REGENERATIVE BRAKING CONTROL STRATEGY EFFECT ON BATTERY DEGRADATION IN ELECTRIC VEHICLE (EV)

A MASTER'S THESIS

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THE SCHOOL OF ELECTRICAL ENGINEERING

BY

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APPROVAL PAGE

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Approved and authorized to fulfill of the requirements of Program of Master of Electrical-Telecommunication Engineering School of Electrical Engineering

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SELF DECLARATION AGAINST PLAGIARISM

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Bandung, December 25, 2024

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ABSTRACT

The use of electric vehicles (EVs) has become a primary focus in efforts to reduce greenhouse gas emissions and dependence on fossil fuels. In this context, regenerative braking technology plays a crucial role in improving energy efficiency in electric vehicles. However, the use of regenerative braking systems also impacts battery degradation, which can affect the performance lifespan of the battery in electric vehicles. This study aims to analyze the effect of using fuzzy logic control, adaptive PID control, and hybrid Fuzzy-PID control on regenerative braking systems on the level of battery degradation in electric vehicles (EVs).

This research employs field experiments and statistical analysis to collect data from electric vehicles equipped with independent regenerative braking systems. Testing was conducted under various operational conditions, including variations in charging cycles and battery operating temperature. The test results were comprehensively analyzed to evaluate energy recovery efficiency, overall system performance, and the impact on battery degradation.

Based on the results, fuzzy control demonstrated the best performance in improving system efficiency, reducing charging cycles, and suppressing battery temperature increases, thereby minimizing battery degradation. Conversely, adaptive PID control and hybrid PID-Fuzzy control tended to produce unstable currents and increase charging cycles, even though they reduced battery temperature. These findings indicate that the application of fuzzy control in regenerative braking systems can optimize energy recovery and extend battery lifespan.

Keywords : Electric Vehicles (EVs), Regenerative Braking, Battery Degradation, Fuzzy Logic Control, Adaptive PID Control, Hybrid PID-Fuzzy Control.

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PREFACE

All praise and gratitude be to Allah SWT for his blessing and mercy, which enable the author to complete this thesis entitled "Regenerative Braking Control Strategy Effect on Battery Degradation in Electric Vehicle (EV)". This thesis was submitted to fulfill one of the requirements of obtaining a Master's degree in Electrical Engineering at Telkom University. May prayers and peace be always upon the Prophet Muhammad SAW, family, friends, and his followers.

This research is dedicated to the scientific community and professionals passionate about the development of electric vehicles, particularly in the field of regenerative braking and battery degradation. The aim of this study is to contribute to the understanding of the effect of control strategy and to provide an innovative approach for analyzing the impact on battery degradation through different control strategy.

The author acknowledges that this research is starting point and is far from perfect. Therefore, constructive feedback and suggestions from readers are highly encouraged to improve this work. It is hoped that this thesis can offer valuable insights for those interested in electric vehicle and control strategy of regenerative braking. Finally, the author expresses deep gratitude to everyone who has supported and contributed to this work. May Allah SWT reward all their kindness abundantly.

Bandung, December 25, 2024

Bintang Kriesna Nugraha

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CHAPTER I

INTRODUCTION

1.1 Background

The use of electric vehicles (EVs) has gained increasing popularity as an environmentally friendly and sustainable solution to reduce greenhouse gas emissions and dependency on fossil fuels. According to a report by the European union, the transportation sector accounts for 28% of total carbon dioxide (CO2) emissions, with road transport contributing 70% of the transportation sector's emissions [1]. Consequently, national governments in most developed countries (European Union, United States, and China) and international organizations (United Nations, International Energy Agency) have been promoted the use of EVs to avoid air pollution concentrations, CO2 emissions, and other greenhouse gases.

One key technology that enhances efficiency in EVs is the regenerative braking system. The goal of this technology is to recover some of the kinetic energy lost during braking and reuse it to recharge the Energy Storage System (ESS) [2]. However, while regenerative braking systems offer these advantages, their usage also brings challenges, particularly concerning battery degradation. The battery lifespan can be shortened by rapid charging and discharging currents, commonly referred to as "inrush current", which also reduces the system's efficiency and reliability [3]. Recent research has identified various control strategies that can optimize the performance of regenerative braking systems. Notable strategies include fuzzy logic control, neural networks, Model Predictive Control (MPC), sliding mode control, and adaptive PID control [4]. However, these studies mainly focus on charging efficiency and have yet to address the impact on the battery comprehensively.

Battery degradation in EVs involves physical and chemical changes within battery cells that lead to reduced energy storage capacity and overall battery performance [5]. The intensity of battery charging and discharging, along with high operating temperatures caused by regenerative braking, are key factors in analyzing battery degradation. Lithium-ion batteries are particularly susceptible to failures caused by intensive charging/discharging and high operating temperatures, accelerating the degradation process [6]. Battery degradation results from rapid increases in temperature and voltage [7]. For automotive applications, increasing internal resistance and capacity loss over time and cycles remain significant challenges [8]. Degradation mechanism such as loss of recycleable lithium due to Solid Electrolyte Interphase (SEI) layer growth on the anode (caused by electrolyte decomposition and lithium consumption), loss of active material due to mechanical stress from structural changes in cathode and anode, increased impedance, and a combination of these factors contribute to battery performance deterioration [8].

Previous studies show that extremely low or high temperatures can accelerate battery life reduction due to high currents generated during regenerative braking, placing stress on battery cells, especially under extreme temperature conditions [6]. These studies also highlight the implementation of various control strategies in regenerative braking systems, including fuzzy logic control. Fuzzy logic control adjusts the regenerative braking ratio by observing the battery's State of Charge (SoC) and temperature in real-time to avoid temperature increases in battery [6].

One significant challenge in regenerative braking systems is managing high charging current surges and increased charging cycles that occur during braking. These surges and increased cycles can lead to battery degradation, impacting the battery's long-term performance [4]. Therefore, control strategies such as fuzzy logic and adaptive PID control are needed to mitigate these current surges.

Fuzzy logic control can adjust the system response based on pre-defined rules for various operating conditions. Type-2 fuzzy logic control effectively manages regenerative braking systems, maintaining braking quality while allowing EVs to decelerate safely [9]. Meanwhile, adaptive PID control dynamically adjust control parameters according to changing operating conditions. Adaptive PID control operates based on control laws that adapt to changing conditions, accommodating continuously varying and uncertain parameters in the system. In the context of regenerative braking, these varying parameters relate to driver conditions such as deceleration, torque demands, speed, SoC, and more

[4]. Both methods can optimize the regenerative braking process and reduce battery degradation.

The use of regenerative braking control systems in EVs plays a crucial role in reducing battery degradation rates. Non-optimal or inappropriate control systems for specific operating conditions can impact battery charging and discharging cycles, accelerating the degradation process. Fuzzy control allows the system to adjust its response based on established logical rules. Meanwhile, adaptive PID control dynamically adjust control parameters according to changing operating conditions and system characteristics. Applying these two control methods to EV regenerative braking systems can help reduce battery degradation, improve charging efficiency, and extend overall battery life when properly configured.

1.2 Problem Identification

Based on the background described, to gain a clear understanding of the impact of regenerative braking on electric vehicles, the research questions can be formulated as follows :

1. What are the significant differences between using fuzzy control, adaptive PID control, hybrid Fuzzy-PID control, and no control in regenerative braking systems in terms of energy recovery efficiency and battery degradation factors (charging cycles & temperature rise) in electric vehicles with Lithium Ion battery?
2. How effective are fuzzy control, adaptive PID control, and hybrid Fuzzy-PID control in regenerative braking systems at reducing battery degradation factors (charging cycles & temperature rise) and extending battery lifespan in electric vehicles with Lithium Ion battery?

1.3 Research Objectives

The research aims to analyze the impact of control strategies in regenerative braking systems on battery degradation levels in electric vehicles (EVs). The specific objectives of this study are as follows :

1. To evaluate the significant differences between using fuzzy control, adaptive PID control, hybrid Fuzzy-PID control, and no control in regenerative braking systems in terms of energy recovery efficiency and battery degradation factors (charging cycles & temperature rise) in electric vehicles with Lithium Ion battery.
2. To optimize the use of fuzzy control, adaptive PID control, and hybrid Fuzzy-PID control in regenerative braking systems to reduce battery degradation factors (charging cycles & temperature rise) with Lithium Ion battery.

1.4 Hypothesis

The initial hypothesis derived from the research questions suggest that fuzzy control, adaptive PID control, and hybrid Fuzzy-PID control in regenerative braking systems can reduce charging cycles and Lithium Ion battery operating temperatures, thereby decreasing Lithium Ion battery degradation levels.

1.5 Scope of Work

The scope of this research is carried out in several stages, including :

1. Designing a regenerative braking system that operates separately from the main components of the electric vehicle.
2. Preparing the vehicle and the regenerative braking system by ensuring the functionality of the regenerative braking mechanism and checking the optimal condition of the vehicle's battery.
3. Testing the regenerative braking system and setting up direct testing scenarios on the electric vehicle, covering various road conditions such as flat, uphill, and downhill.
4. Continuously monitoring the operational temperature of the battery and the battery charging-discharging cycles during testing.
5. Collecting testing data, including the intensity of regenerative braking, battery charging-discharging cycles, and battery operational temperature.
6. Analyzing the collected data to evaluate the overall charging efficiency and performance of the regenerative braking system and comparing the results between

using control strategies and without control strategies in terms of battery degradation factors.

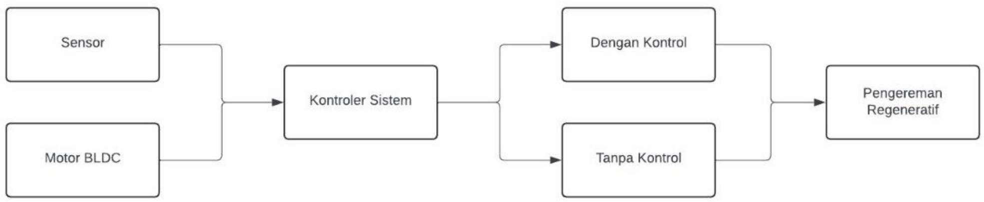


Figure 1. 1 *System's Flowchart*

1.6 Research Methodology

In the research and system development phase, the following processes are carried out :

- Literature Study

  The literature study is conducted to further understand regenerative braking in electric vehicles, how the system works, and to determine the methods to be used. The literature used comes from articles, scientific journals, and other reliable sources related to regenerative braking technology, control systems, and battery degradation, with publication dates not older than 5 years.
- System Design

  This phase involves designing the braking system to be used in the testing. The regenerative braking system is designed by considering the regenerative braking controller, the involved electric motor, sensors to detect braking conditions, and the battery as the main power source.
- System Testing

  Testing is carried out directly on the electric vehicle equipped with the designed regenerative braking system. The testing scenarios include various operational conditions such as vehicle speed, road conditions, and emergency braking situations.
- Data Collection

The collected data includes regenerative braking intensity, charge and discharge cycles of the battery, and battery operational temperature during the testing. Data collection is carried out continuously during the testing to obtain comprehensive information.

- Analysis

  The gathered data is analyzed to evaluate the overall system performance and its impact on battery degradation. The analysis includes comparisons between using control and not using control in the regenerative braking system regarding energy regeneration effectiveness and battery degradation levels.

- Conclusion

  Conclusions are drawn based on the results of the data analysis to determine the impact of using control in regenerative braking on battery degradation and overall system performance.

CHAPTER II

LITERATURE REVIEW AND BASIC THEORY

2.1 Electric Vehicle (EV)

Electric vehicles (EVs) are a type of vehicle that uses one or more electric motors to drive the wheels, replacing the internal combustion engine used in conventional vehicles. The electric motor is a crucial component in the drivetrain system of electric vehicles. In recent years, most traction drive systems have been converged into several forms of permanent magnet motors [10]. The transition to electric transportation technology requires electric drive systems that offer improved performance and capabilities, such as fuel efficiency (in the context of MPGe, miles per gallon gasoline equivalent), range, and fast-charging options [11]. This makes electric vehicles more environmentally friendly as they produce no exhaust emissions and reduce dependence on fossil fuels.

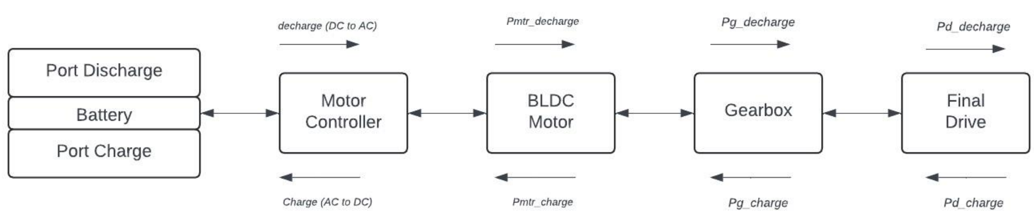


Figure 2. 1 *Electric Vehicle's Power Flowchart*

2.2 BLDC Motor

The electric motor in electric vehicles is a direct current (DC) motor that uses power from the battery as its primary energy source. Brushless Direct Current (BLDC) motors are commonly used for dynamic applications such as in the automotive industry [12]. BLDC motors are a specific type of DC motor that does not use brushes for operation. Instead, an electronic processing system is employed. BLDC motors are typically synchronous motors consisting of EMF waves and permanent magnets [13].

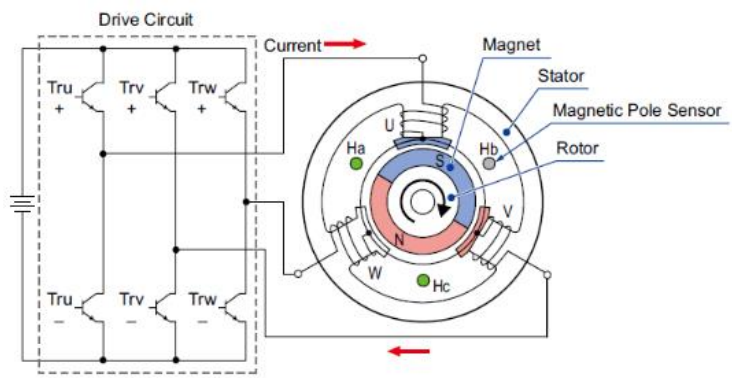


Figure 2. 2 *BLDC Motor's Diagram*

2.3 Regenerative Braking

Regenerative braking is a technology designed to enhance energy efficiency in electric vehicles by converting wasted kinetic energy into reusable electrical energy. The regenerative braking system not only achieves the purpose of braking but also recovers braking energy [14]. During braking, EVs can adjust the operational mode of their electric motors, allowing the vehicle's kinetic energy to be converted into battery energy by switching the electric motor into a generator [15]. According to research, approximately 30-50% of the total braking energy can be recovered through regenerative braking [15].

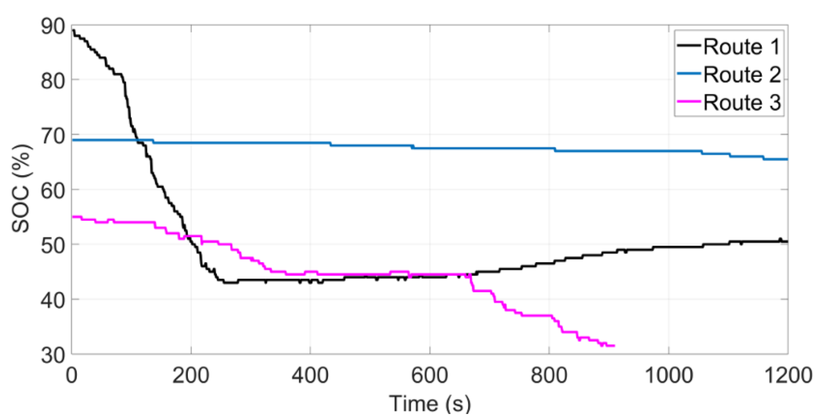


Figure 2. 3 *SoC Behavior Related to Recovered Energy [16]*

Different SoC (State of Charge) performances can be observed for each route and distance [16]. The data shows that routes or road conditions significantly affect the efficiency of regenerative braking as well as the battery's SoC. Route 1, characterized by the most uphill sections, shows the largest battery depletion process.

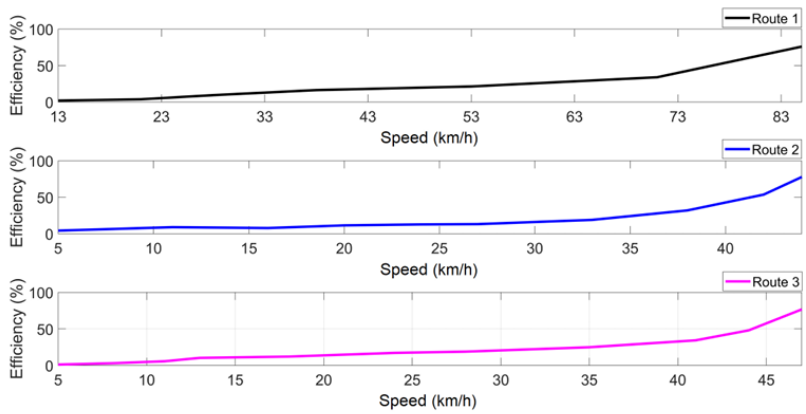


Figure 2. 4 *Regenerative Braking Efficiency at a Specific Speed[16]*

The efficiency of regenerative braking on each route depends on losses and the energy recovered from the vehicle. Road geography, initial braking speed, and braking application time are the main variables influencing the loss value and the energy recovered [16].

The formula used to calculate the efficiency :

$$\frac{E_m}{E_b} = \frac{\int_{t0}^{t} V_b(t)\, i_b(t) dt}{\frac{1}{2} m\left(V_f^2 + V_0^2\right)} (100\%)$$

Where :

- E_m : Available mechanical energy.
- E_b : Electrical energy.
- $V_b(t)$: Battery voltage.
- $I_b(t)$: Battery charging current.
- t_0 : Initial time.
- t : Final time.
- m : Total Mass.

- V_0 : Initial velocity.
- V_f : Final velocity.

Equation above allows to determine efficiency values of regenerative braking mainly using the initial velocity used by the vehicle to start the braking process [16].

Efficiency can also be calculated as the ratio between the power actually used for charging (the total power output during charging) and the maximum power that could be achieved in the system (based on the time).

$$\eta = \left(\frac{Total\ Charging\ Power}{Maximum\ Possible\ Power}\right) x\ 100$$

2.4 Battery Degradation

Battery degradation refers to the physical, chemical and electrochemical changes within a battery cell that result in reduced energy storage capacity, decreased durability, and overall decline in battery performance. This process occurs naturally with regular battery usage but can be accelerated by various external factors. From the user perspective, three main external factors influence degradation: temperature, State of Charge (SoC), and load profile [5]. In general, temperature is the most influential factor, where deviations from the typical temperature of 25^{o}C can lead to accelerated failure. Higher SoC operation accelerates degradation due to the relationship between electrode potential and the rate of parasitic side reactions, while higher current operation increases the likelihood of failure due to mechanical stress developing within the battery during cycles [17].

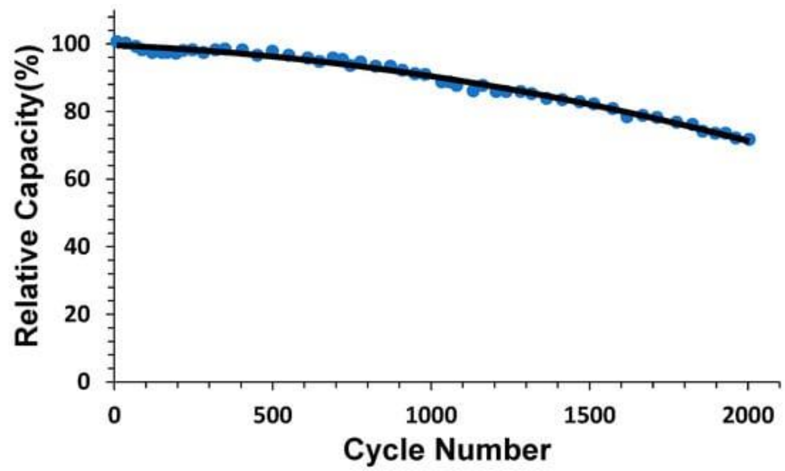


Figure 2. 5 *graph of Relative Capacitance vs. Number of Cycles for Kokam SLBP5520510H Battery [18]*

Based on the data from the graph above, the more cycles a battery undergoes, the more its capacitance decreases. The usable battery capacitance depends on the number of cycles, as shown in **Figure 2. 5**, where battery capacitance diminishes as the number of cycles increases [6]. Carrilero et al. studied charging regimes and determined that the overall performance of cells is suitable for fast charging when more than 90% of their effective capacity can be recharged within 15 minutes or less throughout their lifetime (over 5000 cycles) without significant decline in power capability [6].

2.5 Control System

A control system is a method used to regulate and control the behavior of a dynamic system to achieve desired objectives. The main goal of a control system is to design algorithms or control strategies that can manipulate variables within the system to achieve optimal performance. Several control schemes are used for BLDC motors. The control system for BLDC motors is quite complex, utilizing various electronic components arranged to switch between the motor's three phases with precision. There are two types of control systems: Open-Loop and Closed-Loop. In an Open-Loop system, the output does not affect the system, and no feedback is provided. BLDC motor control systems available in the market already use Closed-Loop systems, which incorporate feedback [19]. Guo et al. proposed a method to maximize regenerative braking. When the maximum regenerative braking force from the motor is sufficient to meet the braking force demand of the driving wheels, only regenerative braking is used on the driving wheels. However, when the braking force demand of the driving wheel exceeds the motor's maximum braking force, friction braking is also required to complement the remaining portion of the braking force, in addition to regenerative braking [20].

Regenerative braking system in EVs play a critical role in enhancing energy efficiency. However, without proper control, these systems can adversely impacts battery life. Therefore, implementing optimal control is essential to balance these factors effectively.

1) Cycle Count

   A high number of charging cycles may indicate that regenerative energy is being utilized, but also signifies accelerated battery degradation. Excessive cycle counts impose mechanical and chemical stress on battery cells, leading to capacitance loss and increased internal resistance overtime.

2) Temperature Rise

   Elevated temperatures during regenerative braking are a major contributor to the battery degradation. High temperatures accelerate electrolyte decomposition and the growth of the Solid Electrolyte Interphase (SEI) layer, reducing battery efficiency and lifespan.

3) Efficiency

   The efficiency of the regenerative braking system reflects how effectively kinetic energy is converted into electrical energy to recharge the battery. While high efficiency indicates optimal energy utilization, it must not come at the expense of the thermal stability or excessive cycle counts.

2.6 Fuzzy Logic Control

Fuzzy logic is a control method that uses fuzzy logic to handle the uncertainty and variability of complex systems. This control does not require an exact mathematical model of the system to be controlled but instead relies on rules established based on knowledge.

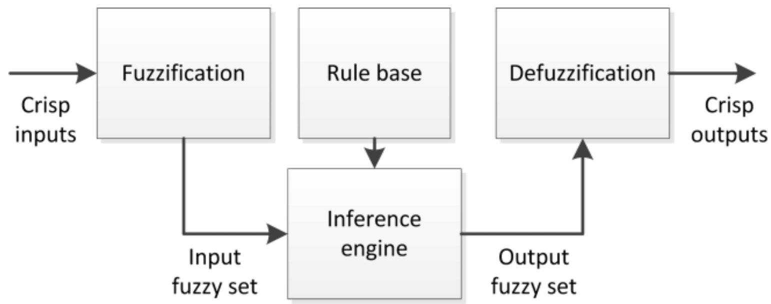


Figure 2. 6 *Fuzzy Logic Control Block Diagram*

The basic principle of fuzzy logic control involves three main steps: fuzzification, rule application, and defuzzification. In the fuzzification stage, the system inputs are transformed into fuzzy variables. Then, fuzzy rules are applied to determine the system's response based on these fuzzy variables. Finally, in the defuzzification stage, the fuzzy variables are converted back into outputs used to control the system. Its mathematical model is non-linear and is generally described through the following steps :

- Fuzzification :
  - Input variables (error *e and* error change Δe) are converted into fuzzy values using membership functions $\mu(x)$.
- Interference Engine :
  - Using linguistic logic rules such as :
    IF e is Negative AND Δe is Negative Then μ is High.
- Defuzzification :
  - $\mu(t) = \frac{\int_{domain} \mu_u(x) \,.\, x \, dx}{\int_{domain} \mu_u(x) \, dx}$

    Where :
    - $\mu(t)$: Defuzzified output value (crisp value).
    - $\mu(u)$: Membership function value.
    - x : Output variable (crisp value range).
    - *domain* : The range over which the membership function $\mu(u)$ is defined.

In the context of regenerative braking in electric vehicles, fuzzy logic can be used to optimize energy recovery and reduce battery degradation acceleration by adjusting braking force based on the vehicle's operating conditions and battery status. Through fuzzy logic control, PWM (pulse width modulation) is used to operate switches, which in turn extends the lifespan of the system [6].

2.7 Adaptive PID Control

Adaptive PID is a control method that can dynamically adjust control parameters based on changes in operating conditions and system characteristics. In regenerative braking for electric vehicles, adaptive PID can be used to adjust the braking force and energy recovery according to road conditions, speed, and battery State of Charge (SoC).

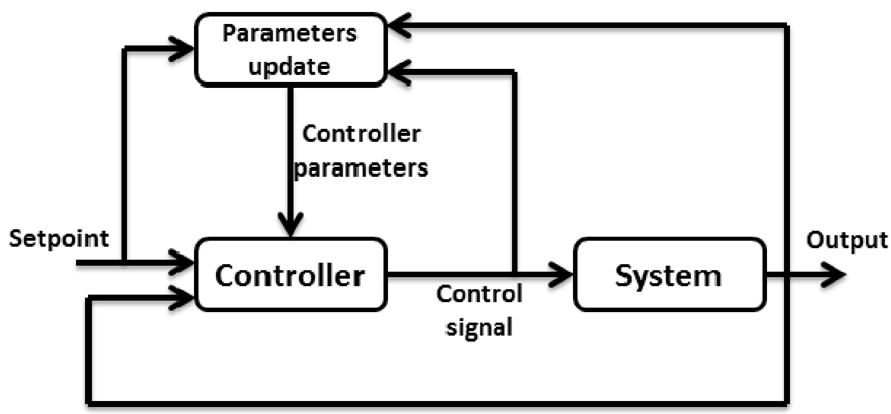


Figure 2. 7 *Adaptive PID Control Block Diagram*

Adaptive PID works by using algorithms that modify the control parameters in real-time to achieve optimal performance. The adaptive PID algorithm includes a predictive model that estimates the system's response to input changes, as well as an adaptation mechanism that adjust the control parameters based on the difference between predictions and actual outcomes. The PID (Proportional-Integral-Derivative) controller is based on the following differential equation :

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

Where :

- $e(t) = r(t) - y(t)$: Error between setpoint ($r(t)$) and output ($y(t)$).
- K_p : Proportional Gain.
- K_i : Integral Gain (eliminates steady-state error).
- K_d : Derivative Gain (improves response to error changes).

In the context of regenerative braking, adaptive PID can help reduce the operational temperature of the battery and extend the battery's lifespan by avoiding high charging current spikes and excessive charging cycle frequencies [4].

2.8 Hybrid PID-Fuzzy Control

Hybrid PID-Fuzzy is a control method that combines the Proportional-Integral-Derivative (PID) approach with fuzzy logic to improve the performance of regenerative braking systems in electric vehicles. This method is designed to overcome the limitations of each approach by leveraging the strengths of both for complex and dynamic applications. In conventional PID control, the tuning process can become complex in non-linear systems [21].

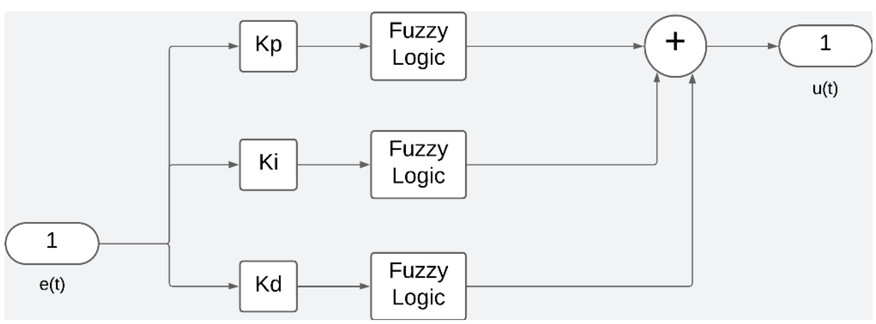


Figure 2. 8 *Hybrid PID-Fuzzy based control [22]*

In general, its mathematical model includes :

- Fuzzy Modulation of PID Gains :
  - The parameters *Kp*, *Ki*, dan *Kd* are dynamically adjusted using the output from fuzzy logic :

    $Kp = f_{fuzzy}(e, \Delta e),\ K_i = g_{fuzzy}(e, \Delta e),\ K_d = h_{fuzzy}(e, \Delta e).$

- Fuzzy logic determines the optimal values of the PID parameters based on linguistic rules.

- PID Output :
  - The PID equations modulated by fuzzy logic :

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

This approach aims to harness the strengths of both methods, where PID provides a linear and structured response to errors, while fuzzy logic allows flexible non-linear adjustments based on complex operating conditions [22]. The hybrid Fuzzy-PID algorithm includes an adaptation mechanism that uses PID parameter settings based on the results from fuzzy logic.

2.9 Metric Comparison

Table 2. 1 *Control Algorithm Metric Comparison Table*

Metric	Fuzzy Logic	Adaptive PID	Hybrid Fuzzy-PID	No Control
Complexity	✓	X	✓	X
Adaptability	✓	✓	✓	X
Precision	✓	✓	✓	X
Computational Load	X	✓	X	✓
Effectiveness	✓	✓	✓	X
Tuning Required	X	✓	X	X
Linearity	X	✓	✓	X

Key :

- ✓ : Strong attribute (good or applicable).
- X : Weak attribute (limited or not applicable).

In the context of regenerative braking system, different control algorithm exhibit varying levels of linearity. Fuzzy Logic is particularly effective for managing non-linear systems, making it less suitable for tasks requiring strict linearity. On the other hand, Adaptive PID is well-suited for linear systems or systems that can be approximated as linear, offering precise control under such conditions. The Hybrid Fuzzy-PID algorithm combines the benefits of both fuzzy logic and PID control, balancing the handling of non-linearity with the need for precision in linear systems. Meanwhile, the No Control approach lacks a control system entirely.

CHAPTER III

SYSTEM'S MODEL AND DESIGN

3.1 System's Model and Scenario

While theoretical models are important, in the context of complex system such as regenerative braking system in this study, direct hardware implementation provides a deeper understanding of the interactions between various components. Testing and iterating on hardware allows for the identification of more practical and applicable solutions. This approach ensures that the developed system is both feasible and efficient under actual operating conditions.

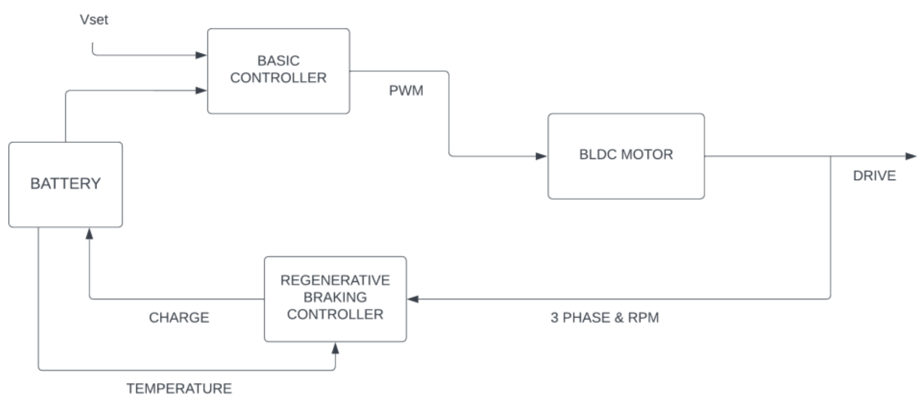


Figure 3. 1 *System's Block Diagram*

The regenerative braking system model used in this study is designed as an independent system, separate from the main controller of the electric vehicle. This system is equipped with a dedicated controller that is solely responsible for regulating the operation of the regenerative braking without affecting the performance of the main controller. The system is designed to optimize kinetic energy recovery, minimize battery degradation, and provide greater flexibility in braking adjustments.

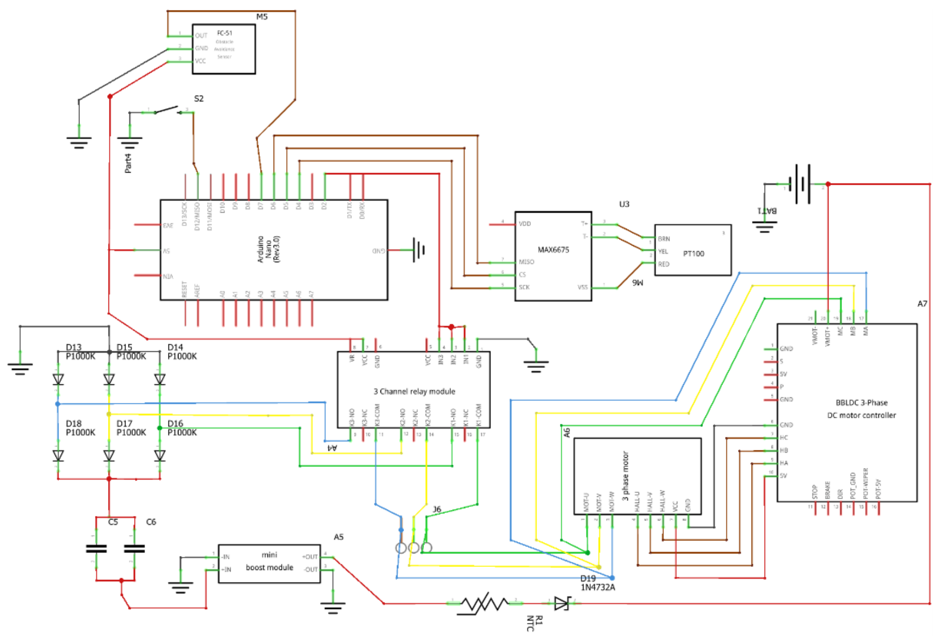


Figure 3. 2 *System's Schematic*

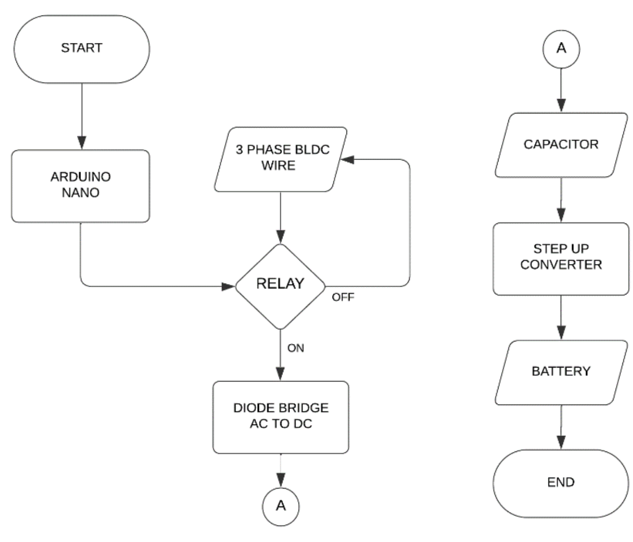


Figure 3. 3 *Regenerative Braking System Flowchart*

The process scenario of this system includes various operational situations that will be tested to evaluate the performance of the regenerative braking system. Some scenarios include variations in vehicle speed and road conditions. The specifications of the regenerative braking used include the regenerative braking controller, the electric motor involved in the braking process, and the regenerative system itself. The regenerative braking controller is designed to optimize the braking process based on data obtained from sensors. The electric motor used in the electric vehicle implementing this system is a BLDC (Brushless DC) motor. The regenerative system can also be designed without control, allowing for comparison of the effects of using control on the system's impact on battery degradation.

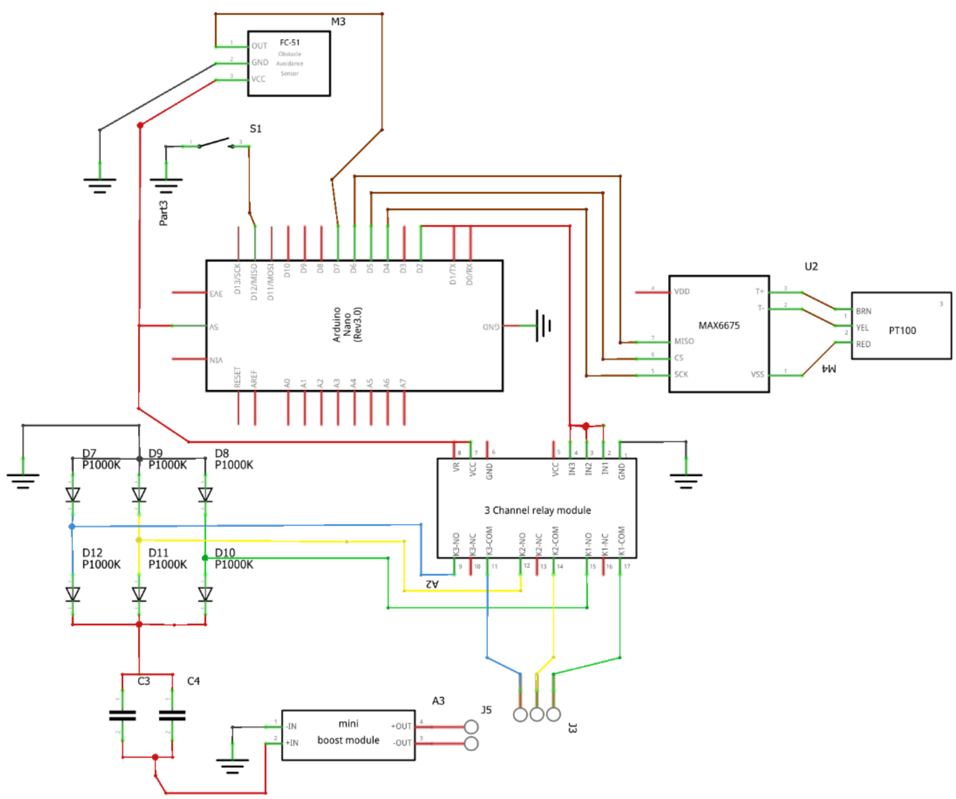


***Figure 3. 4** Regenerative Braking System Schematic*

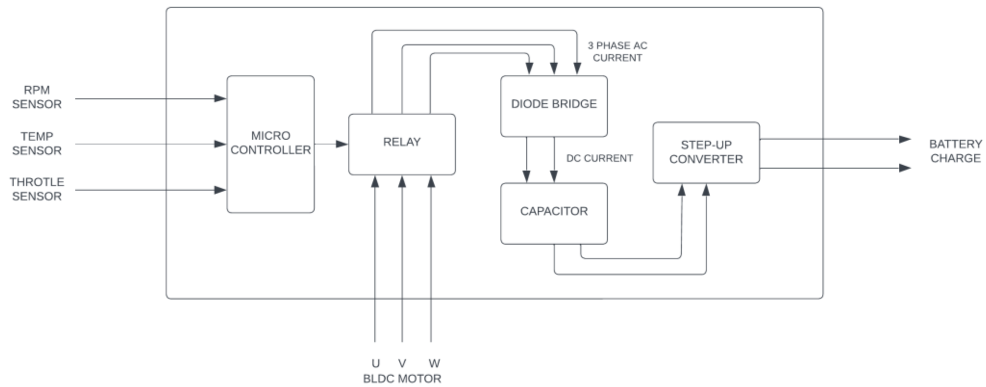
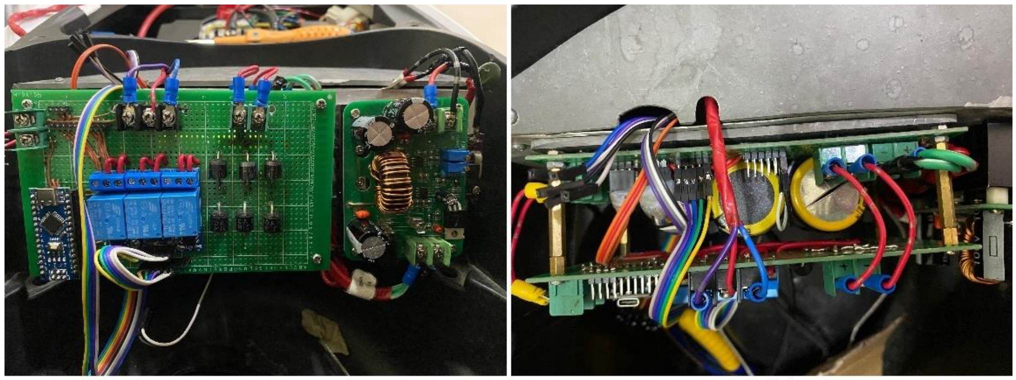


Figure 3. 5 *Regenerative Braking System Function Block Diagram*

The regenerative braking system model includes the electric motor used to generate regenerative force, the regenerative braking controller that regulates the braking operation, sensors to detect braking conditions, and the battery as the main power source.

Figure 3. 6 *(a) Temperature Sensor Position, (b) Battery Position*

The scenarios used in this study include various different situations to evaluate the performance regenerative braking. Some of the scenarios tested include variations in charging cycles, charging efficiency, and battery operating temperature. Each scenario is designed to isolate specific variables that may potentially affect battery degradation, allowing for more in-depth analysis of the impact of regenerative braking.



(a) (b)

Figure 3. 7 *Regenerative Braking System Controller: (a) Top view, (b) Side view*

In the controller, the phase wires are connected to terminals that are linked to a relay, which is then connected to a diode bridge. The function of the diode bridge in the controller is to convert the AC current generated by the BLDC motor into DC current, which is then filtered using a capacitor. The output of the capacitor is then directed to a step-up converter to increase the voltage required for charging the battery. Afterward, the output from the step-up converter is connected directly to the battery, with additional diode and thermistor to prevent reverse current from the battery and excessive current load on the battery, which could damage the components in the controller.

3.2 Simulation Scenario

The simulation is conducted directly on the electric vehicle that has been implemented with the regenerative braking system. The direct testing of the electric vehicle's regenerative braking system involves a series of scenarios to evaluate the performance and effectiveness of the system. The vehicle is prepared by ensuring that the regenerative braking system is properly installed and the vehicle's battery is in optimal condition. Additionally, before testing, all system parameters such as speed, load, and environmental conditions are considered to ensure the validity of the tests.

The testing is conducted under various road conditions, ranging from flat roads to test the regenerative braking capabilities at low to medium speeds, to uphill and downhill roads to assess the system's performance during emergency situations and vehicle stability. The tests include the following scenarios :

1. No Control : The system operates without control to obtain baseline performance.
2. Fuzzy Logic Control : The system uses fuzzy control to optimize energy recovery considering RPM and battery temperature.
3. Adaptive PID Control : The system uses adaptive PID control to adjust the charging parameters based on real-time feedback.
4. Hybrid Fuzzy-PID Control : A combination of fuzzy control and adaptive PID to evaluate the best performance under dynamic conditions.

During the tests, battery temperature and RPM are continuously monitored using sensors installed on the vehicle. This is done to evaluate the impact of regenerative braking on the battery's operational temperature and to ensure that excessive heating (overheating) does not occur, which could damage the battery.

The results of these tests will be comprehensively analyzed to assess the efficiency of energy recovery, overall system performance, and its impact on battery degradation. The data collected during the tests will be documented in detail, including graphs, tables, and other important notes. In-depth analysis will be conducted to draw accurate conclusions and provide recommendations for future improvements in regenerative braking systems.

3.3 Data Collection Scenarios

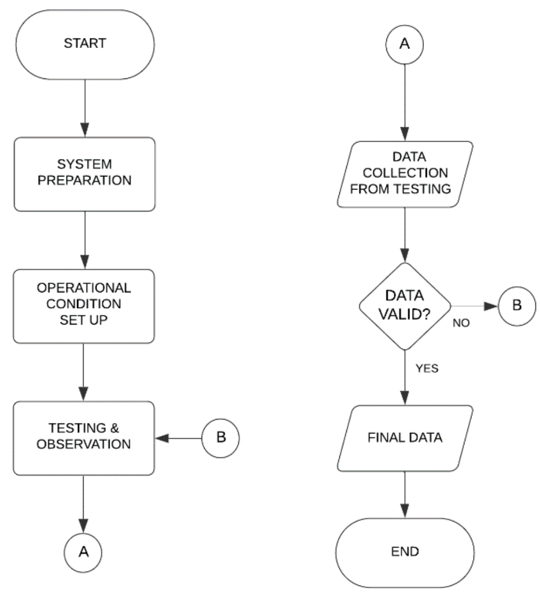


Figure 3. 8 *Data Collection Flow Chart*

Data collection was carried out on an electric vehicle using a regenerative braking system. The data collection includes testing under various operational conditions that were predefined. Factors such as charging cycles, vehicle speed, and operational battery temperature are the primary focus on the data collection in this study.

To measure the performance of the regenerative braking system and its effects on the battery degradation, various accurate measuring instrument were used. These include tools to monitor charging cycles, battery operational temperature, and other relevant measuring instruments. The data collection method used ensures that the obtained data can be used for comprehensive analysis.

The data collection scenario will involve the observation and measurement of the results from simulations conducted on an electric vehicle with regenerative braking system. Parameters observed include the number of battery charging cycles, battery temperature, and other effects of using the regenerative system. The data collection method will include the use of sensors installed on the vehicle and monitoring through appropriate software (controller).

3.4 Analysis Scenario

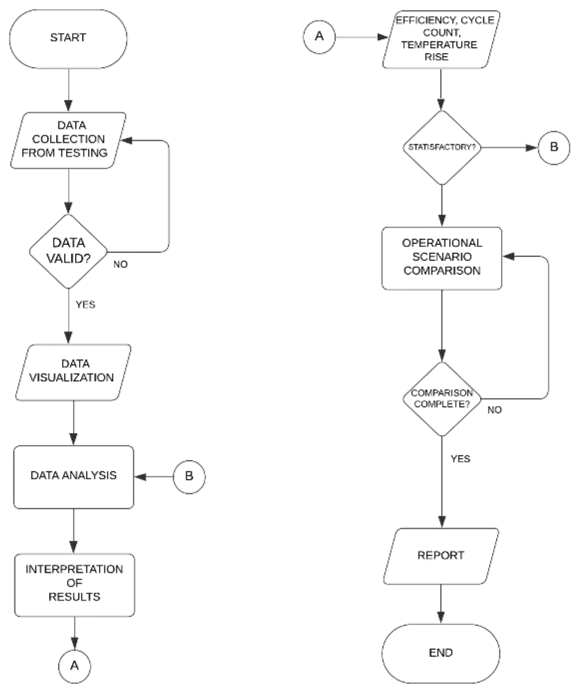


Figure 3. 9 *Analysis Scenario Flowchart*

After the data is collected from the field tests, an analysis scenario will be conducted to evaluate the performance of the regenerative braking system and its impact on the battery. The data obtained from the field testing will be analyzed using appropriate analytical methods, including statistical analysis to evaluate the relationship between the observed variables and battery degradation. This analysis will consider the influence of control on the regenerative braking system on the results obtained.

The analysis will include comparisons between various operational scenarios, identification of patterns emerging from the empirical data, and drawing conclusions regarding the effects of using control on the regenerative braking system on the battery degradation. The analytical methods to be used include statistical analysis, data visualization and a holistic interpretation of the results. The analysis will lead to conclusions that describe the impact of various factors influencing battery degradation in the regenerative braking system.

CHAPTER IV

RESULTS AND ANALYSIS

4.1 System Testing

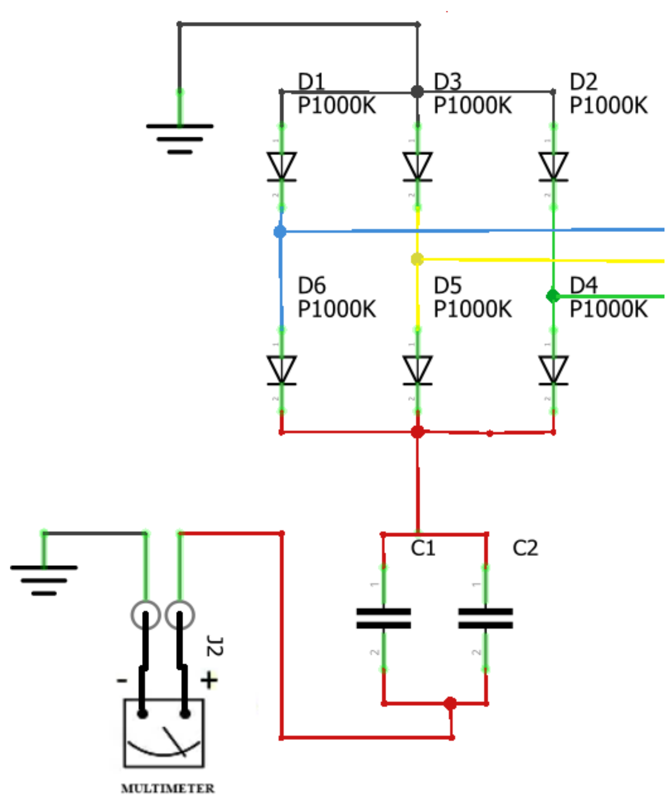


Figure 4. 1 *Schematic of Voltage Output Check for Regenerative Braking System*

The regenerative braking system testing begins in the lab on a test track using real vehicle. The initial phase involves testing the system's voltage output with motor suspended. In this phase, the functionality of the system and sensors is checked to ensure that no components are damaged. After that, the experiment proceeds with road testing to monitor the voltage output of the regenerative braking system under real conditions.

Figure 4. 2 *Voltage Output Check of the Regenerative Braking System*

In **Figure 4. 2**, the initial voltage produced is 49v, which is considered insufficient to charge the vehicle's battery. Therefore, a step-up converter is added to increase the voltage to 54.7v, meeting the battery charging requirements.

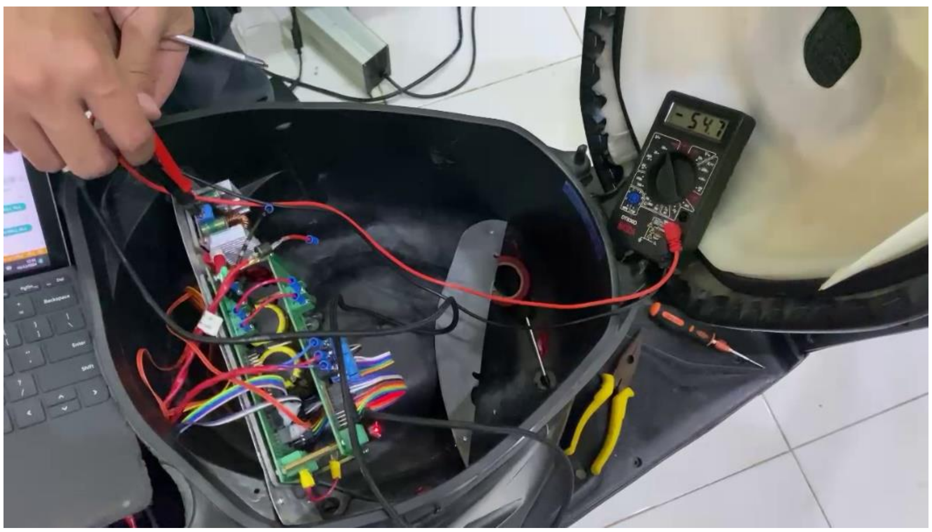


Figure 4. 3 *Voltage Check of the System with Step-up*

The testing procedure includes measuring parameters such as battery temperature, RPM, and time, all of which are done in real-time using integrated sensors. An IR sensor is used to measure the motor's RPM, while thermocouple sensor is used to monitor the battery temperature during regenerative braking.

Figure 4. 4 *Regenerative Braking System Load Testing Using a Battery Tester*

As part of the system validation, testing was conducted using a battery tester as shown in **Figure 4. 4** to ensure that the regenerative braking system functions according to specifications. The battery tester was used to measure the system's ability to generate current at specific loads. The test was carried out with varying loads of 4A, 6A, and 8A. the test results showed that the system was able to produce output consistent with the applied load, proving that the system can operate stably under these conditions.

The testing also included variations on the road with different speeds, adjusting to real-world driving conditions. Additionally, the comparison of regenerative braking systems with control (Fuzzy, Adaptive PID, and Hybrid Fuzzy-PID) and without control was performed to evaluate system performance in terms of charging cycles, efficiency, and battery temperature increase.

During testing, several technical challenges were encountered, including :

1) The initial output voltage of the regenerative braking system was only 49v, which was insufficient to charge a 13s battery. A step-up converter was added to increase the voltage.

2) When the system was connected to the battery, there were frequent damages to components such as diodes, relays, and burned cables due to high current draw. This issue was addressed by adding a thermistor to limit the initial inrush current, thus protecting the component.
3) Diodes often overheated and eventually failed. Another problem occurred with the relay, which sometimes got stuck in the ON position, causing the phase wires to remain connected to the diodes even when the system was off. This caused further damage to the diodes due to overheating.

The regenerative braking system was designed separately from the vehicle's BLDC motor controller. The phase wires from the BLDC motor were connected to the regenerative braking system, which includes a rectifier to convert AC to DC. The converted current was filtered using capacitors, then directed to a step-up converter to raise the voltage to 54.7v. The output from the step-up converter was connected to the battery with additional thermistor and diodes to prevent reverse current from the battery, which could damage the system.

4.2 Regenerative Braking System with No Control

The regenerative braking system was first tested without any control algorithm in place as a baseline. This approach allowed for the observation of the system's natural performance and behavior under basic conditions. By operating the system without control algorithm, it was possible to establish a reference point for subsequent tests that involve control strategies.

The results of the regenerative braking testing without control showed a battery temperature increase of 77.86% during the test, with an initial temperature of 36.75ºC at the start of the log, and an overall average temperature of 65.46ºC. During the regenerative braking process, the average RPM was recorded at 341.73 RPM. Additionally, the braking status distribution showed 285 instances of braking OFF and 122 instances of braking ON, with an estimated current of 2.65A during braking ON. The recorded number of charging cycles was 31 cycles, with total charging cycle duration of 122 seconds, and a charging efficiency of 93.60%.

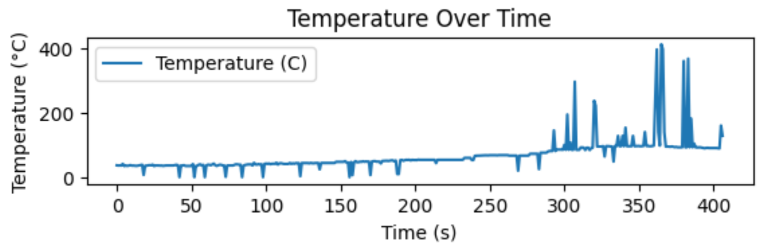


Figure 4. 5 *Graph of Temperature vs. Regenerative Braking Time with No Control*

Figure 4. 5 shows a temperature increase of 77.86% during the testing, indicating a significant energy loss, where most of the energy generated by the system is converted into heat. This suggests that although the system operates efficiently, much of the energy cannot be optimally utilized and is wasted as heat. This continuous temperature increase can accelerate battery degradation, as higher temperatures can speed up chemical reactions in the battery, increase internal impedance, and worsen battery capacity over time.

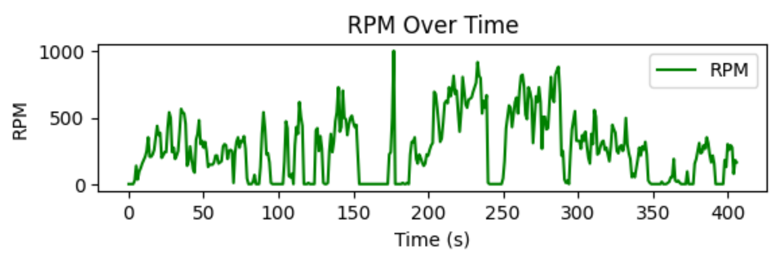


Figure 4. 6 *Graph of RPM vs. Regenerative Braking Time with No Control*

The number of charging cycles that occur indicates that the system is still suboptimal in capturing regenerative energy. The rapid charging process leads to short charging cycles, meaning energy is not utilized to its full potential. Quick and unstable charging cycles can also put stress on the battery, increasing the strain on the battery cells and potentially accelerating capacity degradation. Although the system's efficiency is recorded as quite high, these limited charging cycles suggest that the system could perform better in managing and optimizing the energy generated, as well as minimizing energy losses and the negative impact on battery degradation.

Table 4. 1 *Table of Results with No Control*

Control Type	Initial Temperature	Average Temperature	Temperature Rise	Total Cycles	Charging Efficiency
No Control	36.75ºC	65.46ºC	77.86%	31	93.60%

Table 4. 1 presents the results of regenerative braking system with no control, showing a total of 407 data, the braking status distribution consist of 285 instances with Braking OFF and 122 instances with Braking ON.

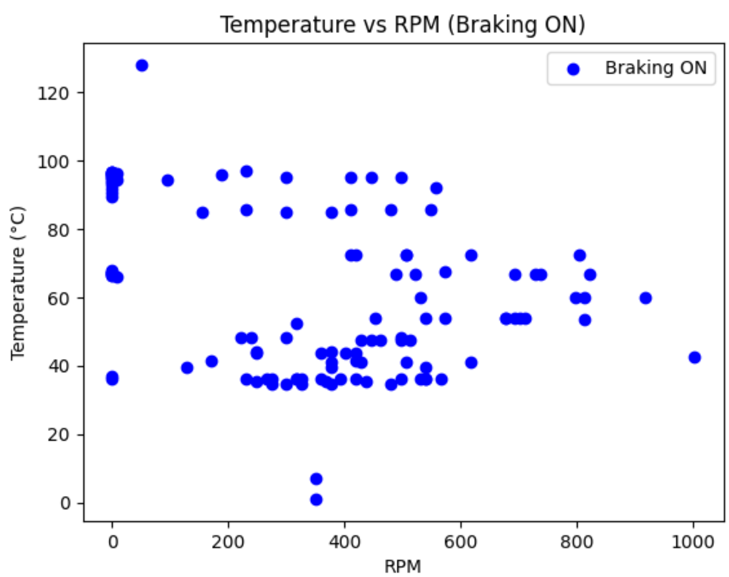


Figure 4. 7 *Scatter Plot of Regenerative Braking with No Control*

The scatterplot in **Figure 4. 7** reveals most data points clustered between 60-80ºC for RPMs in the 200-600 range, where braking is likely more consistent. This indicates that during medium RPM ranges, the braking system operates effectively, generating heat as byproduct of energy conversion. However, as RPM increases beyond 600, the decrease in temperature suggest that braking is either less active or completely off, leading to lower heat generation.

4.3 Regenerative braking System with Fuzzy Logic Control

The results of the regenerative braking test with fuzzy logic show an initial temperature of 30.00°C and overall average temperature of 34.44°C from the log data, indicating a temperature increase of 14.80%. This increase is lower compared to the system with no control, suggesting that fuzzy logic is able to manage regenerative energy more effectively, thus reducing wasted heat.

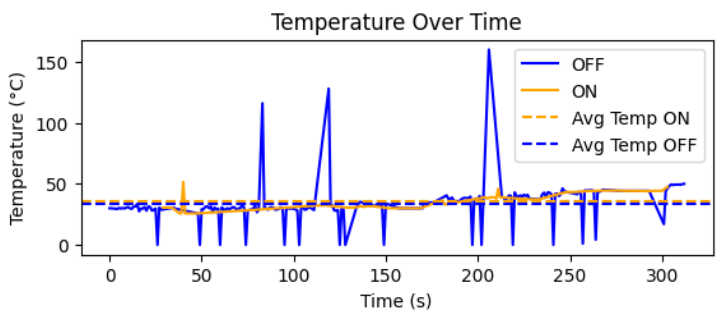


Figure 4. 8 *Graph of Temperature vs. Regenerative Braking Time with Fuzzy Logic*

During the braking ON condition, the average recorded temperature was 35.81°C, with an average of rotational speed (RPM) of 745.62, indicating that the system operated at high speed and within optimal temperature range. Conversely, during braking OFF, the average temperature recorded was 33.88°C with an RPM of 378.56, showing that the system avoided activation at lower speeds to prevent inefficient charging.

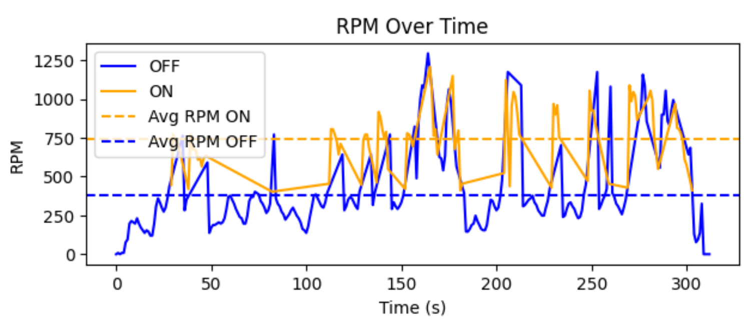


Figure 4. 9 *Graph of RPM vs. Regenerative Braking Time with Fuzzy Logic*

The distribution of braking status showed 90 instances of regenerative braking ON and 223 instances of braking OFF, indicating that the fuzzy logic activated regenerative braking only under optimal conditions, thereby enhancing energy efficiency.

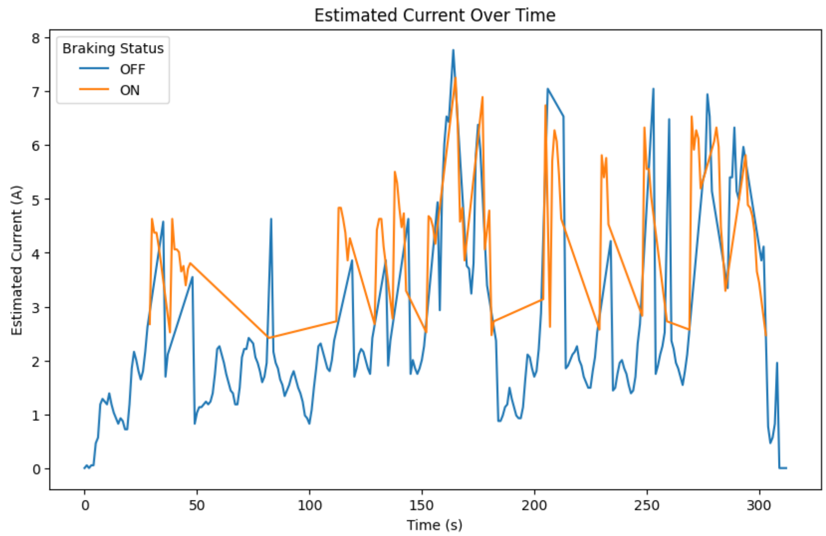


Figure 4. 10 *Graph of Estimated Current vs. Regenerative Braking Time with Fuzzy Logic*

The estimated average current generated during braking ON was 4.48A. the total recorded number of charging cycles was 19, with a total duration of 90 seconds, resulting in an estimated total energy output of 25,923.74 Watt-seconds (Joules).

Table 4. 2 *Table of Results with Fuzzy Logic*

Control Type	Initial Temperature	Average Temperature	Temperature Rise	Total Cycles	Charging Efficiency
Fuzzy Logic	30.00ºC	34.44ºC	14.80%	19	38.64%

Table 4. 2 presents the results of regenerative braking system with fuzzy logic, showing a total of 313 data, the braking status distribution consist of 223 instances with Braking OFF and 90 instances with Braking ON.

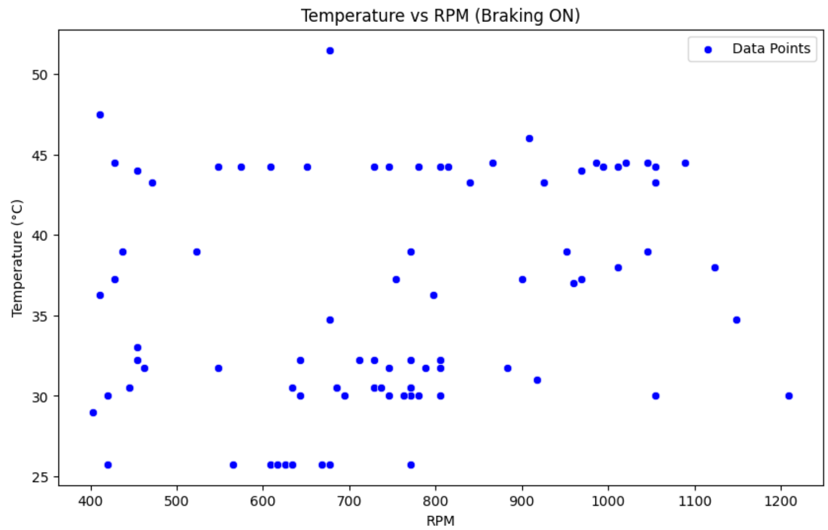


Figure 4. 11 *Scatter Plot of Regenerative Braking with Fuzzy Logic*

The scatter plot shown in **Figure 4. 11** illustrates the relationship between RPM and temperature during the braking ON condition. The temperature range observed in the plot appears more controlled compared to the no control scenario, staying within approximately 25ºC to 50ºC. This suggest that the fuzzy logic contributes to maintaining thermal stability during regenerative braking, even at varying RPM levels.

4.4 Regenerative Braking System with Adaptive PID

The results of the regenerative braking system test with adaptive PID showed a temperature increase from 30.5ºC to an average of 37.48ºC, reflecting a temperature rise of 22.89%. the average temperature during braking ON was recorded at 38.35ºC. This indicates that, although the system generates energy during braking, a significant portion of the recovered energy is dissipated as heat due to internal resistance and conversion inefficiencies.

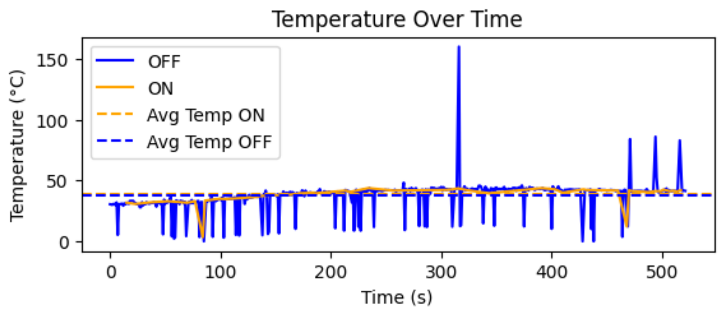


Figure 4. 12 *Graph of Temperature vs. Regenerative Braking Time with Adaptive PID*

The braking status distribution indicates that the system remained in braking OFF mode most of the time, with total of 470 occurrences compared to only 52 occurrences for braking ON. This may suggest that the system does not frequently activate the regenerative braking mode, potentially due to non-optimal RPM values or PID parameters.

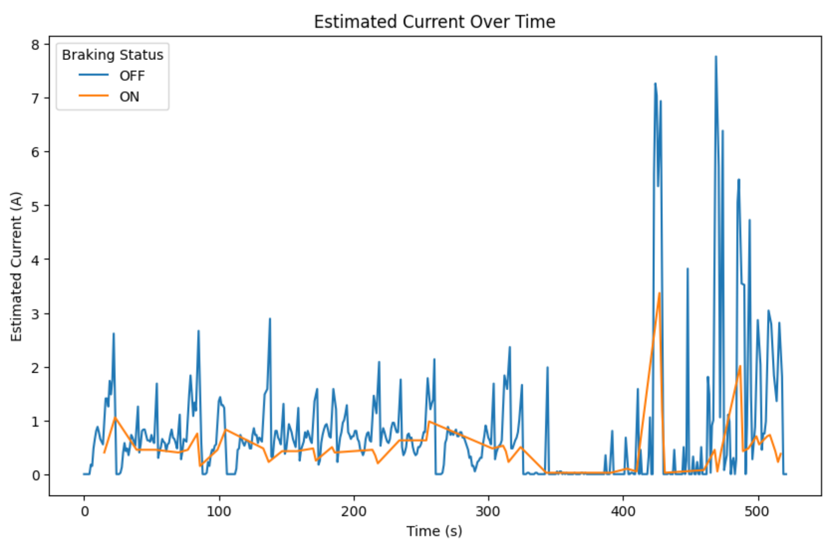


Figure 4. 13 *Graph of Estimated Current vs. Regenerative Braking Time with Adaptive PID*

The estimated current generated during regenerative braking was relatively small, with an average current of 0.52A during braking ON. This value significantly lower compared to testing with no control, indicating that the system was unable to fully utilize the potential regenerative energy.

From the testing results, a total of 52 charging cycles were recorded with total duration of 52 seconds, yielding a total energy output of 1762.14 Watt-Seconds (Joules). The overall charging efficiency reached only 6.18%, highlighting the need for further improvement in the adaptive PD control system to optimize the capture of regenerative energy. Further tuning of PID parameters and adjustments to the RPM threshold are required to enhance the system's responsiveness to a broader range of braking conditions.

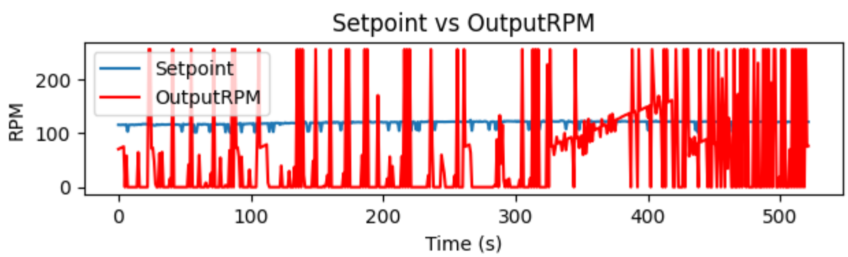


Figure 4. 14 *Graph of Setpoint vs. OutputRPM in Adaptive PID*

The relatively high number of charging cycles is likely caused by the phenomenon of bouncing in the OutputRPM variable (PID output), which occurs when its value oscillates around the setpoint threshold determined by the PID control, as shown in **Figure 4. 14**. When OutputRPM approaches the setpoint value, the small changes in the measured RPM causes the system to continuously switch between ON and OFF states within a short period. This results in a higher number of charging cycles, despite the short charging durations and relatively low energy output.

Table 4. 3 *Table of Results with Adaptive PID*

Control Type	Initial Temperature	Average Temperature	Temperature Rise	Total Cycles	Charging Efficiency
Adaptive PID	30.5ºC	37.48ºC	22.89%	52	6.18%

Table 4. 3 presents the results of regenerative braking system with adaptive PID, showing a total of 522 data, the braking status distribution consist of 470 instances with Braking OFF and 52 instances with Braking ON.

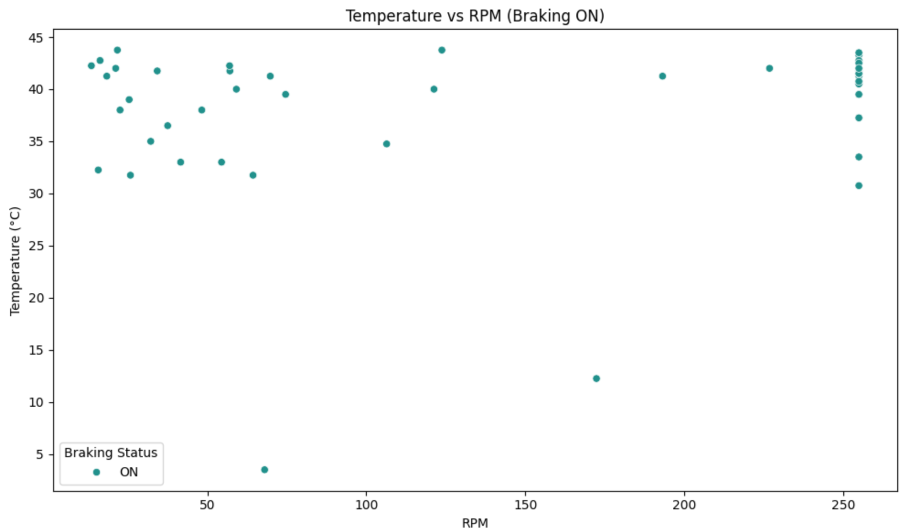


***Figure 4. 15** Scatter Plot of Regenerative Braking with Adaptive PID*

The scatter plot shown in **Figure 4. 15** demonstrates the relationship between temperature and RPM during the Braking ON condition. From the graph, it is evident that most data points are concentrated at lower RPM (below 250 RPM), with a range of temperatures spanning approximately 5ºC to 45ºC. The clustering of points at specific RPM levels may suggest consistent system performance or limited variation in braking condition at those RPMs.

4.5 Regenerative Braking System with Hybrid Fuzzy-PID

4.5.1 SetPoint : 100, OutputRPM > 30 ON

The log results show an initial temperature of 28.5ºC, which increased to an average of 38.5ºC after the regenerative braking process, representing a temperature rise of 36.28%. This increase indicates significant energy conversion into heat during braking, suggesting that a substantial portion of the energy is still lost as heat. The system's efficiency remains hindered by energy losses in the form of heat.

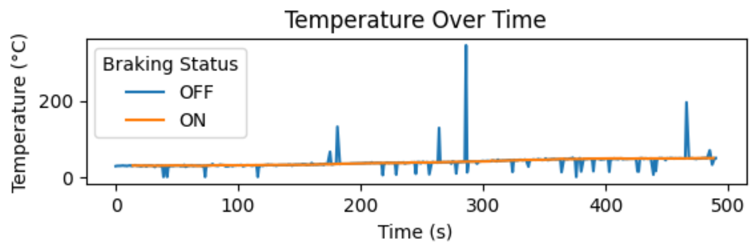


Figure 4. 16 *Graph of Temperature vs. Regenerative Braking Time with Hybrid Fuzzy-PID 1*

The average temperature during braking ON was recorded at 40.55°C, while during braking OFF, the average temperature was slightly lower at 38.32°C. The decrease in temperature when braking is deactivated indicates that the regenerative braking system generates more heat when active, reflecting the conversion of mechanical energy into electrical energy. However, despite the temperature increase during active braking, the recorded RPM during braking ON was very low at 122.57 RPM. This could be attributed to a threshold RPM that is set too high.

The braking status distribution shows the system was in braking OFF mode 451 times and in braking ON mode only 40 times. This indicates that, although the system is designed to activate regenerative braking under certain conditions, regenerative braking occurred in very limited cycles. This might be due to a control setting requiring the RPM to reach a certain threshold, which is further adjusted by temperature, thereby reducing the frequency of regenerative braking activation. During the test, 40 braking cycles were recorded with a total cycle duration of 40 seconds. During these cycles, the system delivered a total energy output of 1580.12 Watt-Seconds (Joules).

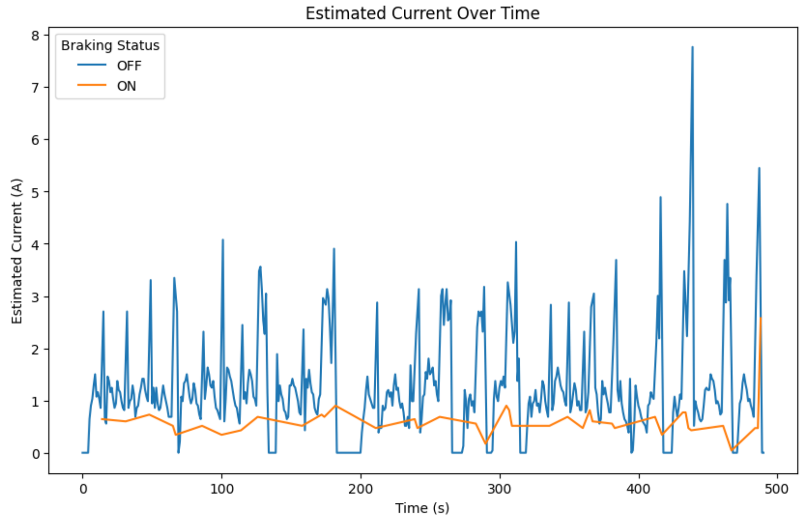


Figure 4. 17 *Graph of Estimated Current vs. Regenerative Braking Time with Hybrid Fuzzy-PID 1*

In terms of current, the estimated average current during braking ON was 0.16A, which is significantly lower compared to the average current during braking OFF, recorded at 1.18A. This comparison indicates that less energy was recovered during active braking. The total charging efficiency was recorded at 5.90%, demonstrating that the system managed to recover only a small fraction of the energy lost during braking.

4.5.2 SetPoint : 100, OutputRPM >10 ON

In this log, the initial recorded temperature was 32.75ºC, which increased to an average of 44.28ºC, representing a temperature rise of 35.21%. This increase indicates a significant conversion of kinetic energy into heat, signifying that a portion of the energy from regenerative braking was lost as heat during the process.

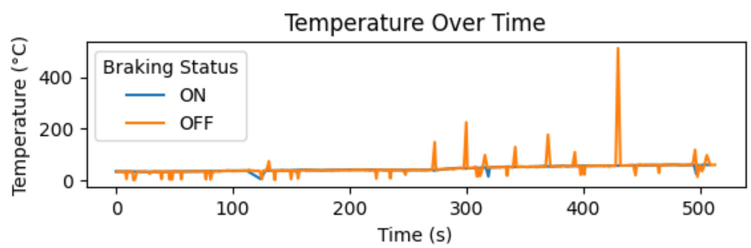


Figure 4. 18 *Graph of Temperature vs. Regenerative Braking Time with Hybrid Fuzzy-PID 2*

The average temperature during braking ON was recorded at 42.27°C, while during braking OFF, the temperature decreased slightly to 44.12°C. this small temperature difference between the two conditions indicates that, although the system was active during the charging cycles, the regeneration process did not result in a significant temperature increase.

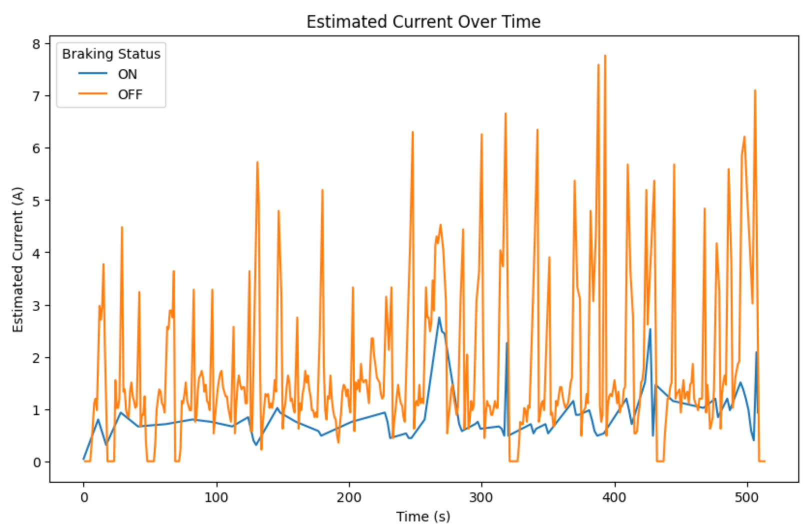


Figure 4. 19 *Graph of Estimated Current vs. Regenerative Braking with Hybrid Fuzzy-PID 2*

The estimated average current during braking ON was recorded at 0.91A, while during braking OFF it was 1.59A. This indicates that the current generated during regenerative braking was lower than when the system was inactive.

Although the system was active in charging during braking, the current generated was still relatively low.

During testing, a total of 70 charging cycles were recorded, with a total duration of 72 seconds. The total energy recovered amounted to 4211.43 Watt-Seconds (Joules), with an overall charging efficiency of 15.01%.

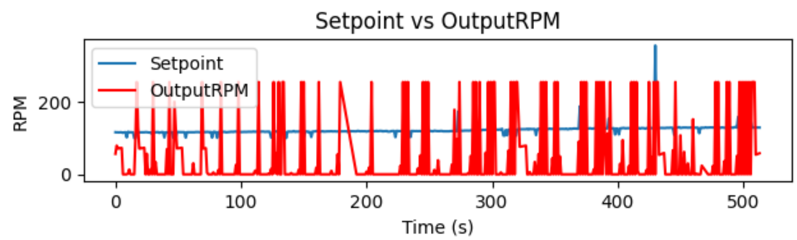


Figure 4. 20 *Graph of Setpoint vs. OutputRPM in Hybrid Fuzzy-PID 2*

The high number of recorded charging cycles was caused by the bouncing phenomenon in the OutputRPM variable, which occurred when its value fluctuated around the system activation threshold. When the OutputRPM exceeded the threshold, the system activated regenerative braking, while drop below the threshold caused the system to deactivated braking. This process resulted in numerous charging cycles with short durations.

Table 4. 4 *Table of Results with Hybrid Fuzzy-PID 1*

Control Type	Initial Temperature	Average Temperature	Temperature Rise	Total Cycles	Charging Efficiency
Hybrid Fuzzy-PID 1	28.5ºC	38.5ºC	36.28%	40	5.90%

Table 4. 4 presents the results of regenerative braking system with hybrid Fuzzy-PID 1, showing a total of 491 data, the braking status distribution consist of 451 instances with Braking OFF and 40 instances with Braking ON.

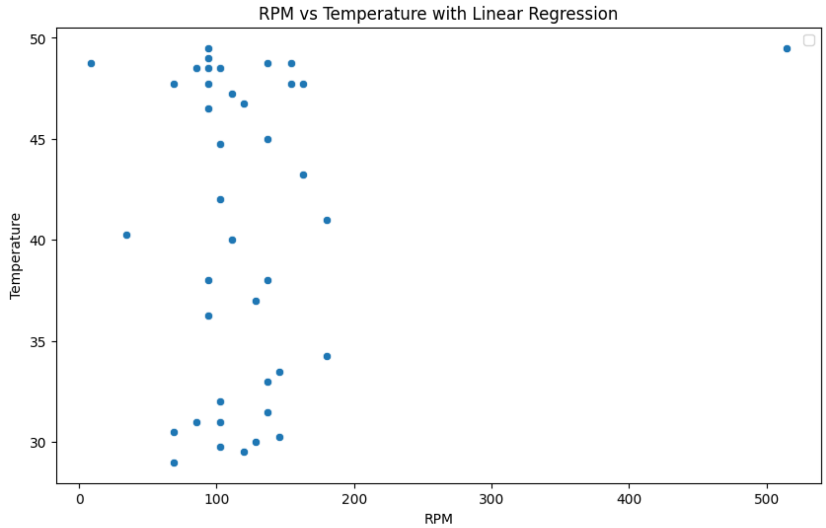


Figure 4. 21 *Scatter Plot of Regenerative Braking with Hybrid Fuzzy-PID 1*

Figure 4. 21 shows the relationship between RPM and temperature during the Braking ON state, alongside the linear regression line. The distribution of data points reflects significant variability, with clusters at specific RPM ranges and some outliers. The observed temperature range appears to be concentrated mostly between 30ºC and 50ºC, showing that the system operates within a controlled thermal range.

Table 4. 5 *Table of Results with Hybrid Fuzzy-PID 2*

Control Type	Initial Temperature	Average Temperature	Temperature Rise	Total Cycles	Charging Efficiency
Hybrid Fuzzy-PID 2	32.75ºC	44.28ºC	35.21%	70	15.01%

Table 4. 5 presents the results of regenerative braking system with hybrid Fuzzy-PID 2, showing a total of 514 data, the braking status distribution consist of 442 instances with Braking OFF and 72 instances with Braking ON.

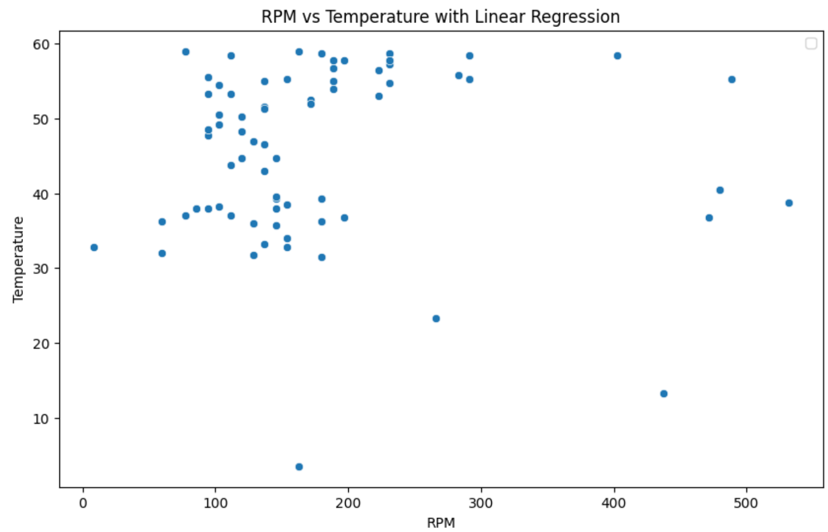


Figure 4. 22 Scatter Plot of Regenerative Braking with Hybrid Fuzzy-PID 2

In **Figure 4. 22**, the regression line is almost flat, indicating an extremely weak or negligible correlation between RPM and temperature. This implies that the temperature remains relatively stable regardless of RPM changes, this may be due to the regenerative braking only active in low RPM conditions. The data points reveal a significant clustering around the temperature range of 40ºC to 60ºC, with most points concentrated at lower to mid-range RPM values. There are also few notable outliers, with temperatures falling below 30ºC or above 60ºC, which might indicate exceptional conditions or measurements anomalies.

4.6 Summary of Results

Table 4. 6 summarizes the test results of the regenerative braking system for various implemented control methods: no control, fuzzy logic, adaptive PID, and hybrid Fuzzy-PID. The results demonstrate differing trends in efficiency, temperature management, charging cycles, and their impact on battery degradation,

In the no control scenario, the system exhibited the highest temperature increase of 77.86%, indicating significant energy loss in the form of heat. Charging efficiency was the highest at 93.60% due to the absence of control restriction that could limit the energy transfer to the battery. However, the high operating temperature and the 31 recorded charging cycles could accelerate battery degradation. Short charging cycles and frequent charging increase thermal and electrochemical stress on the battery cells, which can reduce storage capacity and battery life over time.

Testing with fuzzy logic showed significant improvements in temperature stability, with temperature increase of only 14.80%. The number of charging cycles decreased to 19, indicating more optimal control in capturing regenerative energy without overburdening the battery. Charging efficiency dropped to 38.64%, but the reduction in energy loss as heat helped slow thermal degradation of the battery. This approach demonstrates a balance between utilizing regenerative energy and maintaining long-term battery health.

The adaptive PID scenario resulted in the highest number of charging cycles, at 52, with the lowest charging efficiency of 6.18%. Instabilities in the OutputRPM variable, which often oscillated around the setpoint threshold, caused frequent ON-OFF transitions within a single braking cycle, resulting in an unstable charging pattern. This pattern can accelerate electrochemical degradation, particularly due to stress on electrode materials from fluctuating currents. Additionally, the temperature increase of 22.89%, although lower than in the no control scenario, still posed a significant thermal impacts on the battery.

For the hybrid Fuzzy-PID, two variations were evaluated based on the OutputRPM threshold: > 30 and > 10. The higher threshold (OutputRPM > 30) resulted in 40 charging cycles with a temperature increase of 36.28% and charging efficiency of 5.90%. In contrast, the lower threshold (OutputRPM > 10) increased the number of cycles to 70, with the largest temperature increase of 25.21% and higher charging efficiency of 15.01%. In both hybrid Fuzzy-PID scenarios, charging was more stable compared to adaptive PID control. However, the increased number of cycles at the lower threshold suggests potential for faster battery degradation due to more frequent charging processes. Similar to adaptive PID control, instabilities in OutputRPM oscillating around the setpoint threshold caused repeated ON-OFF transitions within a single cycle.

The results across all control and non-control methods highlight a trade-off in the design of regenerative braking systems. Systems without control achieve higher efficiency but are thermally unstable and result in shorter charging cycles, increasing stress on the battery. Fuzzy logic provides better thermal stability, reduces charging cycles, and mitigates battery degradation. Adaptive PID requires further refinement to prevent current fluctuations that may accelerate degradation. Hybrid Fuzzy-PID control offers better flexibility in managing charging cycles, but the results indicate that this approach does not always provide an optimal balance between charging efficiency and cycle management. In scenarios with a low threshold, the increased number of cycles may heighten the risk of battery degradation due to more frequent charging processes.

Table 4. 6 *Comparison of Control Types*

Control Type	Initial Temp	Final Temp	Total Cycle	Charging Efficiency
No Control	36.75ºC	65.36ºC	31	93.60%
Fuzzy	30.00ºC	34.44ºC	19	38.65%
PID Adaptive	30.5ºC	37.4ºC	52	6.18%
Hybrid Fuzzy-PID 1	28.2ºC	38.50ºC	40	5.90%
Hybrid Fuzzy-PID 2	32.7ºC	44.28ºC	70	15.01%

Table 4. 6 highlights a clear trade-off between cycle count, temperature rise, and efficiency across different control methods. The No Control method demonstrates the highest efficiency (93.60%), making it ideal for energy conservation. However, this comes at the cost of a significant temperature rise (from 36.75ºC to 65.36ºC), which poses a risk of thermal damage. The cycle count (31 cycles) is moderate, suggesting balanced yet limited control duration.

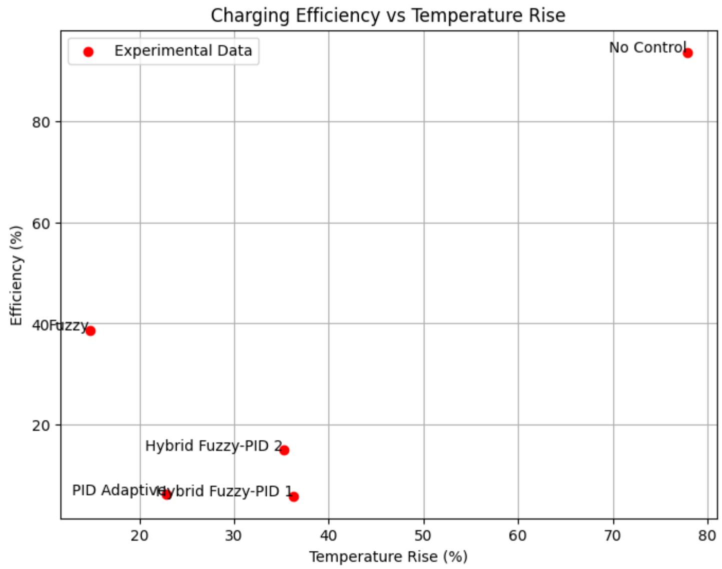


***Figure 4. 23** Charging Efficiency vs Temperature Rise Graph*

The relationship between efficiency and temperature rise in Figure 4. 23 demonstrates a clear trade-off. As efficiency increases, the temperature rise also becomes more significant. The "No Control" method achieves the highest charging efficiency (93.60%), but it also results in the highest temperature rise (77.86%), which can be detrimental to system components.

On the other hand, control methods such as Fuzzy Logic, Adaptive PID, and Hybrid Fuzzy-PID exhibit a more balanced approach, where charging efficiency is lower, but temperature rise is significantly reduced. The Fuzzy Logic, for example shows a charging efficiency of 38.64% while keeping the temperature rise at much lower level (14.80%).

This trade-off implies that if maximizing charging efficiency is the main priority, proper thermal management is crucial to prevent overheating. Conversely, if maintaining a lower temperature rise is the focus, charging efficiency must be sacrificed to some extent.

The Fuzzy Logic method prioritizes minimizing temperature rise, achieving the lowest temperature rise of 14.80% and a total charging cycle of 19 cycles. This approach significantly reduces the risk of battery degradation but compromises efficiency, which drops to 38.65%.

The Adaptive PID and Hybrid Fuzzy-PID methods exhibit unstable current generation due to the bouncing phenomenon in OutputRPM. This instability negatively impacts both efficiency and the factors contributing to battery degradation. The bouncing phenomenon leads to an increase in the total number of charging cycles, which places additional stress on the battery and accelerates its degradation. Furthermore, the drop in efficiency is attributed to the fact that in these methods, the braking ON condition is only active at low RPM ranges, significantly reducing current generation and overall efficiency. However, despite these limitations, these methods successfully minimize the temperature rise, which could partially mitigate the adverse effects of battery degradation.

CHAPTER V

CONCLUSION

This thesis evaluates a regenerative braking system using four approaches: no control, fuzzy logic, adaptive PID, and hybrid Fuzzy-PID for electric vehicles with Lithium Ion type battery. Based on the research findings, several conclusions can be drawn in line with the formulated problem statements and hypotheses :

1. The regenerative braking system with fuzzy logic demonstrated the best performance, achieving energy efficiency of 38.65%, higher than adaptive PID (6.18%) and hybrid Fuzzy-PID 1 (5.90%). The battery's operational temperature increased only from 30.00^{o}C to 34.44^{o}C, the smallest rise compared to other methods. Additionally, fuzzy logic resulted in only 19 charging cycles, fewer than the no control system (31 cycles) or Hybrid Fuzzy-PID 2 (70 cycles).
2. Testing of regenerative braking systems with adaptive PID and hybrid Fuzzy-PID produced a large number of cycles due to the oscillation of the PID OutputRPM variable around the setpoint, as shown in **Figure 4. 12** and **Figure 4. 17**. This caused frequent ON-OFF transitions within a single cycle, resulting in unstable current generation.
3. Implementing control mechanism in the regenerative braking system significantly reduced temperature increases, minimized charging cycles, and improved efficiency, as shown in **Table 4. 6**. Collectively, these improvements help mitigate battery degradation.
4. The application of fuzzy logic in this study effectively reduced battery degradation by decreasing charging cycles and limiting temperature rise. In contrast, while adaptive PID and hybrid Fuzzy-PID managed to reduce battery temperature increases during regenerative braking, they also increased the number of short-duration charging cycles and produces unstable currents.
5. The trade-off between charging efficiency and temperature rise implies that if maximizing charging efficiency is the main priority, proper thermal management is crucial.

6. If maintaining lower temperature rise is the focus, charging efficiency must be sacrificed to some extent.
7. The regenerative braking system does not impact vehicle braking performance as it does not generate braking force.

For future research, several limitations can be addressed, including :

1. Optimizing PID and fuzzy parameters to achieve a more stable and optimal system.
2. Incorporating additional relevant sensors, such as battery SoC and current sensors, to provide more comprehensive data for enhanced control decision-making.
3. Conducting long-term analysis to evaluate the prolonged effects of the regenerative braking system on battery health.
4. Introducing techniques to inject the current generated from regenerative braking back into the BLDC motor to produce back EMF, which could generate braking force.

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