking power use specifically in rapid electric vehicles.

4.5. Voltage Stability at Different RPMs

The voltage stability measurements in terms of the flywheel-assisted regenerative braking system (FARBS) under various rotational speed conditions are illustrated in Figure 8. At higher speeds, the flywheel maintains more stable and higher voltage output before a gradual decline caused by energy losses. From the initial 0.5 seconds at 4500 RPM until 2.5 seconds, the system sustains 9.8V until reaching a final voltage of 6.5V. Starting at 7.2V, the system regulates voltage during braking at 3500 RPM, while the voltage drops to 5.2V by the end of braking. The system maintains voltage more effectively because higher rotational inertia at increased speeds enhances power delivery. When operating at reduced RPM speeds, the voltage fails to stabilise sufficiently. During the first 0.7 seconds, the output voltage drops from 6.0V to 4.2V at 3000 RPM. When operated at 2500 RPM, the system begins at 5.1V prior to establishing a steady drop-down to 3.9V. However, the 2000 RPM test exhibits the worst voltage stability, as it starts at 4.0V, then decreases

rapidly to 2.5V. Additionally, RPM levels above 3000 contribute to improved voltage stability through their ability to minimise fluctuations which enhance power control efficiency in regenerative braking operations [31]. With respect to hybrid and electric vehicle systems, the system's operational stability benefits both the durability of electric components and total braking efficiency.

4.6. Power and Energy Recovery Rates

The energy recovery rate describing how flywheel inertia affects energy conversion during braking operations is shown in Figure 9. When operating at 4500 RPM, the system achieves its peak recovery rate of -6.15 J/s, which stabilises to -3 J/s after 1.5 seconds. The flywheel speed boosts its ability to store kinetic energy because the system can convert energy more quickly. The decrease in the energy recovery rate occurs rapidly as the RPM drops. When operating the system at 3500 RPM, it begins to recover energy at a rate of -5.6 J/s and stabilises at -1.5 J/s after

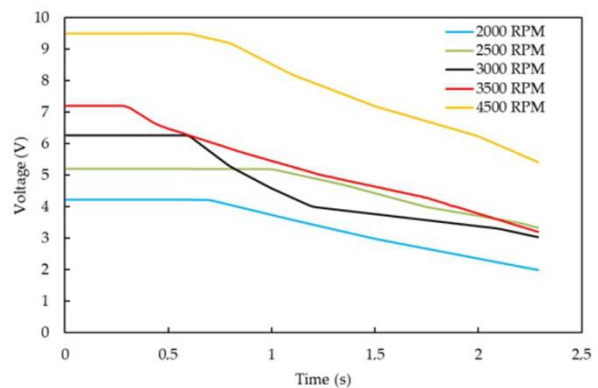


Figure 8. Voltage stability during different RPMs

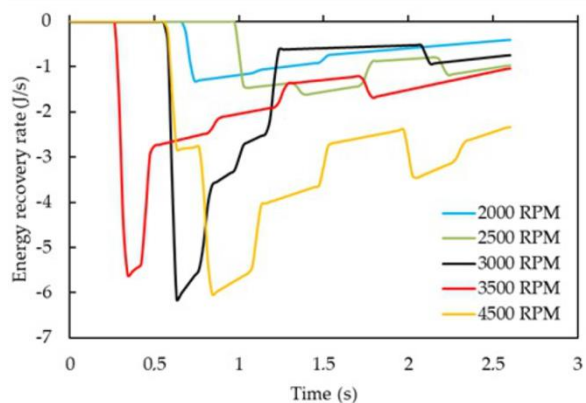


Figure 9. Braking energy recovery rate at different RPMs

operating for 1.5 seconds. At 3000 RPM, the peak energy output reaches -6.14 J/s and requires longer to stabilise. The FARBS operates at recovery rates of -1.6 J/s for the 2500 RPM propulsion and -1.3 J/s for the 2000 RPM propulsion, as these speeds have less potential to capture energy. **Figure 10** explains the power delivery timeline for the FARBS, in which the system maintains power distribution capabilities at different RPM settings. From 0.8 to 2.5 seconds, the system delivers 5.9 W at 4500 RPM before the power output steadily decreases to 2.8 W at 1.5 seconds and 2.4 W at 2.5 seconds. The system achieves its maximum power level of 5.6 W while operating at 3500 RPM. However, it reduces power output to 1.3 W at 1.5 seconds and then further to 1.1 W at 2.5 seconds. When operating at 3000 RPM, the system commences at 6.1 W and falls rapidly to 0.6 W at 1.5 seconds. Subsequently, it attains 0.8 W at 2.5 seconds. The decreasing RPM result in increased power dissipation until 2500 RPM reaches the highest point of 1.6 W during the first 1.5 seconds prior to settling at 1 W at 2.5 seconds. The system begins at 1.3 W when running at 2000 RPM before reaching 0.75 W at 1.5 seconds and ending at 1 W at 2.5 seconds. The research confirms that increasing the RPM extends the power storage duration, which, in turn, boosts energy recovery whilst improving the braking performance. Similarly, low-speed operations necessitate optimised energy management strategies because the energy recovery continues to outperform conventional systems, although power dissipates at a faster rate.

4.7. Energy Recovery Efficiency

Figure 11 portrays how effectively the system recovers energy several different RPM speeds, both with and without the flywheel system. The results show that energy recovery in the flywheel-assisted system exceeds the performance of the system without the flywheel in terms of each of the tested speeds. When operated at 2000 RPM, the standard system recovers only 1 J, whereas the integration of the flywheel system delivers 3 J of energy recovery. Hence, double the amount of energy is saved. The system with the flywheel enables energy recovery to increase from 1 J at

2500 RPM to 5 J, which represents a 400% increase. When running at 3000 RPM, the flywheel maintains energy from 3 J to 5 J. This represents an improvement of 66.7% in storage capacity. The implementation of the flywheel at 3500 RPM generates energy recovery that increases from 3 J without the flywheel to 7 J with the implementation of the flywheel demonstrating an improvement of 133%. At 4500 RPM, the flywheel system generates 5 J of power output amounting to a 275% improvement compared to the 4 J baseline with no flywheel. The experimental findings denote that, as the RPM increases, the energy retention is greater as the flywheel continuously delivers superior results in comparison to the baseline test without the flywheel system. Maximum improvement occurs at faster speeds for the reason that the flywheel prevents energy waste and prolongs the power generation time. As a result of its implementation, the flywheel demonstrates its ability to optimise braking energy use and the system's operational efficiency. **Figure 12** explains the improvement in the FARBS non-linear efficiency at different motor

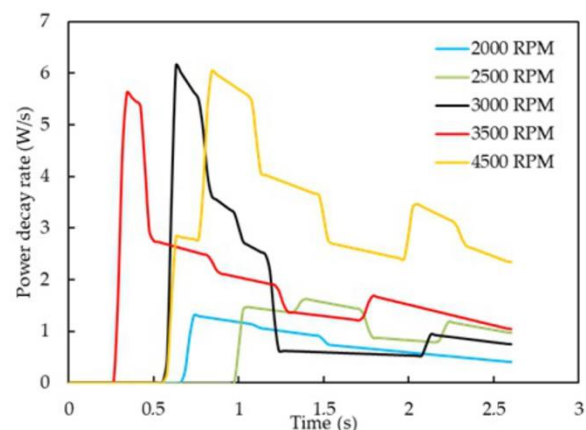


Figure 10. Power decay rate at different RPMs

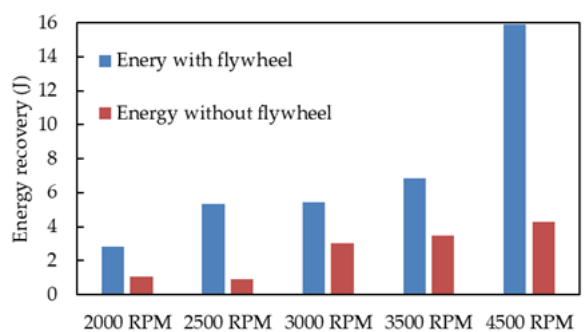


Figure 11. Energy recovery comparison

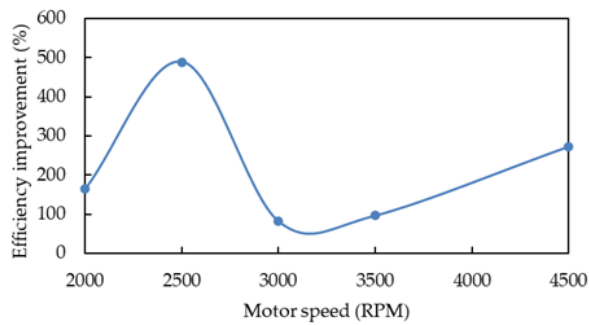


Figure 12. Improvement in efficiency at different RPMs

speeds. The efficiency attains its maximum improvement at 2500 RPM, increasing by 500%. At 2000 RPM, the improvement reaches 180%. The system experiences a reduction in efficiency to 90% above 3000 RPM because of the mechanical losses and control constraints. Nonetheless, it recovers maximum efficiency at 120% at 3500 RPM and attains 250% at 4500 RPM. The data demonstrates that the flywheel achieves maximum efficiency at speeds of 2500 and 4500 RPM, determining the requirement for optimised control systems regarding consistent efficiency at different speeds.

The observed increase in energy recovery efficiency is primarily attributed to reduced energy losses at higher RPMs due to improved flywheel momentum and lower relative frictional impact. During testing, energy losses were categorized into mechanical friction (bearing and shaft resistance), belt transmission losses, and electrical conversion inefficiencies at the generator. At lower RPMs, frictional losses consumed a larger portion of the rotational energy, while at higher speeds (e.g., 4500 RPM), the higher stored kinetic energy outweighed these losses, resulting in greater net recovery. Estimated frictional and mechanical losses accounted for approximately 15–20% of total energy input, with conversion losses contributing an additional 5–8%, depending on speed. These loss components were consistent across repeated trials and help explain the marked efficiency gains observed at elevated RPMs.

4.8. Analysis of the Electrical Power Balance

Figure 13 illustrates how the total power in the system occurs together with the resistive losses over time. The system's total power reveals a

linear increase during the simulation until it reaches 20 W at 10 seconds and resistive losses exhibit a quadratic ascent that grows more rapid with rising current. During the simulation, the system's total power increased linearly, reaching 20 W at 10 seconds, whilst the resistive losses follow a quadratic increase, increasing in speed as the current increases. When time equals 0, the system exhibits a minimal power output together with minimal resistive losses. The resistive losses increase rapidly until they attain total power at 10 seconds, leading to a decrease in system efficiency. Consequently, the increased power consumption underlines the need for improved materials, conductor design and heat dissipation to achieve maximum energy efficiency. Similarly, energy management systems employing regenerative recovery and thermal dissipation methods improve the performance characteristics, specifically in high-power applications.

4.9. Energy Recovered, Stored and Lost

Figure 14 describes how the energy is distributed between recovery, storage and loss at varying rotational speeds, while demonstrating

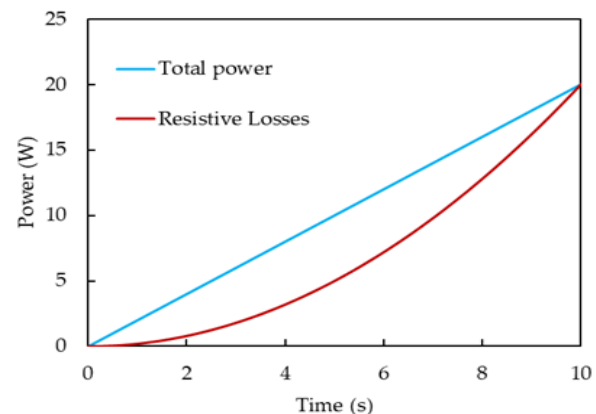


Figure 13. Total power and resistive losses over time

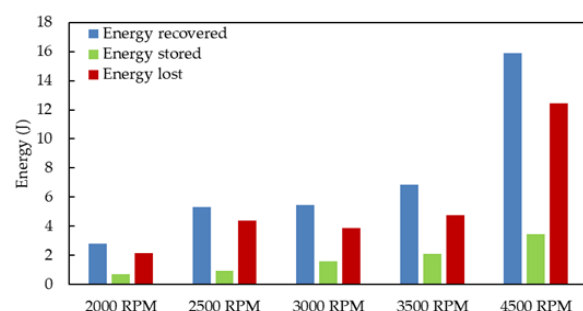


Figure 14. Energy recovered, stored and lost at different RPM levels

the system's energy conversion efficiency and dissipation patterns. The amount of recovered energy rises significantly when the RPM increase, as the availability of kinetic energy is greater. The energy recovery process at 2000 RPM produces 2.8 J before attaining 15.9 J at 4500 RPM, generating an output which is 6.3 times greater. A steady increase in the recovered energy values occurred between 2500, 3000 and 3500 RPM, with the results exhibiting 5.3 J, 5.4 J, and 6.8 J, respectively. Due to the storage limitations, the system recovers energy faster than it is capable of storing it. When the RPM reaches 2000, the system stores 0.7 J, whereas 3.4 J is available at 4500 RPM. The storage values at RPM speeds ranging between 2000 and 4500 are 0.93 J, 1.6 J and 2 J, respectively. The system exhibits a storage capacity limit in spite of recovering additional energy at higher speeds. The RPM values directly affect energy loss because the system dissipates 2.1 J at 2000 RPM but 12.5 J at 4500 RPM. The energy losses increase from 4.4 J at 2500 RPM to 3.9 J at 3000 RPM and subsequently to 4.7 J when the RPM reaches 3500 RPM. At higher speeds, the combination of increased thermal effects, mechanical friction, in addition to electrical resistance increase dissipation. Notwithstanding the higher energy recovery on account of the increase in RPM, the increased losses significantly reduces the operational efficiency. Improvements in system performance require advanced energy storage solutions in conjunction with optimised regenerative braking strategies and enhanced thermal dissipation mechanisms. Likewise, energy use achieves its maximum potential by means of loss reduction techniques which are essential for high-speed systems.

5. Mathematical Model for the Proposed Flywheel-Assisted Regenerative Braking System

The mathematical description of the flywheel-assisted regenerative braking system (FARBS) comprises voltage analysis at various rotational speeds over time. A quadratic regression model was developed as follows using MATLAB curve

fitting software to describe the voltage as a function of time and RPM. Hence Eq. (18).

Figure 15 demonstrates that experimental voltage results match model-predicted values throughout the entire RPM interval. The model performs closely to the experimental data at 4500 RPM, but reveals slight changes at the end of the braking period. The model exhibits a reliable performance for 3500 RPM and 3000 RPM by means of error margins that are between 1 and 4%. The model predictions achieve an accuracy rate lower than 5% when analysing the test conditions at 2000 RPM and 2500 RPM. The model demonstrates its effectiveness in predicting voltage changes during braking via these results which establish it as a fundamental optimisation tool in terms of braking efficiency. Future predictive models should include thermal and frictional components to improve precision, given that this will deliver a more accurate simulation of genuine braking conditions.

6. Optimisation

This section outlines a comprehensive optimisation plan that examines various parameters affecting the energy recovery capabilities of FARBS in conjunction with testing each parameter at five different levels. Several important properties, for example the flywheel mass and moment of inertia along with the parameters of the flywheel, material types, thickness and radius, as well as the rotati-

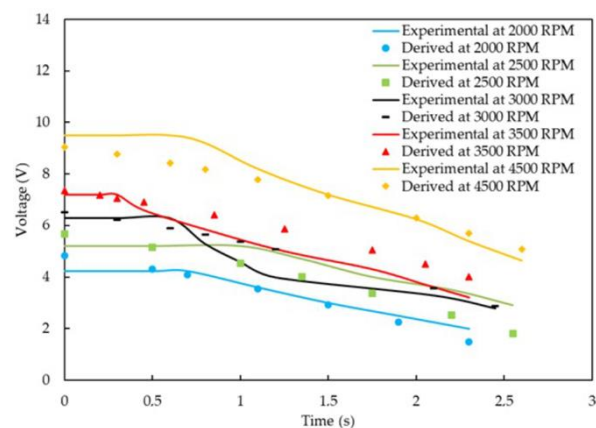


Figure 15. Comparison of the experimental results with the mathematical model predictions

$$V(t, RPM) = -0.24038t^2 - 0.90420t + 0.00169 \times RPM + 1.45189 \quad (18)$$

onal speed were calculated, in an attempt to assess their impact on energy recovery metrics, as illustrated in [Figure 16](#). Increasing the flywheel mass from 1 kg to 3 kg brought about a 194% increase in energy recovery, which resulted in an increase from 160 J to 470 J. The system recovered 330 J of energy when the inertia attained 0.015 kg·m² while achieving an improvement of 94%. Simultaneously, the flywheel geometry had a significant impact on the performance. The spherical shell flywheel design delivered a superior performance compared to the solid disk configuration, seeing as it recovered 327 J, although the solid disk only reached 162 J. The choice of carbon fibre as the material produced flywheels with better energy recovery ability. The use of carbon fibre materials gave rise to 330 J of recoverable energy; nonetheless, the 170 J steel limit remained unchanged due to its increased weight. The energy recovery rate quadrupled from 160 J to 320 J when the thickness value was increased from 10mm to 20mm in the flywheel design. The energy recovery measurements improved by 102%, whereas the flywheel radius rose from 100 mm to 120 mm. This change produced an increase in recovered energy from 162 J to 327 J. The energy recovery value increased by 23.4% owing to variations in speed from 2000 RPM to 4500 RPM. Additionally, the maximum recovery achieved 580 J on testing the final RPM. The maximum energy recovery occurred when the design parameters included a 3 kg spherical shell flywheel with a radius of 120 mm and thickness of 20 mm operating at 4500 RPM. The

exact combination attained the maximum recorded energy recovery level because of its importance in advancing the regenerative braking performance.

A comparative analysis between spherical shell and solid disk flywheel configurations indicates that geometry significantly influences energy recovery efficiency. The spherical shell design, used in this study, offers superior specific energy (energy per unit mass) due to its higher moment of inertia relative to mass, making it ideal for high-speed rotational applications. In contrast, a solid disk of equivalent mass stores less energy due to lower peripheral mass distribution. For light-duty EVs, compact designs with moderate energy requirements may benefit from solid or hybrid geometries prioritizing structural simplicity. However, for heavy-duty applications such as electric buses or high-speed rail systems—where energy demand and braking intensity are higher—the spherical shell configuration is more suitable due to its ability to store and release larger energy volumes efficiently without excessive weight penalties. These distinctions support geometry-driven flywheel design tailored to specific transport sectors.

7. Conclusion

This study implemented and optimized a flywheel-assisted regenerative braking system (FARBS) to improve energy recovery, voltage stability, and braking power output. The flywheel significantly enhanced power retention, achieving a 439% increase in energy recovery duration, from 1.15 s to 6.2 s, at 4500 RPM. Voltage retention

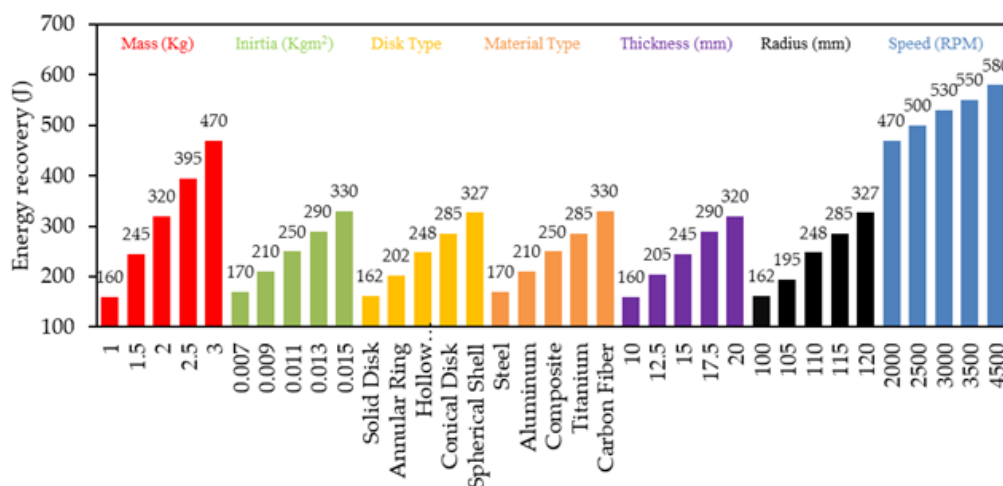


Figure 16. Optimisation analysis of key parameters influencing energy recovery efficiency

improved from 10.3 V at 2000 RPM to 19.2 V at 4500 RPM, demonstrating reduced fluctuations during braking. Power output tests showed that at 4500 RPM, the flywheel system sustained 6.40 W for 6.2 s, while the non-flywheel setup operated for only 2.2 s.

Energy recovery improved across all tested speeds, increasing by 200% at 2000 RPM (from 1 J to 3 J) and by 275% at 4500 RPM (from 4 J to 15 J). Design optimization revealed that increasing flywheel mass from 1 kg to 3 kg raised total recovered energy from 160 J to 470 J. The spherical shell geometry outperformed the solid disk (327 J vs. 162 J), and carbon fibre construction delivered 330 J—94% higher than steel. Increasing thickness (10 mm to 20 mm) and radius (100 mm to 120 mm) improved efficiency by 200% and 102%, respectively. The system's peak performance reached 580 J at 4500 RPM, exceeding the 2000 RPM case by 23.4%.

The findings affirm the viability of flywheel-based braking systems in enhancing energy storage and stability. Optimal results were achieved using a 3 kg spherical shell flywheel with a 120 mm radius, 20 mm thickness, and 4500 RPM speed. Future research should explore dynamic control strategies, hybrid storage integration, and AI-based real-time energy management [32, 33]. Additional focus on lightweight composite flywheel materials, vibration and noise control, and full-scale vehicle testing in varied conditions, including emergency braking, will support real-world application. Integration with vehicle-to-grid (V2G) systems and lifecycle assessments (LCA) will further clarify environmental impact and long-term sustainability [34].

Author's declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

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