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Eddy Current Braking-An Auxiliary Brake in Electric Vehicles

Afna[1], Aiswarya C R[2], Neha Elizabeth Sabu[3], Surjith S[4], Kavitha Issac[5], Reenu George[6]
[1, 2, 3, 4]Student, Dept of Electrical and Electronics Engineering, Mar Athanasius College of Engineering (Autonomous), Kothamangalam, Kerala, India
[5, 6]Associate Professor , Dept of Electrical and Electronics Engineering, Mar Athanasius College of Engineering (Autonomous), Kothamangalam, Kerala, India

Abstract: Braking systems are critical in any vehicles, including electric vehicles. But, the excessive use of friction brakes results in decreased braking performance and system degradation. Regenerative braking which is widely used in EVs to recover kinetic energy during deceleration, converting it into electrical energy for storage. However, this system becomes inefficient when the battery is fully charged (90-100 %) and unable to store additional energy. Moreover, regenerative braking may not provide sufficient braking force at certain speeds, requiring traditional friction brakes, which leads to increased wear and maintenance. One alternative solution is to use eddy current braking (ECB). Due to the uncertain characteristics of ECB in low speed range integration of eddy current braking as an auxiliary to regenerative braking in electric vehicles (EVs) is suggested. Unlike regenerative braking, eddy current brakes are independent of the battery's state of charge and offer consistent performance. Real-time speed feedback from a sensor enables dynamic adjustment of the braking force, ensuring effective braking at varying speeds. Experimental results validate the theoretical model, demonstrating efficient braking performance with minimal energy loss. The proposed system provides a non-contact, maintenance-free alternative to mechanical braking, enhancing braking efficiency and safety in EV applications. Additionally, a comparative analysis is conducted between the ECB system and existing braking mechanisms in two-wheelers, evaluating factors such as energy efficiency, braking force, and maintenance requirements. This system aims to design, simulate, and test an integrated system, improving braking efficiency, enhancing safety, and reducing mechanical wear across various operating conditions.
Keywords: Eddy Current Brake, Electromagnetic brake, Electric Vehicle, Regenerative Braking, Frictionless

I. INTRODUCTION

Braking systems are a fundamental component of motorized vehicles, ensuring driving safety by reducing or halting vehicle motion. The effectiveness of a braking system is especially critical in areas with varying terrain, such as hilly and mountainous regions, where steep inclines and declines demand reliable and efficient braking performance. A well-designed braking system not only enhances safety but also improves vehicle control, stability, energy efficiency and thereby reducing accidents. With the increasing adoption of electric vehicles (EVs), there is a growing demand for innovative braking solutions that address the limitations of conventional braking systems.Traditional mechanical braking relies on friction-based components such as brake pads and discs, which suffers from continuous wear and tear, leading to maintenance costs, noise generation, and reduced braking efficiency over time. Additionally, prolonged or excessive braking can cause brake fading, where the braking force diminishes due to overheating. These drawbacks have prompted the search for alternative braking technologies that minimize mechanical contact and improve durability.Regenerative braking, commonly used in EVs, offers a significant advantage by converting kinetic energy into electrical energy, thereby improving energy efficiency. However, this method becomes ineffective at high speeds, where it cannot provide sufficient braking force due to system limitations (1). As a result, there is a need for an auxiliary braking system that complements regenerative braking and ensures efficient deceleration under all driving conditions. This study investigates the implementation of an eddy current braking (ECB) system as a supplementary braking solution for electric vehicles (2). Unlike conventional brakes, ECB operates without physical contact, utilizing electromagnetic induction to generate resistive forces that slow down the vehicle. The proposed ECB system consists of a DC-excited coil positioned near a rotating metallic disc mounted on the vehicle shaft. When current flows through the coil, it generates a magnetic field that induces eddy currents in the disc. These eddy currents, in turn, create opposing magnetic fields that exert a braking force on the rotating disc, effectively slowing down the vehicle without direct mechanical interaction. To enhance the performance and adaptability of the ECB system, a speed-based control strategy is incorporated.

A proportional-integral (PI) controller regulates the 2 excitation currents supplied to the coil through a buck converter. This allows precise control of the braking force based on the vehicle's speed, ensuring optimal braking performance under various driving conditions. By integrating this intelligent control mechanism, the ECB system can dynamically adjust braking intensity, making it a viable and efficient solution for electric vehicles. This design aims to analyze the feasibility and effectiveness of the proposed ECB system in improving braking performance while reducing the drawbacks of traditional braking methods (3). The study will evaluate key performance parameters, including braking force, energy efficiency, response time, and thermal effects, to determine ECB as an advanced braking solution for future electric mobility.

II. METHODOLOGY

The experimental setup consists of an aluminum disc rotating at a controlled speed, with an electromagnet positioned adjacent to its edge. When current flows through the electromagnet, it generates a magnetic field that induces eddy currents in the aluminum disc. These eddy currents create an opposing magnetic field, producing a braking force that slows down the disc due to electromagnetic damping. The braking performance is analyzed by varying the electromagnet's current and measuring the corresponding deceleration of the disc. The design parameter optimization of the model is calculated on the basis of equation as proposed by (17).

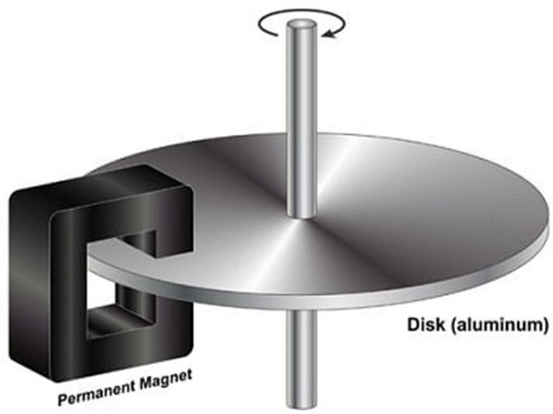

Fig.1 Eddy current braking system

A. *Material for Disc*

A comparison of Aluminium and Copper for the disc material is given in Table 1.

TABLE I. Comparison of Aluminium and Copper

Property	Aluminium	Copper
Electrical Conductivity	3.5 x 10^7	5.8 x 10^7
Thermal Conductivity	Moderate	High
Weight	Lightweight	Heavy
Corrosion Resistance	High	Moderate
Cost	Affordable	Expensive

While copper has higher electrical conductivity and generates stronger eddy currents, it is significantly heavier and more expensive than aluminum. In automotive applications, reducing weight is a critical factor in improving efficiency.(10) Aluminum disc Fig. 2 offers a balanced trade-off between conductivity, weight, and cost, making it the preferred choice for eddy current braking discs in EV applications (12).

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Fig. 2 Aluminium Disc

B. Electromagnetic Coil

The design of the electromagnetic coil in the eddy current braking system is critical, as it directly influences the strength of the magnetic field and the braking force. The key parameters for designing the coil include number of turns,wire gauge,core material and excitation current.

Selection of Core Material

The core material should have high magnetic permeability to concentrate the magnetic flux effectively and improve braking efficiency (9). Common core materials are ferrite, Laminated steel and Soft iron.

Determining Number of Turns(N)

The number of turns influences the magnetic field. The magnetic field strength (B) inside the coil is given by:

$$B = \frac{\mu_0 \mu_r N L}{l} \quad (1)$$

where, μ_0=Permeability of free space ($4\Pi * 10\hat{}-7$), μ_r=Relative permeability of the core material, N=Number of turns, I=Excitation Current, l=Length of coil.

Wire Gauge Selection

The current carrying capacity of the wire is determined by the American Wire Gauge(AWG). For 5-15A excitation current, AWG 12-14 is typically used. The resistance of the wire should be minimized to reduce heat losses.

C. Excitation Current and Braking Force

The braking force is directly proportional to the excitation current:

$$F = K_1 I^2 \quad (2)$$

where k1 is a proportional constant based on coil design and disc material. The excitation current is regulated using a buck converter, which adjusts the voltage supplied to the coil according to the speed feedback (8).

Schiebers Model

A common solution was adopted by Schieber inorder to achieve the braking torque which gave accurate results on varying speed range is given in eq(3). The electrical conductivity, thickness, and radius of the disc were directly proportional to the braking torque of the system.(6)

$$T = \frac{\sigma\rho\omega\Pi R^2 m^2 B^2}{2} \text{x} \frac{1-\left(\frac{R}{a^2}\right)}{1-\left(\frac{m}{a^2}\right)} \quad (3)$$

Where σ =electrical conductivity of rotating disc, δ =sheet thickness rotating disc , ω =angular velocity , R = radius of electromagnet , m = distance of disc axis from pole-face center , a = disc radius , B = magnetic flux density

D. Buck Converter For Current Regulation

A buck converter(Step down voltage) is used to regulate the DC voltage applied to the coil, enabling precise control of the excitation current (13).

The buck converter is a step down switching regulator that adjusts the voltage and current to the coil based on the control signal. A switching element controls the duty cycle of the input voltage. Inductor will store the energy and smoothen the output current variations. Capacitor filters out voltage ripples to maintain a stable output. Diode provides a freewheeling path for current when the switch is off. The duty cycle D of the Pulse Width Modulation (PWM) signal determines the output voltage, Vout = DVin ,where Vin is the input voltage from the battery.

By adjusting the Duty ratio, the excitation current in the coil can be finely tuned, ensuring optimal braking performance under varying speeds and load.

III. SYSTEM DESIGN

The principle behind eddy current braking is based on the interaction between changing magnetic field and conducting disc. When the coil is activated, fluctuating magnetic field induces eddy currents in the disc, resulting in an opposing force in accordance with Lenz's Law, which ultimately reduces the rotation speed. he proposed Eddy Current Braking (ECB) system is designed to provide contactless braking for electric vehicles (EVs) by inducing eddy currents in a conductive rotating disc. These currents generate a resistive force that opposes the disc's motion, slowing it down efficiently without mechanical wear.

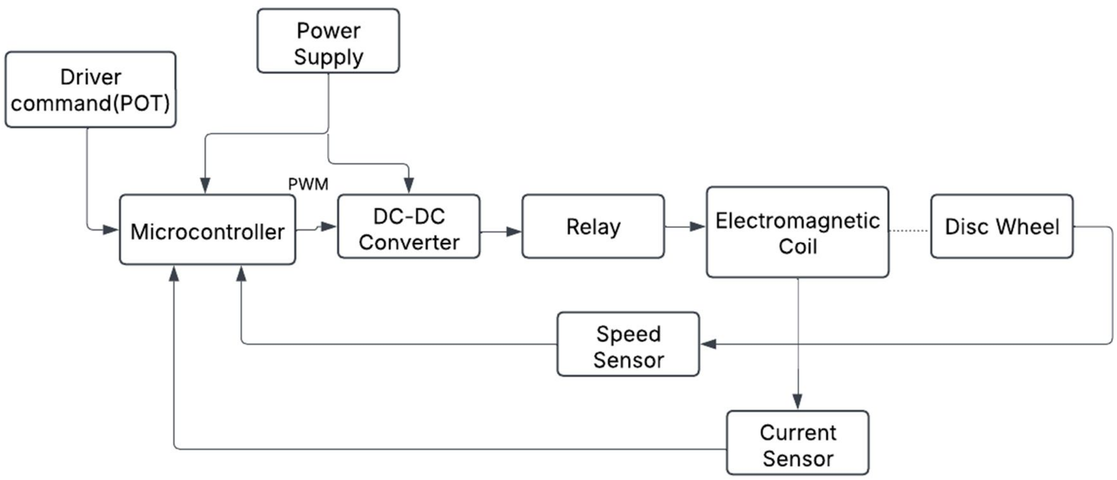

Fig.3 Block diagram of proposed system

The system consists of several key components: a driver command input (POT), a microcontroller, a DC-DC buck converter, a relay, an electromagnetic coil, a rotating metallic disc, and sensors for speed and current measurement. The driver command sets the desired braking intensity, which is processed by the microcontroller. The microcontroller generates a PWM signal to control the buck converter, regulating the coil's excitation current. A relay acts as a switch to activate the braking system based on speed conditions. When current flows through the electromagnetic coil, it produces a magnetic field that interacts with the conductive disc. This interaction induces eddy currents, which generate an opposing force that slows the disc down. The speed sensor and current sensor provide real-time feedback, enabling the microcontroller to adjust braking force dynamically for optimal performance. This closed-loop control system ensures efficient braking while minimizing power loss.

A. Design of Electromagnetic coil

The coil design directly impacts the braking force and response time of the system (16).

Inductance of the coil is,

$$L = N^2 \mu A\ l \qquad (4)$$

where N is the number of turns , μ is the permeability of the core material, A is the area of the cross-sectional area, l is the length of the coil.

The resistance of the coil is calculated as,

$$R = \rho . l\ A \qquad (5)$$

where ρ is the resistivity of the wire material.

A well-optimized coil ensures effective eddy current generation with minimal power loss. Fig 4 shows the 4-core design of the electromagnetic coil.

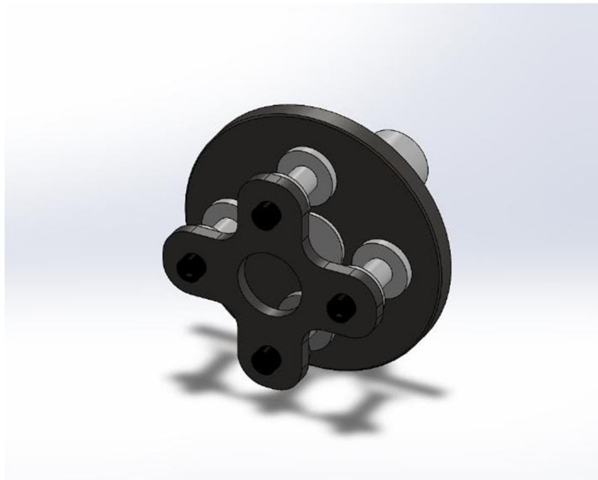

Fig. 4 Electromagnetic coil design

B. Design of Buck converter

Design of a converter requires selection of an input inductor that always functions in continuous conduction mode (CCM), reducing stress on converter components and devices.

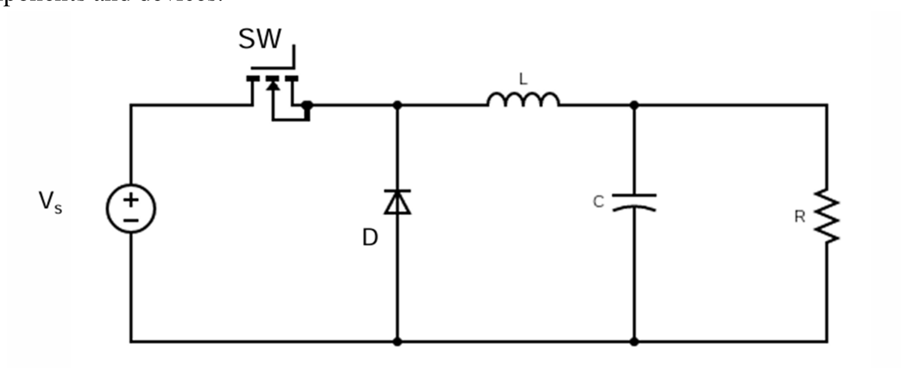

Fig. 5 Schematic diagram of buck converter

Duty ratio in buck mode,

$$D = \frac{V_R}{V_S} \tag{6}$$

Inductor value in buck mode,

$$L = \frac{D(V_S - V_R)}{f s_W \Delta I_S} \tag{7}$$

Capacitance on buck mode,

$$C = \frac{\Delta I_S}{8 f s_w \Delta V_0} \tag{8}$$

where V_s is the input source voltage, V_R is the load voltage across the coil (here load resistor), f is the switching frequency, ΔI_s is the ripple current and ΔV_0 is the ripple voltage.

C. Hall Effect speed sensor (A3144)

The Hall Effect Speed Sensor is used to measure the rotational speed of the disc by detecting changes in the magnetic field as the disc moves. It operates based on the principle that a voltage is generated when a conductor carrying current is exposed to a perpendicular magnetic field. The sensor outputs pulses proportional to the speed of the disc, providing real-time speed data for the control system. It is highly reliable and contactless.

D. Current Sensor (ACS712)

The ACS712 Current Sensor is a widely used Hall-effect-based sensor designed to measure current flow through the system. It works by detecting the magnetic field produced by the current flowing through a conductor and converting it into a proportional voltage output. The ACS712 provides high accuracy and low noise. This sensor is crucial for real-time monitoring of the excitation current supplied to the electromagnetic coil, allowing precise control and optimization of the braking force.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. Analysis of Aluminium Disc

Investigation of heat distribution and deformation due to eddy currents through the analysis of aluminum with the help of ANSYS software selected for advanced thermal and structural analysis functions using finite element analysis (FEA).(11) SolidWorks is used to create accurate 3D models of CDs. The integration of Solid works into ANSYS allows for accurate design and detailed analysis. In other words, the performance of a braking system is visualized and understood under operating conditions. The diameter of the disk should be taken into consideration in this way. The inertia of a disk is proportional to the four diameters of the disk, and the time constant of the disk is directly proportional to the square of the disk's diameter. The disc diameter is chosen as 200 mm and 4 mm thick. Figs. 6,7 and 8 shows the analysis of Aluminium disc.

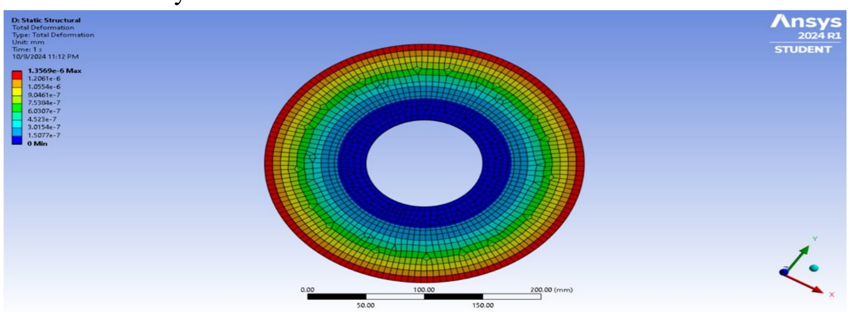

Fig. 6 Steady state structural deformation using ANSYS

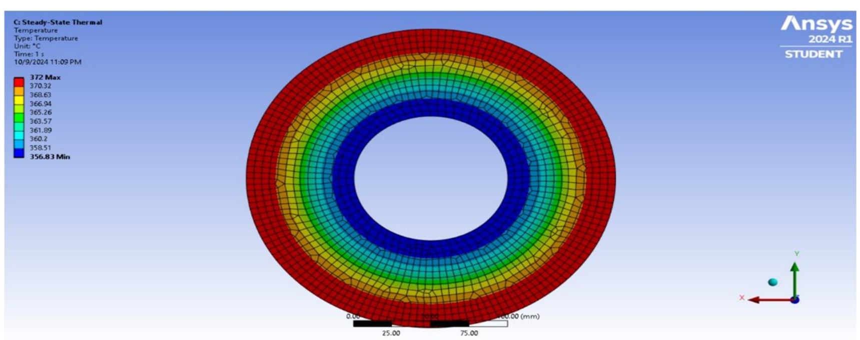

Fig. 7 Steady state thermal heat flux using ANSYS

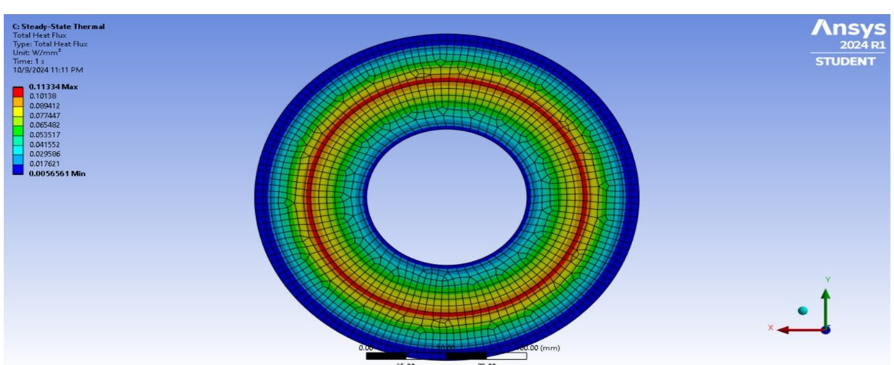

Fig. 8 Steady state thermal temperature using ANSYS

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B. Electromagnetic Core Analysis

COMSOL Multiphysics simulation of electromagnetic core in Fig. 9 illustrates the magnetic flux density norm within an electromagnetic system, likely representing a coil wound around a ferromagnetic core. The multislice view reveals flux distribution across different cross-sections, with the highest density concentrated near the coil and decreasing outward. The color scale indicates values from approximately 1.67×108 T to 4.33 T, highlighting the field's intensity variations. Contour lines and vector paths illustrate the magnetic field flow, essential for analyzing core saturation and optimizing coil excitation. This analysis ensures that sufficient magnetic field interacts with the disc and less leakage to the air gap.

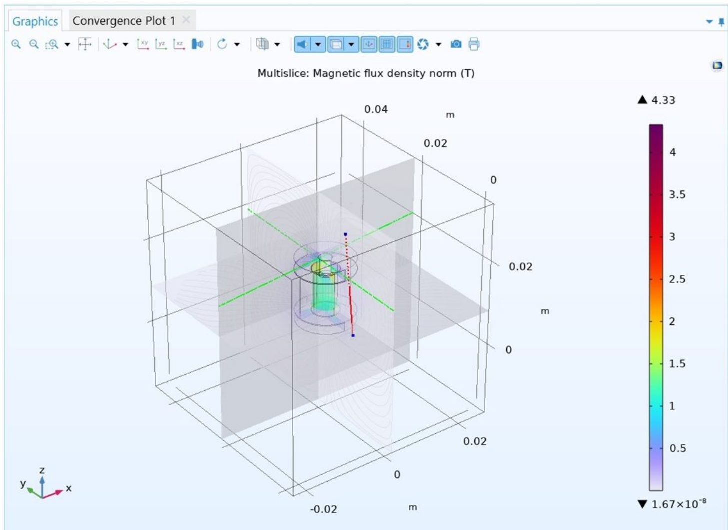

Fig. 9 COMSOL Analysis of Core

C. Hardware prototype of ECB

The hardware prototype was implemented on a Honda Aviator wheel to test the eddy current braking system. A stationary electromagnetic coil with a 1 cm air gap induces eddy currents in the rotating wheel when excited with DC, generating a

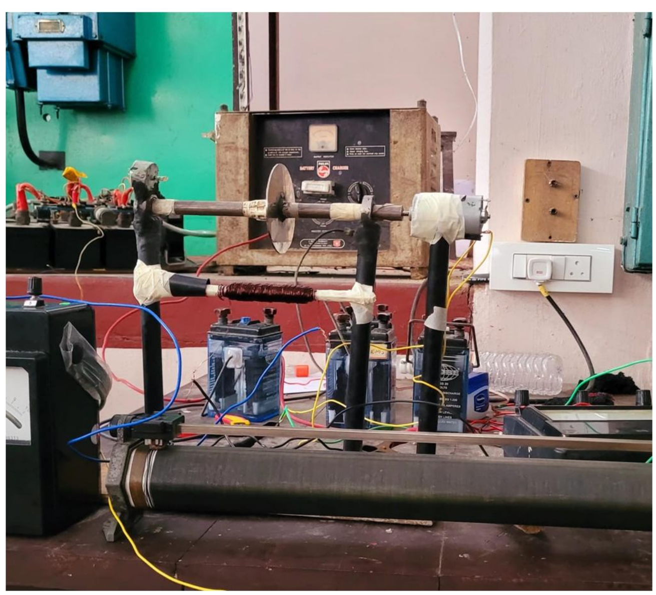

Fig. 10 Prototype of Hardware setup

braking force. A speed sensor detects RPM, and a buck converter adjusts the coil excitation based on speed. This setup demonstrates the feasibility of a wear-free braking system for two-wheelers, potentially enhancing EV braking efficiency.

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V. DISCUSSIONS

TABLE II . Comparison with Conventional Braking Systems

Feature	Eddy Current Braking	Regenerative Braking	Conventional Braking (Disc/Drum)
Braking Mechanism	Braking force through electromagnetic induction	Conversion of Kinetic energy to electrical energy	Friction between brake pads and rotor
Contact Type	Wear free	Non-contact	Wear and Tear
Maintenance	Low	Depends on battery and motor	High (sometimes require replacement)
Heat	Moderate	Minimal	High
Effectiveness at High Speed	Stronger braking force with increasing speed	Less effective	Reduced (Due to high temperature)
Braking Force control	Precise, adjustable via current control	Limited by battery charge state and motor efficiency	Fixed (depends on brake pressure applied)
Suitability for Two-wheelers	Feasible for supplementing regenerative braking	Suitable for EVs	Standard braking method

VI. CONCLUSION

An improved braking system strategy to be implemented in electric two-wheelers is presented in this work. Braking force is formed using the principle of electromagnetic induction, thereby generating the sufficient eddy current which opposes the wheel rotation. Excitation current is estimated using the controller circuit which gets input from the speed sensors and current sensors mounted on the disc. Conventional braking systems produce fixed force for different speeds. In ECB's the road conditions are also taken into consideration. The PWM technique based control provides better braking performance. Cumulative drive performance is stable and suitable for designing in an Electric two-Wheeler.

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