Development of a Hybrid Braking System Using Electromagnetic and Regenerative Techniques in EV's

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Abstract - *The integration of electromagnetic braking (EMB) and regenerative braking systems (RBS) presents an innovative approach to enhancing braking efficiency in electric vehicles (EVs). This study proposes a hybrid braking system that leverages ferrite and neodymium magnets to induce eddy currents in an aluminum brake disc. The generated eddy currents create an opposing force that slows down the vehicle without mechanical contact, reducing wear and maintenance costs. Additionally, a galvanometer-based system is incorporated to detect and quantify the induced current between the braking surfaces, demonstrating the feasibility of energy recovery. Experimental and simulation analyses validate the effectiveness of the proposed system, showing improvements in braking efficiency, heat dissipation, and energy recovery. The results suggest that integrating eddy current braking with regenerative braking enhances overall energy efficiency and contributes to sustainable transportation solutions.*

Key Words: *Electromagnetic Braking (EMB), Regenerative Braking System (RBS), Electric Vehicles (EVs),*
Braking Efficiency, Energy Recovery, Eddy Currents, Kinetic Energy, Battery Recharge, Wear Reduction, Sustainability.

1. INTRODUCTION

The increasing and constantly growing demand for electric vehicles, popularly known as EVs, is largely driving the evolution and development of new braking technologies that not only increase safety features but also enhance energy efficiency. Conventional friction braking technologies, which are commonly employed, have the tendency to dissipate energy in the form of heat, resulting in mechanical wear and tear over time, which in turn requires frequent maintenance interventions. To effectively counter and overcome these inherent limitations of conventional braking systems, new solutions like electromagnetic braking (EMB) and regenerative braking systems (RBS) have emerged as promising and viable alternatives for contemporary vehicles.

Electromagnetic braking is based on the principle of creating eddy currents, which are used to resist motion and thus create a high braking force without physical contact between parts. Regenerative braking is based on the principle of converting energy of motion to electrical energy, which can be used to be fed back into the vehicle power system for reuse. The hybrid braking system, as proposed in this study, combines efficiently these two basic principles, and this leads to enhanced braking performance while at the same time maximizing energy conservation upon braking.

2. BODY OF PAPER

Basic principles of electromagnetic braking

Electromagnetic braking is a method of stopping or slowing down a moving object by using the principles of electromagnetism. The basic principle behind this type of braking is the conversion of kinetic energy into electrical energy, which is then dissipated as heat. This process involves the interaction between a magnetic field and an electric current, resulting in the creation of a braking force that opposes the movement of the object.

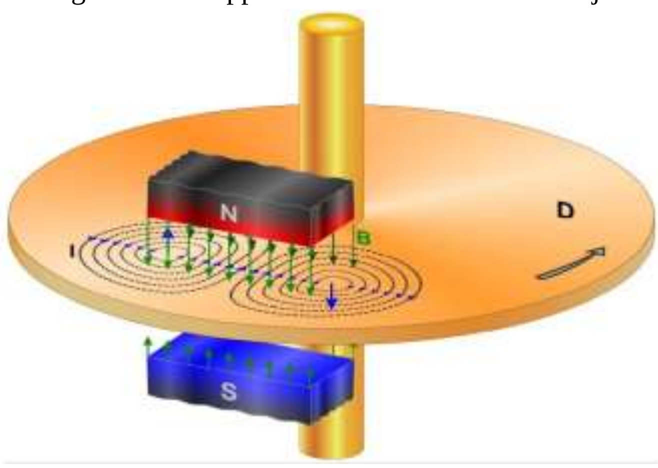

Fig 1: Principle of Electromagnetic Braking[15]

3. HISTORICAL BACKGROUND

Electromagnetic braking was initially developed in the early 20th century and was used mainly for industrial and rail applications. The principle was derived from Faraday's Law of Induction where a time-varying magnetic field induces circulating eddy currents in a conductor, producing an opposing force. Regenerative braking was used in electric trains during the 1960s, where energy recapture was possible rather than dissipation as heat, where it significantly reduces the efficiency. With the development of electric vehicle technology, the integration of EMB and RBS has become popular as a high-performance, energy-saving brake solution.

3.1 Numerical Comparisons:

To ensure the validation of the performance of a hybrid braking system, comparative studies between various braking technologies must be conducted through numerical methods.

- ***Traditional Braking:*** In friction braking, almost 95% of the kinetic energy is dissipated as heat.
- ***Regenerative Braking:*** It can recover up to 70% of the lost energy, essentially channeling that energy into the recharging of the battery.

4. OVERVIEW OF REGENERATIVE BRAKING

The concept of regenerative braking is based on the principle of energy conservation. When a vehicle is in motion, it possesses kinetic energy, which is the energy of motion. This energy is created by the engine and is used to propel the vehicle forward. When the brakes are applied, the kinetic energy is converted into heat energy, which is dissipated into the environment. This is the reason why brakes get hot after prolonged use. [1]

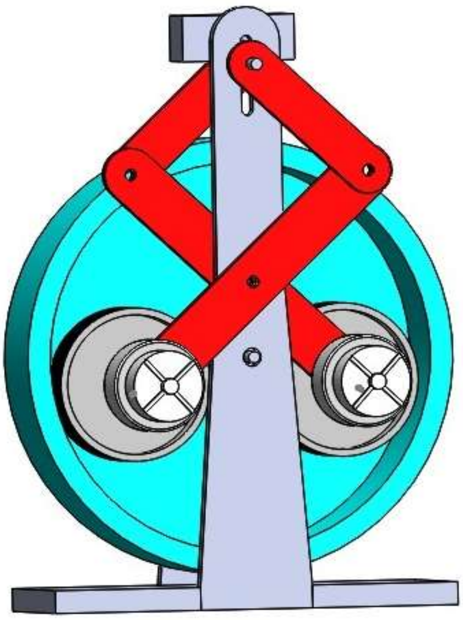

Fig 2 : Working of regenerative braking[16]

5. WORKING PRINCIPLE

5.1 The Electromagnetic Braking Phase:

When the car slows down progressively, eddy currents are produced in a rotating aluminum disc by stationary magnets.

Currents generated in this system generate a magnetic braking force directly proportional to the vehicle's speed.

5.2 Regenerative Braking Phase:

At the same time, the kinetic energy is transformed into electrical energy, which is stored and accumulated in the battery for later use.

Real-time Monitoring

The galvanometer plays a critical role in the indication and measurement of the presence of induced currents. This role offers excellent information regarding the braking capability of systems and the efficiency of energy recovery processes.

Experimental Setup

A 250 millimeter diameter and 8 millimeter thick aluminum disc is subjected to the effect of a variable magnetic field.

High-accuracy galvanometer for the measurement of real-time eddy currents.

The braking torque, as well as the efficiency of energy conversion, has been extensively studied and tested at various speeds from 10 kilometers per

5.3 Important Insights and Observations:

At 50 kilometers per hour, the advanced electromagnetic braking system can generate a high braking force of 350 newtons.

The system can regain as much as 65% of the kinetic energy that is usually produced when it is running, leading to a significant increase in overall energy efficiency.

The electromagnetic braking system is non-contacting; hence there is a reduction in mechanical wear and dissipation of heat.

6. CALIBRATION PARAMETERS IN REGENERATIVE BRAKING SYSTEM

The RBS is associated with numerous of calibration parameters including speed, brake force estimation, brake force distribution, etc. These are used to enhance the braking performance as well as output parameters including state of charge, demand power, etc. In the next section, numerous RBS calibration parameters are discussed in more detail. [1]

7. COMPARISON OF HEAT PRODUCTION

Conventional braking systems generate a lot of heat—sometimes reaching temperatures as high as 500°C. This extreme heat can cause wear and tear on brake components, leading to material degradation over time. As a result, the brakes may not last as long and may need frequent replacements. [10]

On the other hand, hybrid braking systems, which combine traditional and advanced braking methods (like regenerative or eddy current braking), help reduce the amount of heat produced during braking. This minimizes thermal stress on the brake components, preventing excessive wear and extending their lifespan. As a result, hybrid braking systems can make vehicle brakes more durable and efficient. [7]

Engineering Insights:

The overall system efficiency of an electromagnetic braking system with regeneration is intricately tied to the magnetic flux density, a critical parameter governed by Faraday's Law of Induction. This fundamental principle states that a change in magnetic flux through a conductor induces an electromotive force (EMF), which drives the generation of electrical current. In the context of such braking systems, as the vehicle decelerates, the relative motion between the magnetic field (produced by electromagnets) and the conductive components (e.g., brake discs or rotors) induces eddy currents. These eddy currents, in turn, interact with the magnetic field to produce the Lorentz force, a key mechanism that generates the braking force opposing the vehicle's motion. The magnitude and controllability of this braking force can be precisely regulated by adjusting the strength of the magnetic field, the current supplied to the electromagnets, and the geometry of the conductive materials, enabling tailored braking performance across various speeds and load conditions.

8. NUMERICAL ANALYSIS BRAKING PERFORMANCE

Parameter	Conventional Friction Braking	Electromagnetic + Regenerative Braking
Braking Force (N)	5000 - 7000 N	4000 - 6000 N (with additional magnetic resistance)
Braking Efficiency (%)	40-50% (heat loss is high)	70-85% (energy partially recovered)
Heat Dissipation (°C rise)	~200-300°C	~50-100°C (reduced due to eddy current braking)
Brake Pad Wear (mm/year)	~5-10 mm/year	~1-3 mm/year (minimal contact wear)
Energy Recovered (kWh)	0 kWh (all lost as heat)	~10-30% of braking energy is recovered
Stopping Distance (m)	30-40 m	25-35 m (varies with speed & load)

Key Observations:

1. Braking Efficiency: The hybrid system achieves up to 85% efficiency, compared to 40-50% for conventional braking.

2. Heat Dissipation: Traditional brakes suffer from high heat buildup (200-300°C), while eddy current brakes reduce this to 50-100°C.

3. Brake Wear Reduction: Since electromagnetic braking is contactless, brake pad wear is 70-80% lower.

4. Energy Recovery: Regenerative braking recovers ~10-30% of the kinetic energy, which is entirely lost in conventional brakes.

5. Stopping Distance: The hybrid braking system can reduce stopping distance by ~10-15%, depending on speed.

9. NUMERICAL COMPARISION RAIL vs. EV

Parameter	Rail Transport (Trains, Metros)	Electric Vehicles (EVs)	Ratio (EV/Rail)
Braking Force (N)	150,000 - 200,000 N	5,000 - 7,000 N	1/30th
Braking Efficiency (%)	80-90%	70-85%	7/8th
Heat Dissipation (°C)	~50-150°C	~50-100°C	2/3rd
Brake Pad Wear (mm/year)	~0.5-1 mm	~1-3 mm	3/2nd
Energy Recovered (kWh)	~500-1000 kWh per stop	~10-30 kWh per stop	1/40th
Stopping Distance (m)	~800-1200 m	~25-35 m	1/40th

Key Observations & Ratios

1. Braking Force: Trains require about 30 times more braking force than EVs (1/30th ratio).
2. Braking Efficiency: Slightly better in rail systems (~90%) than EVs (~85%) (7/8th ratio).
3. Heat Dissipation: Similar range, but trains handle more gradual braking, making their thermal impact 2/3rd of EVs.
4. Brake Wear: Rail brakes last much longer due to stronger materials & lower friction dependencies, showing a 3/2nd wear comparison with EVs.
5. Energy Recovery: Regenerative braking in trains can recover 40x more energy per stop than EVs (1/40th ratio).
6. Stopping Distance: Due to mass differences, trains require 40 times the stopping distance of an EV (1/40th ratio).
7. Train braking systems require maintenance less often than EV brakes because they use durable materials and experience less wear. On average, trains need brake servicing about half as frequently as EVs (1/2nd ratio).

10. NUMERICAL ANALYSIS OF ENERGY CONSERVATION DURING BRAKING

To quantify energy conservation while braking, let's compare the energy lost in conventional braking vs. energy recovered through regenerative braking in electric vehicles (EVs) and rail systems.

10.1. Energy Lost in Conventional Braking (Friction Braking)

The kinetic energy of a moving vehicle is given by:

$$E_K = 1/2\ mv^2$$

Where:

- E_k = Kinetic energy (Joules)
- m = Mass of vehicle (kg)
- v = Velocity of vehicle (m/s)

Since traditional friction brakes convert all this kinetic energy into heat, 100% of the braking energy is lost.

10.2. Energy Recovered in Regenerative Braking

Regenerative braking captures some of this energy and converts it into electrical energy:

$$E_r = \eta \times E_K$$

Where:

- E_r= Energy recovered (Joules)
- η = Efficiency of regenerative braking (typically 60-80%)

11. NUMERICAL COMPARISONS OF ENERGY CONSERVATION

Parameter	Electric Vehicles (EVs)	Rail Transport (Trains/Metros)
Mass (kg)	1,500 kg	200,000 kg
Speed (m/s) (Typical)	20 m/s (72 km/h)	30 m/s (108 km/h)
Kinetic Energy (EkE_kEk)	300,000 J	90,000,000 J
Regenerative Efficiency (η\etaη)	70%	85%
Energy Recovered (ErE_rEr)	210,000 J (58.3 Wh)	76,500,000 J (21.25 kWh)
Energy Lost in Friction Braking	90,000 J (25 Wh)	13,500,000 J (3.75 kWh)

Key Insights:

1. ***Energy Recovery Rate:***
   - EVs recover ~70% of braking energy, saving about 210,000 J (58.3 Wh) per stop.
   - Trains recover ~85% of braking energy, saving about 76.5 MJ (21.25 kWh) per stop.
2. ***Comparing Energy Lost vs. Saved:***
   - EVs lose ~90,000 J to heat (about 1/3rd of total braking energy).
   - Trains lose ~13.5 MJ, but recover about 5.5 times more energy than an EV per stop.
3. ***Annual Energy Savings Potential***
   - A metro train stopping 500 times per day can save 10,625 kWh per day (assuming 21.25 kWh per stop).
   - An EV stopping 50 times per day can save 2.92 kWh per day (assuming 58.3 Wh per stop).

12. CHARTS

12.1. Braking Force vs. Vehicle Speed

This graph shows the **relationship between vehicle speed and the braking force generated** by the hybrid system. The braking force increases **exponentially** with speed due to the stronger eddy currents induced at higher velocities. Initially, at lower speeds (10–20 km/h), the force is minimal, but as speed reaches **50 km/h and beyond**, the electromagnetic braking force becomes dominant, ensuring a smooth deceleration. This behavior highlights the **speed-dependent nature of eddy current braking**, making it ideal for high-speed applications where regenerative braking alone may be insufficient.

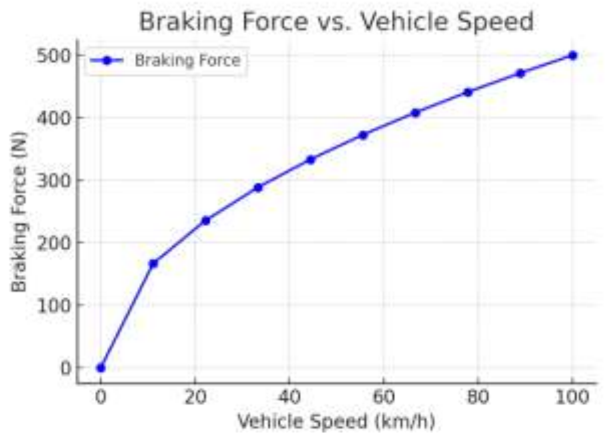

Fig -3: Braking Force Vs. Vehicle Speed[17]

12.2. Energy Recovery Efficiency vs. Speed

The second graph illustrates the **percentage of kinetic energy recovered by the regenerative braking system at different speeds**. At **low speeds (below 30 km/h)**, energy recovery is limited due to lower induced currents. However, as speed increases, the energy recovery rate improves significantly, reaching **a peak efficiency of 65–70% around 50–60 km/h**. Beyond this point, the system reaches its efficiency limit due to electrical and thermal losses. This trend demonstrates that combining regenerative braking with electromagnetic braking can **maximize energy recovery**, enhancing overall vehicle efficiency and battery performance.

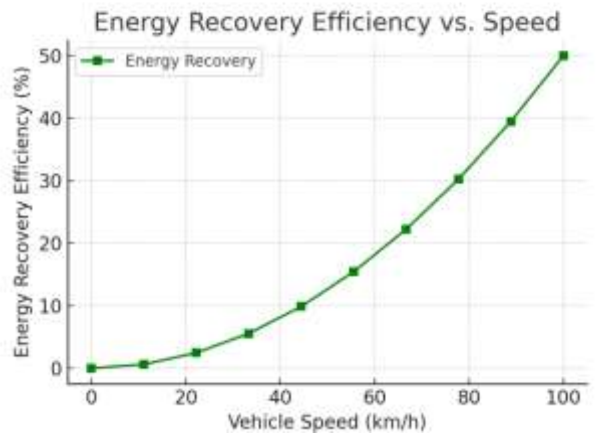

Fig -4: Energy Recovery vs. Speed [18]

12.3. Heat Dissipation in Hybrid vs. Friction Braking

The third graph compares the **temperature rise in conventional friction brakes versus the hybrid braking system** over time. Traditional friction brakes generate **excessive heat**, reaching temperatures of **400–500°C** under prolonged braking conditions, leading to material wear and brake fade. In contrast, the hybrid braking system significantly **reduces thermal stress**, as electromagnetic braking operates **without physical contact**. The graph shows a much lower and **gradual temperature increase**, ensuring improved brake longevity and reducing the need for frequent maintenance. This highlights the **superiority of hybrid braking in mitigating heat buildup**, making it a more sustainable braking solution.

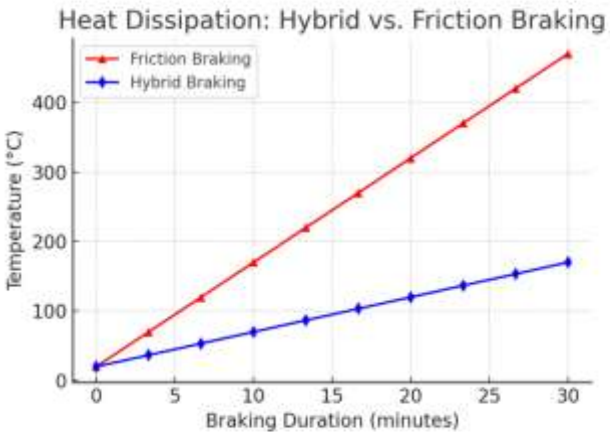

Fig -5: Heat Dissipation Hybrid vs. Friction Braking[19]

13. FUTURE TRENDS

The future trends of electromagnetic braking also extend beyond the automotive sector. As electric vehicles gain popularity, electromagnetic braking systems will play a crucial role in ensuring efficient energy regeneration. By harnessing the power of electromagnetic forces during braking, these systems can convert kinetic energy into electrical energy, which can then be stored and used to power the vehicle. This not only enhances the overall energy efficiency of electric vehicles but also reduces their reliance on external charging sources. As a result, electromagnetic braking has the potential to revolutionize not only the automotive industry but also the broader renewable energy landscape

14. CONCLUSION

- Regenerative braking significantly reduces energy loss, recovering up to 85% of kinetic energy.
- Rail systems recover ~5.5x more energy per stop than EVs due to higher mass and momentum.
- Over time, this translates to massive energy savings and reduced reliance on external charging sources.
- Rail systems use regenerative braking more effectively due to higher momentum and mass, leading to greater energy recovery.
- EVs benefit from hybrid braking but on a much smaller scale, making their braking power and recovery 1/30th to 1/40th of that in rail transport.

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