



IMPLEMENTATION OF REGENERATIVE BRAKING FOR ENHANCED LOPIFIT PERFORMANCE

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Abstract— This paper focuses on enhancing the performance of the Lopifit, a unique walking by implementing regenerative braking technology. The aim is to improve braking efficiency and simultaneously capture and store kinetic energy during braking and deceleration. The system integrates both disc brakes for immediate stopping power and eddy current brakes for energy recovery through electromagnetic induction. The harvested energy is converted into electrical energy and stored, increasing the Lopifit's sustainability and range. Extensive testing and performance evaluations confirm the system's effectiveness in improving safety, efficiency, and environmental impact. This study highlights the potential of regenerative braking for eco-friendly urban transportation solutions and suggests opportunities for further research in this area.

Keywords: *Lopifit, eddy current braking, disc braking, regenerative braking.*

INTRODUCTION

The Lopifit is a unique hybrid between a bicycle and a treadmill, designed to provide a different walking experience while being environmentally friendly. The Lopifit Treadmill electric walking bike stands at the forefront of this movement, offering a unique blend of exercise and commuting that aligns with the principles of environmental responsibility. By merging the principles of a treadmill with the design of a bicycle, the Lopifit transforms human motion into a source of locomotion, bridging the gap between physical activity and daily

mobility. It incorporates various braking mechanisms, including disc braking, eddy current braking, and regenerative braking. The combination of these braking methods offers enhanced control and energy efficiency to the Lopifit, contributing to its distinctive functionality. The realization of the Lopifit's hinges on its braking system, a critical aspect that ensures user safety, operational reliability, and energy efficiency. This study researches the realm of braking technologies, with a focus on three distinct methods: disc braking, eddy current braking, and regenerative braking. The Lopifit stands as a compelling example of an integrated solution that combines physical activity, energy recovery, and enhanced safety.

The emergence of Lopifit

Traditional modes of transportation have long relied on fossil fuels, contributing to pollution, congestion, and environmental degradation. In response to these challenges, the Lopifit emerges as a creative response, offering a unique blend of a treadmill and a bicycle. This amalgamation not only promotes an active lifestyle but also harnesses the potential of human effort to drive personal transportation, reducing carbon emissions and promoting a healthier way of commuting.

Importance of braking system

The success of any transportation mode hinges on its safety and operability, with braking systems at the forefront of ensuring user well-being. While the Lopifit's design encourages natural walking motion, it also necessitates effective braking mechanisms to control speed and ensure prompt deceleration. The integration of braking technologies has the dual responsibility of not only providing safety to the user but also enhancing the overall efficiency and sustainability of the Lopifit.

Three braking systems

This study centers on the incorporation and evaluation of three distinct braking technologies: disc braking, eddy current braking, and regenerative braking. Each method offers a unique approach to achieving controlled deceleration while bringing specific advantages to the table.

1. Disc braking

Disc braking is a common mechanism in traditional bicycles. It involves using brake pads to apply pressure to a rotating disc attached to the wheel hub [1]. These braking systems consist of several key components, primarily the brake calliper, brake pads, and a rotor (or disc). When the rider activates the brake lever, hydraulic or cable tension forces the brake pads to contact the rotor.

This creates friction and slows down the wheel's rotation, ultimately reducing the bicycle's speed. In the context of a Lopifit, disc braking provides a reliable method to control speed and bring the walking bicycle to a stop. The disc braking system efficiency depends on the quality of its components and the maintenance of the brake pads, rotors, and hydraulic system to ensure safe and reliable stopping power.

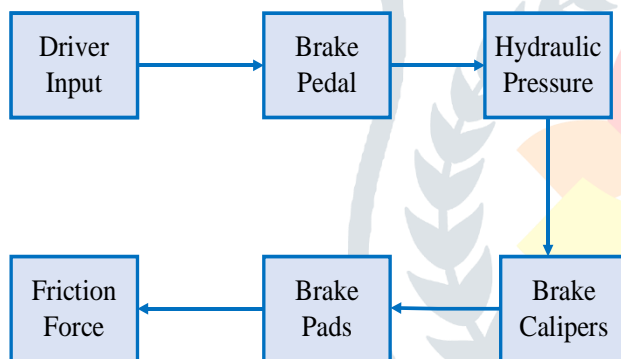


Figure 1: Block diagram of disk braking

2. Eddy current braking

Eddy current braking is an innovative method that takes advantage of electromagnetic induction to create resistance and slow down the motion of a conductive material, such as a metal wheel. As the Lopifit's wheel rotates within a magnetic field, the changing magnetic flux induces electric currents (eddy currents) within the wheel [2]. These currents generate their own magnetic fields, opposing the original motion and resulting in braking. Eddy's current braking is efficient, quiet, and requires minimal physical contact, reducing wear and tear.

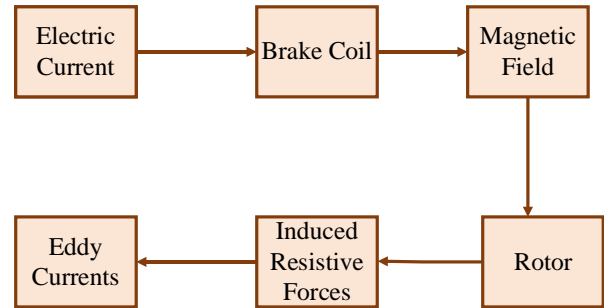


Figure 2: Block diagram eddy current braking

3. Regenerative braking

Regenerative braking, also known as regen braking, is a method that converts some of the kinetic energy of the moving lopifit back into electrical energy [3]. This energy is then stored in a battery or capacitor for later use. When the Lopifit slows down, a motor/generator can reverse its operation, acting as a generator that converts the motion's energy into electricity. This innovative approach contributes to energy conservation and extends Lopifit's range.

The combination of these three braking mechanisms provides a comprehensive solution for controlling speed, increasing safety, and enhancing energy efficiency in the Lopifit. Each method has its advantages and limitations, and the integration of these techniques demonstrates a holistic approach to addressing various challenges in the context of a unique walking bicycle design.

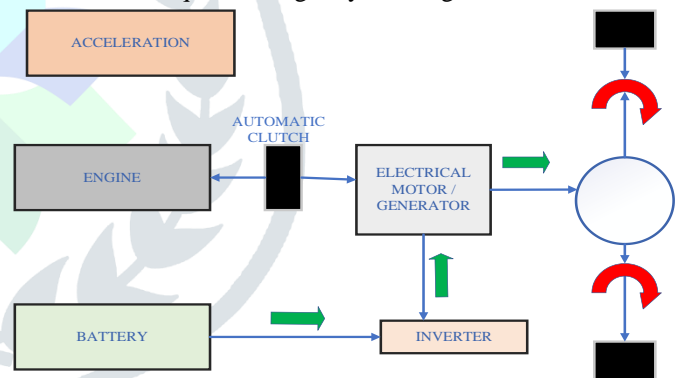


Figure 3: Flow of energy in acceleration condition

As the vehicle accelerates, its electric motor operates in two modes: propulsion and generation. While providing torque for acceleration, the motor can seamlessly switch to generator mode when the driver eases off the accelerator or applies light brakes. During this phase, the spinning wheels turn the motor into a generator, transforming the kinetic energy of the vehicle's motion back into electrical energy. This energy is then sent back to the vehicle's battery, effectively recharging it. When acceleration is needed again, the vehicle draws power not only from the battery but also from the stored energy, enhancing torque delivery and improving overall energy efficiency. Regenerative braking during acceleration thus contributes to extended range and reduced energy consumption in electric vehicles.

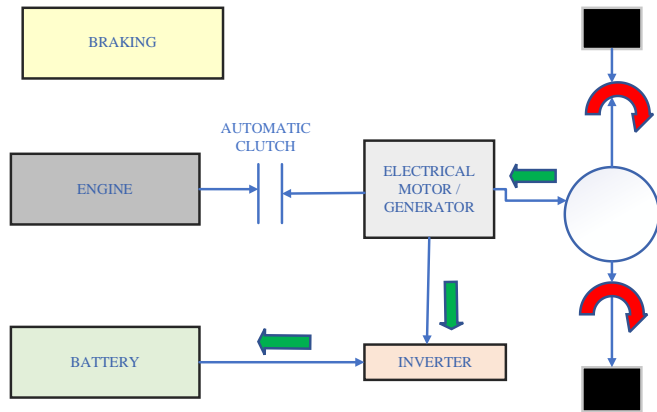


Figure 4: Flow of energy in braking condition

When the driver applies the brakes, regenerative braking temporarily transforms the electric motor into a generator. As the vehicle slows down, the wheels turn the motor, converting kinetic energy into electrical energy. This generated electricity is then fed back into the vehicle's battery for storage, effectively recharging it. This process not only slows down the vehicle but also harnesses some of the energy that would otherwise be lost as heat in traditional friction-based braking systems. Regenerative braking thus enhances energy efficiency, extends battery life, and contributes to the overall sustainability of electric and hybrid vehicles, making it a crucial component of modern automotive technology.

begin with, the traditional disc braking mechanism delivers immediate and robust stopping power when the rider engages the brake lever. This ensures safety during sudden stops and emergency situations. Complementing this, the eddy current braking system utilizes electromagnetic induction to generate resistance within metal components, allowing for precise control over deceleration. It smoothly slows down the Lopifit when the rider eases off the pedals or brake lever. Furthermore, regenerative braking adds a sustainable aspect by converting kinetic energy into electricity during braking, which is then stored in the battery for later use. This not only extends the bike's range but also reduces energy wastage. Together, this combination of braking technologies creates a versatile and eco-friendly braking system, offering both safety and energy efficiency to Lopifit riders.

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MATHEMATICAL MODELLING

Disc braking

Disc braking involves using friction to slow down the Lopifit. The key parameters are the brake force and the coefficient of friction between the brake pads and the disc [4].

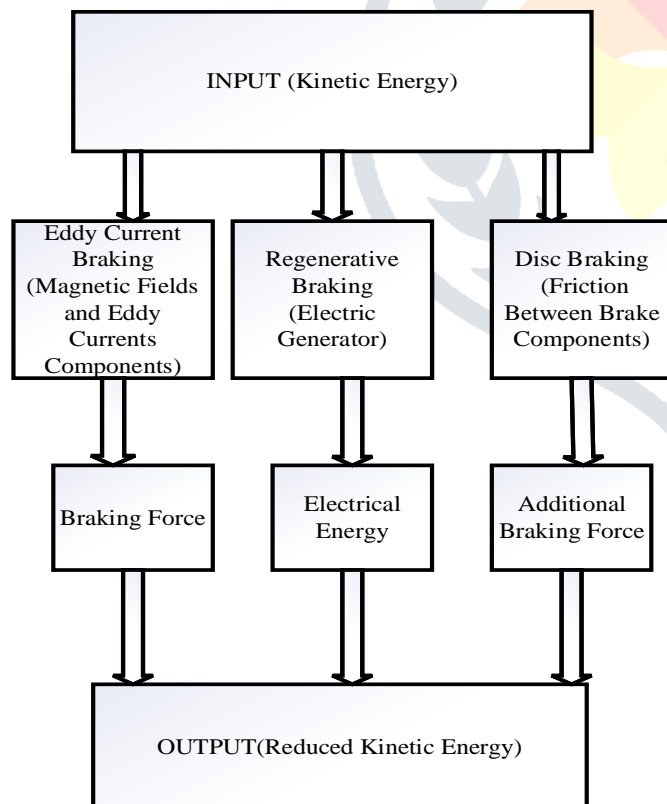


Figure 5: Block diagram of braking systems used in Lopifit.

The integration of disc, eddy current, and regenerative braking in a Lopifit creates a multifaceted and efficient braking system that caters to various riding scenarios. To

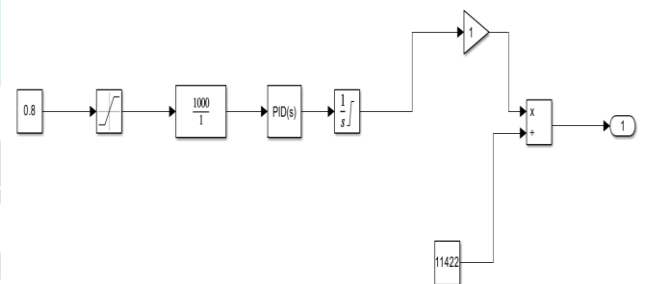


Figure 6: simulation diagram of disc brake at single wheel

1. Brake force calculation

The brake force is calculated based on the pressure applied to the brake pads:

$$\text{Brake force} = \text{pressure} * \text{brake pad area}$$

2. Brake torque calculation

The braking torque generated by the disc brake is proportional to the brake force and the radius of the brake disc.

$$\text{Braking torque} = \text{Brake force} \times \text{brake disc radius}$$

The deceleration(*a*) of the vehicle can be expressed using the equation:

$$a = (\mu * g * F) / m \tag{1}$$

Where:

μ is the coefficient of friction between the brake pads and the disc

g is the acceleration due to gravity

F =force applied by the brake pads

m =mass of the vehicle

$$\text{Kinetic energy} = \frac{1}{2} MV^2 \quad (2)$$

Heat flux =Thermal energy/2 area of the rubbing surface

The heat generated by the disc brake:

$$Q = mC_p\Delta T \quad (3)$$

Where:

m = mass of disc

C_p =specific heat capacity

ΔT =Temperature difference

Friction-Based Disc Brake

The friction-based disc brake force (F_f) can be modeled using the equation for frictional force:

$$F_f = \mu \cdot N \quad (4)$$

Where:

F_f = Friction-based disc brake force (N)

μ = Coefficient of friction for the friction-based disc brake

N is the normal force on the brake pads. (N) can be calculated as the weight of the vehicle (mg),

where (g) is the acceleration due to gravity

Friction-Based Disc Brake (T_{disc})

$$T_{disc} = F_{disc} \cdot r \quad (5)$$

Where:

T_{disc} is the braking torque provided by the friction-based disc brake (N·m).

F_{disc} is the braking force applied by the disc brake (N).

r is the effective radius of the disc brake (m or ft).

Eddy current braking

Eddy current braking uses electromagnetic induction to create a braking force. The induced current and the magnetic field strength are critical parameters [5].

The expression upon which the braking torque analysis will be based is given by :

$$T_b = \sigma R^2 S d w \left(\frac{\mu_0 n}{l_g} \right)^2 i^2 \quad (6)$$

Where:

T_b =Eddy current braking torque

σ =Brake disc electrical conductivity

R =radial distance between the brake disc Centre and the Centre of the field winding core

S =surface area of the magnetic pole

d =Brake disc thickness

w =Common angular speed of road wheel and brake disc

μ_0 =Air gap permeability

n = Number of turns of electromagnetic winding

l_g =Air gap length

i =Applied current

The above braking torque expression applies to the case of eddy current braking when the magnetic field is stationary.

Only the brake disc combines with the moving wheel (through the magnetic field) to create relative motion between the magnetic field and itself, the brake disc conducts electricity.

Modification to the braking torque expression:

A necessary modification here is that the angular velocity will be generated by the relative motion between the brake disc and the rotating magnetic field.

Hence,

$$w = w_w - w_f \quad (7)$$

Where:

w_w = angular speed of Road wheel or brake disc

w_f = angular speed of rotating magnetic field

The direction of rotation of magnetic field relative to the direction of rotation of the brake disc, is considered.

Rotation in the direction of the road wheel is taken as positive.

Braking torque model

If the torque coefficient,

$$T_b = \sigma R^2 S d \left(\frac{\mu_0 n}{l_g} \right)^2 \quad (8)$$

The braking torque expression of eq (4) can be rewritten as

$$T_b = T_i w_i^2 \quad (9)$$

Using equation (5) in eq. (7),

$$T_b = T_i (w_w - w_f)^2 \quad (10)$$

Eddy Current Brake

The eddy current brake force (F_e) can be modeled as:

$$F_e = k \cdot B^2 \cdot r^2 \cdot v \quad (11)$$

Where:

$$F_e = \text{Eddy current braking force (N)}$$

k is a constant related to the eddy current brake design and materials.

B is the magnetic field strength.

r is the effective radius of the eddy current brake components.

v is the vehicle speed.

The general formula to calculate the eddy current braking torque is:

$$T_{eddy} = K \cdot B^2 \cdot r^2 \cdot w \tag{12}$$

Where:

T_{eddy} is the braking torque provided by the eddy current brake (N·m).

K is a constant that depends on the material properties and design of the conductive disc.

B is the magnetic field strength (T or Gauss)

r is the effective radius of the conductive disc (m or ft)

w is the angular velocity of the disc (rad/s)

Power dissipation

It's crucial to assess the power lost during a stop in order to create a brake that operates consistently and under control. The condition of the brake pads is impacted by this.

The total energy absorbed during the stop must be calculated in order to determine the power dissipation, and is estimated as follows:

$$\text{Mean power dissipation} = KE / t_b \text{ (watts)} \tag{13}$$

Regenerative braking

Regenerative braking involves recovering energy during braking. The change in kinetic energy is used to calculate the recovered energy [6]-[8].

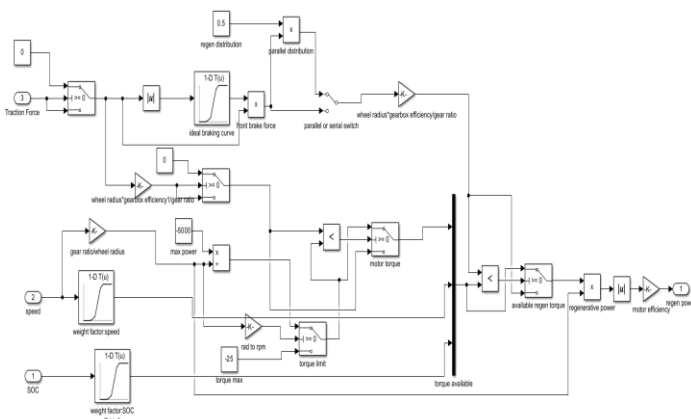


Figure 7: simulation diagram of regenerative braking system

1. Change in kinetic energy calculation

The change in kinetic energy during braking is calculated using the initial and final speeds:

$$\text{Change in kinetic energy} = KE_{\text{final}} - KE_{\text{initial}}$$

The deceleration force F_{dec} is given by

$$F_{dec} = m_{veh} \frac{dv(t)}{dt} = F_t - F_a - F_r - F_g, N \tag{14}$$

Where m_{veh} is vehicle mass, kg

$\frac{dv(t)}{dt}$ is acceleration or deceleration, m / s^2

F_t is traction force; N

F_a is aerodynamic resistance force, N

F_r is rolling resistance force, N

F_g is so called uphill(slope) driving force, N

$$F_a = \frac{1}{2} \rho_a S_{fr} C_d v^2, N \tag{15}$$

Where ρ_a is air density, kg / m^3

S_{fr} is frontal area, m^2

C_d is drag coefficient

V is the vehicle's velocity, m / s

$$F_r = C_r m_{veh} g \cos(\alpha), N \tag{16}$$

Where C_r is the rolling friction coefficient

g is gravitational acceleration, m / s^2 ;

α is slope angle, degrees.

$$F_g = m_{veh} g \sin(\alpha), N \tag{17}$$

$$P_{dec} = F_{dec} v, W$$

Where P_{dec} is required power to decelerate, w.

$$P_{dec} = P_{front} + P_{rear}, W \tag{18}$$

Where P_{front} and P_{rear} are powers provided to the front and rear wheels respectively, W.

$$P_{mot-el} = P_{dec} \eta_g \eta_m, W \tag{19}$$

Where P_{mot-el} is motor's electric power, W

η_g is efficiency of gear and η_m is motor's efficiency.

Efficiency of the gear is assumed to be constant, while motor's efficiency is given by

$$\eta_m = \frac{T_m W_m}{T_m W_m + K_c T_m^2 + K_i W_m + K_w W_m^3 + C} \tag{20}$$

The regenerative braking force (F_r) is dependent on the efficiency of the regenerative system (η), the vehicle's speed (v), and the state of charge of the battery (Soc).

It can be modeled as:

$$F_r = \eta \cdot \frac{1}{2}mv^2 \cdot \frac{dSoc}{dt} \tag{21}$$

This equation represents the rate of change of energy in the battery due to regenerative braking.

Where:

F_r = Regenerative braking force (N)

v = Vehicle speed (m/s)

Where:

$T_{regenerative}$ is the regenerative braking torque (N·m)

η is the efficiency of the regenerative braking system (expressed as a fraction).

ΔKE is the change in kinetic energy of the vehicle (Joules)

Integration of disc, eddy current and regenerative braking system

Total Braking Force

The total braking force (F_{total}) is the sum of the forces from the three brake systems:

$$F_{total} = F_f + F_e + F_r \tag{22}$$

Total braking torque

The total braking torque (T_{total}) is the sum of the forces from the three brake systems:

$$T_{total} = T_{regenerative} + T_{eddy} + T_{disc} \tag{23}$$

Gear system

The gear system in a Lopifit, which is a type of electric walking bike, is used to optimize the mechanical advantage and power transfer between the rider's walking motion and the bike's propulsion. Inside the rear wheel hub, there may be a gearing system that helps optimize the power transfer from the electric motor to the rear wheel [9]. This gearing allows the bike to achieve different speeds and provide various levels of assistance.

Efficiency

Gears allow the Lopifit to efficiently convert the rotational motion of the pedals into linear motion to move the bike forward. Different gear ratios can be selected to match the rider's walking speed and terrain.

Mechanical advantage

Mechanical advantage means is a measure of how efficiently a machine or mechanical system amplifies force or motion.

$$MA = \frac{OutputForce}{InputForce} \tag{24}$$

A mechanical advantage greater than 1 indicates that the machine amplifies force or motion. In such cases, you get more output force (or displacement) than the input force (or displacement) applied. On the other hand, a mechanical advantage less than 1 indicates a reduction in force or motion, which is often used to trade force for speed.

Speed and Resistance

Gears provide the rider with options to increase or decrease resistance when walking on various terrains or at different speeds. Lower gears offer more resistance for uphill climbs, while higher gears are used for flat or downhill terrain to achieve greater speed.

$$Gear\ Ratio = \frac{W1}{W2} = \frac{N1}{N2} = \frac{d2}{d1} = \frac{T2}{T1} \tag{25}$$

Where:

$W1$ and $W2$: Angular velocity in radian/sec for driver and driven gear

$N1$ and $N2$ =Gear speed in RPM for driven and driven gear

$d1$ and $d2$ =driver and driven gear diameter

$T1$ and $T2$ =Number of teeth on driver and driven gear

Comfort and Control

Gear shifting allows riders to find the optimal walking pace and effort level, making it more comfortable and less fatiguing during long rides. It also provides better control over the bike's speed and performance.

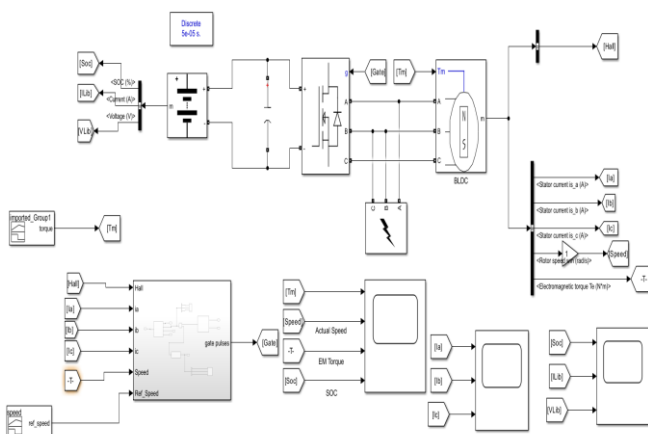


Figure 8: Simulation model of a BLDC motor vehicle

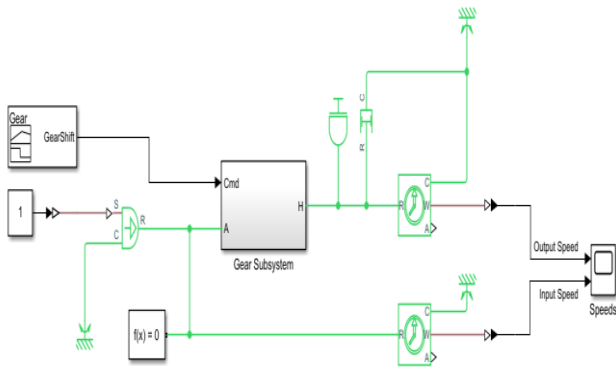


Figure 9: simulation diagram of Gear system in a vehicle

RESULTS

The gear system's output graph, displaying output speed versus input speed, provides valuable insights into the mechanical performance of the system.

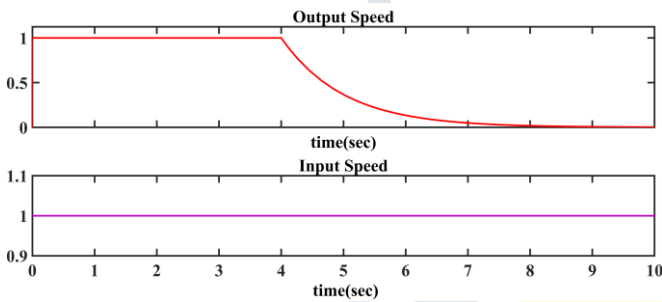


Figure 10: Input speed vs output speed

Firstly, in a linear gear system, a direct proportionality is observed between the input and output speeds. As the input speed increases or decreases, the output speed follows suit, maintaining a constant ratio. This linear relationship signifies a consistent transmission of rotational motion. However, in more complex gear systems, the output graph exhibits nonlinear behavior. This is due to the changing gear ratios within the system, causing output speed fluctuations in response to varying input speeds.

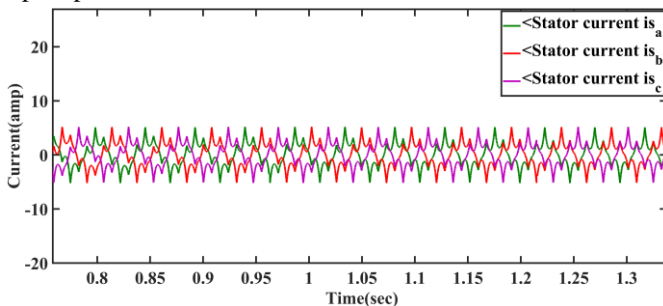


Figure 11: Simulated current curves of a vehicle

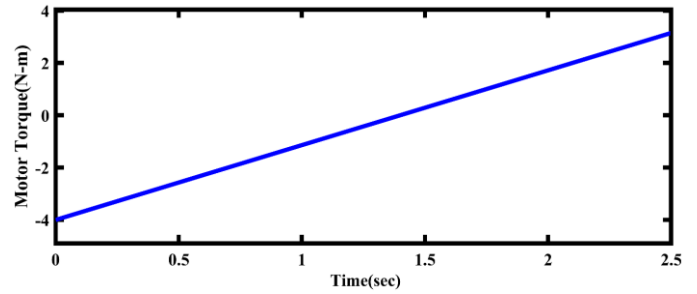


Figure 12: Motor torque vs Time

As time progresses, the torque might decrease or stabilize as the motor reaches its intended speed or load. Analyzing this graph provides insights into how well a motor accelerates, maintains speed, and responds to changes in the load over time.

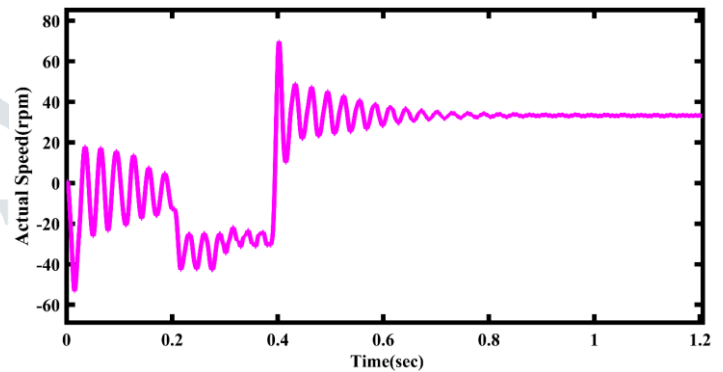


Figure 13: Actual speed vs Time

The graph shows acceleration at the start, a stable speed during cruising, and variations during obstacles or downhill sections.

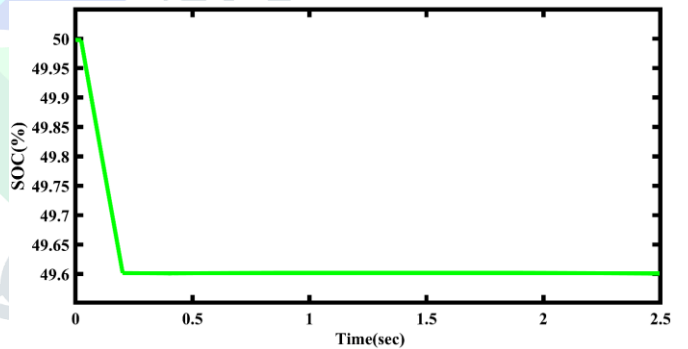


Figure 14: soc vs Time

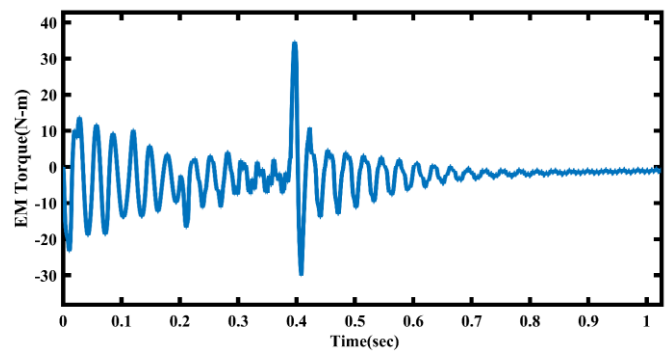


Figure 15: EM torque vs Time

The graph often shows an initial torque surge during motor startup, followed by a gradual decline as the motor reaches its desired speed.

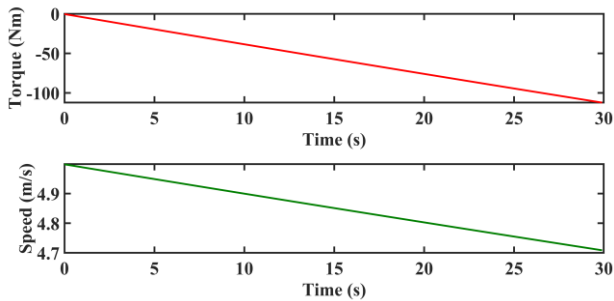


Figure 16: Torque vs time and speed vs time

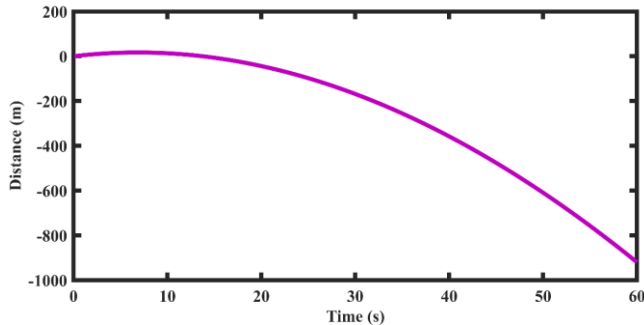


Figure 17: Distance vs Time

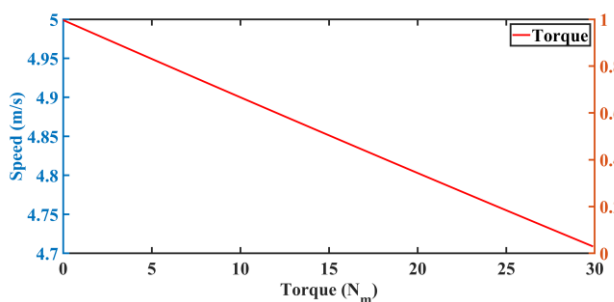


Figure 18: speed vs torque

Here the object's speed decreases due to the braking action, the torque exerted by the eddy current system also gradually decreases. This exponential decay signifies that the rate of deceleration progressively slows down as the object's speed reduces.

CONCLUSION

In this paper, the implementation of regenerative braking, specifically utilizing a combination of disc and eddy current braking systems, offers significant potential for enhancing the performance of LOPIFIT devices is done. This innovative approach not only improves the braking efficiency but also contributes to sustainability and energy conservation. The combination of these technologies has resulted in a notable improvement in braking performance, ensuring rider safety and control. Moreover, the implementation of regenerative braking allows us to capture and store energy during deceleration, promoting greater energy efficiency and sustainability. This project has not only improved the performance of the Lopifit but has also paved the way for more eco-conscious and advanced transportation solutions in the ever-evolving world of personal mobility.

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