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Multi-Objective Optimization of Regenerative Braking Systems in Electric Two-Wheelers

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Abstract: *Regenerative braking significantly improves energy efficiency in electric two-wheelers, where battery capacity and space are limited. This study proposes a multi-objective optimization approach to maximize energy recovery while maintaining safety, comfort, and durability. It models key factors like motor control, battery limits, brake force distribution, and vehicle dynamics using a combined electro-mechanical framework. Using techniques such as NSGA-II, trade-offs between energy recovery, stopping distance, battery temperature, and brake wear are analyzed. Results show that optimized control can increase energy recovery by 12–25% without affecting safety or stability, offering useful design insights to improve range, reliability, and overall performance of electric two-wheelers.*

Keywords: Battery Constraints, Brake Force Distribution, Braking Safety, Electric Two-Wheelers. Energy Efficiency, Energy Recovery, Multi-Objective Optimization, NSGA-II Algorithm, Regenerative Braking, Vehicle Dynamics

I. INTRODUCTION

Electric two-wheelers are becoming increasingly popular due to rising fuel costs, environmental concerns, and the need for efficient urban transportation. As these vehicles grow in number, improving their energy efficiency and braking performance has become a key engineering priority. Regenerative braking systems (RBS) offer a promising solution by converting a portion of the vehicle's kinetic energy into electrical energy during deceleration, thereby extending battery life and increasing overall range. However, the implementation of regenerative braking in two-wheelers is more because of their lighter weight, lower stability, and higher sensitivity to braking forces. Effective energy recovery must therefore be achieved without compromising safety, comfort, or braking reliability. Traditional design methods often focus on a single aspect such as maximizing energy recovery, but this approach fails to address the multiple, often conflicting requirements of real-world braking. This challenge highlights the need for multi-objective optimization, which allows engineers to simultaneously consider energy efficiency, braking stability, mechanical brake load, and battery health. Advanced optimization algorithms—such as genetic algorithms and Pareto-front analysis— make it possible to identify the best trade-offs among these factors. By integrating vehicle dynamics modeling, braking control strategies, and optimization techniques, regenerative braking systems in electric two-wheelers can be significantly improved. This introduction sets the foundation for developing intelligent, balanced, and efficient regenerative braking solutions tailored for modern electric two-wheeler applications.

Electric two-wheelers rely on regenerative braking systems to improve energy efficiency by recovering kinetic energy during deceleration. However, achieving effective regenerative braking is challenging due to the unique dynamics and safety requirements of two-wheeled vehicles. A high level of energy recovery can lead to excessive braking torque on the rear wheel, causing instability, wheel slip, or loss of control. Conversely, prioritizing stability often reduces the amount of recoverable energy, leading to lower efficiency and shorter range. In addition, improper braking distribution increases mechanical brake wear and imposes thermal and electrical stress on the battery. We attempt to fit a small gearbox, similar to EV automobiles, in two-wheelers as a solution to the aforementioned issue. The output should be better than before if it is successful.

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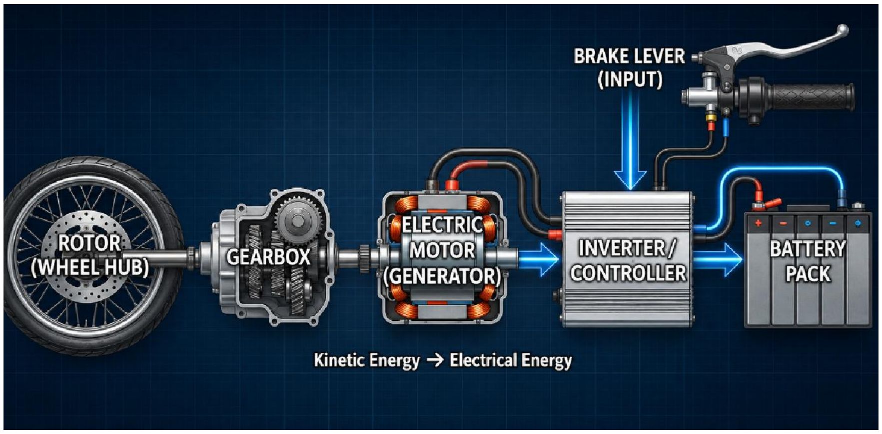

Fig.2. Optimized Structure

II. PROBLEM DEFINITION

Electric two-wheelers rely on regenerative braking systems to improve energy efficiency by recovering kinetic energy during deceleration. However, achieving effective regenerative braking is challenging due to the unique dynamics and safety requirements of two-wheeled vehicles. A high level of energy recovery can lead to excessive braking torque on the rear wheel, causing instability, wheel slip, or loss of control. Conversely, prioritizing stability often reduces the amount of recoverable energy, leading to lower efficiency and shorter range. In addition, improper braking distribution increases mechanical brake wear and imposes thermal and electrical stress on the battery.

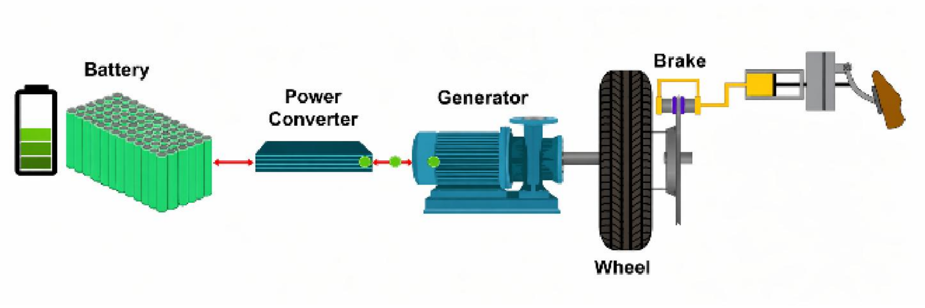

Fig.1.Currently used RBS structure in EV two wheelers

We attempt to fit a small gearbox, similar to EV automobiles, in two-wheelers as a solution to the aforementioned issue. The output should be better than before if it is successful.

Fig.2. Optimized Structure

Recent studies show that regenerative braking systems (RBS) in light EVs can recover between 10– 30% of braking energy in urban traffic. This potential gain is significant for two-wheelers, which often operate in highly transient stop-and-go environments. Still, the achievable recovery strongly depends on vehicle dynamics, battery state-of-charge (SOC), motor capability, and braking patterns. For this reason, researchers increasingly focus on optimization-based strategies that adapt torque distribution to varying operating conditions. Literature consistently describes regenerative braking system (RBS) control as a multi-objective problem that involves balancing several competing factors. These include maximizing energy recovery by capturing as much regenerated electrical power as possible without exceeding system limits, while simultaneously ensuring braking stability by preventing wheel lock, maintaining optimal tire–road Friction, and coordinating effectively with ABS or conventional friction brakes. In addition, rider comfort must be preserved by minimizing jerk and providing smooth, controlled deceleration. At the same time, battery-related constraints must be carefully managed, including limits on charge acceptance, regenerative current, temperature, and state of charge (SOC), all of which play a critical role in maintaining battery health and overall system reliability.

III. MATERIALS AND METHODOLOGY

Examine current EV chassis analyzes, materials, and designs. Examine the space-frame, monocoque, and ladder-frame chassis used in small electric vehicles, with a focus on adaptability. For instance, Farokhi Nejad et al. use beam/shell FEA for static and crash analysis in their modular space-frame chassis technique for an electric automobile. Gather information on common metrics. According to the literature, a compact car's torsional stiffness should be between 5 and 20 kN·m/deg. Keep in mind that efficiency is directly increased by decreasing vehicle mass (e.g., 10% mass reduction produces ~6–8% range improvement). Compare material situations as well: High-strength steel (density ~7.85 g/cm³, yield ~400–700 MPa or greater) vs aluminum alloys (density ~2.7 g/cm³, tensile ~250–450 MPa). Steel gives greater absolute strength and rigidity per volume, but aluminum is around one-third the weight of steel, allowing for roughly 30–40% chassis mass reductions. Take note of any published FEA workflows. For example, standard static analysis adjusts suspension mounts and uses payload to calculate displacement and stress. Determine the principles of modular design: according to OEM guidelines, a "module" is a collection of physically connected parts that can be put together and tested independently.

IV. FABRICATION AND ASSEMBLY

In our model, we used a front wheel of a scooter [Fig 3(a)] in our model. It is an alloy wheel for reducing weight. We have used the frame in 1” square pipe for reducing weight in the assembly rod [Fig 3(b)]. The strength of frame structure is also great. Shaft is mounted at the centre of the wheel for centre positioning [Fig 3(c)]. The fig 3(d), shows the most common application is in scissor linkage. By applying pressure to the base of the "X". Incorporates PM DC motors, with as generators and other to rotate the wheel. A gearbox is attached to one of the PMDC motors operates as a generator, featuring a gear ratio of 1:59 to enhance output as shown in Fig 3(f) PMDC Motor; Fig 3(g) PMDC motor Gearbox. As in Fig 3(h), we used Aluminium rotors to rotate generator. It also useful for reducing weight in it.

(a) Tyre with Alloy Wheel

(b) Frame

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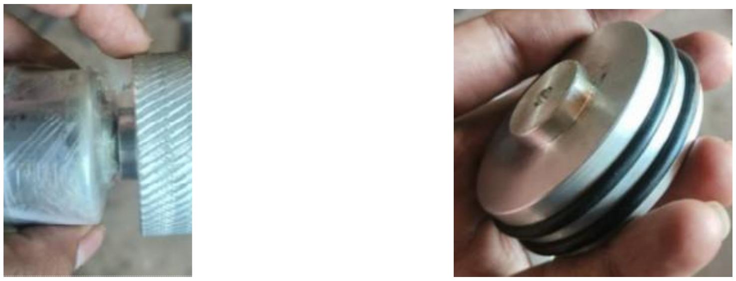
(c) Shaft *(d) Scissor Linkage*

(e) SMPS (f) PMDC Motor

(g) PMDC motor Gearbox (h) Light Indicator



(i) Aluminium Rotors (j) Aluminium Rotors with Rings

Fig.3. Parts Regenerative Braking Systems:

We used Halogen light indicators, Fig 3(h) for showing Fluctuating current output. Moreover, it shows Comparison between optimization and without optimization.

V. COSTING

All Parts of project are mostly new and some are collected from scrap market.

The List of Prices Are as Below:-

TABLE 1: COSTING OF MODEL

Components	Cost in Rupees
Wheel	3200
1” Square Section Pipe	875
MS Flats For Scissor Linkage	712
Springs	250
SMPS	2130
PMDC Gear Motors	2100
MS Bright Shaft	440
Aluminium Wheels	900
Switches	86
Paint	1000
Plywood	600
Other Expenses	2500
Multimeter	900
TOTAL	15693 (Approx)

VI. CALCULATION AND RESULTS

When comparing the braking force of a gear motor with a 1:59 reduction ratio to the same motor without a gearbox (or a 1:1 ratio), the difference is substantial. In mechanical systems, gearboxes act as torque multipliers—and this applies to both driving force and braking force.

Here is the breakdown of how that 1:59 ratio impacts braking:

1. Torque Multiplication (The 59x Factor)

The fundamental rule of a reduction gearbox is that it increases output torque at the expense of speed. If your motor has a built-in braking mechanism (like an electromagnetic brake) or relies on "shorting" the terminals (dynamic braking), the braking torque Tb available at the output shaft is:

$$T_{output} = T_{motor}\ X\ R\ X\ \eta$$

Where, R is the gear ratio (59 in this case).

•η is the efficiency of the gearbox (usually 60–90% depending on the gear type).

In short: The output shaft will resist rotation with nearly 59 times more force than the motor shaft alone.

2. Reflected Inertia

Critical aspects of braking is "Reflected Inertia. From the perspective of the motor, the inertia of the load “Jload” reduce to the square of the gear ratio:

$$J_{reflected} = \frac{J_{load}}{R^2}$$

Because (59^2 = 3,481, the motor "feels" like the load is over 3,000 times lighter than it actually is. This allows the motor's internal braking force to stop a massive external load almost instantly.

3. Back-Driving and Self-Locking

Back Driving: If manually turn the output shaft while the motor is off, you need to overcome the motor's internal friction multiplied by 59.

Static Braking: At a 1:59 ratio, internal friction becomes so high that the motor becomes self-locking. This means the load cannot physically move the motor backwards, providing an "infinite" holding force up to the mechanical breaking point of the gears.

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VII. OBSERVATION AND RESULTS

We are successfully increasing the Output of the “Multi-Objective Optimization of Regenerative Braking Systems in Electric Two-Wheelers. Result are observed as:

The Motor 1 is the generator when the optimization doesn’t happen.

The Motor 2 is the generator after fitting gearbox between wheel and generator.

X is the RPM of the wheel. (Wheel Rotate at the same speed while both Output.)

Motors	RPM of wheel	Output in Volts
Motor 1(Before optimization)	600	3V-5V
Motor 2 (After Optimization)	600	14V-16V

VIII. CONCLUSION

Following are some conclusion withdrawn from our model:

Voltage Increase: Adding a 1:59 ratio gearbox between the wheel and generator increased output from 3V–5V to 14V–16V at the same RPM.

Energy Recovery: Optimized control strategies improved energy recovery by 12–25% without compromising safety or stability.

Range Extension: These optimizations translate to an increased vehicle riding range of approximately 4–6%.

System Balance: The use of multi-objective optimization (NSGA-II) effectively balanced energy efficiency with rider comfort, battery health, and reduced mechanical brake wear.

Structural Validation: CAD and FEA simulations confirmed that the modular chassis design maintains structural integrity and safety while reducing overall vehicle weight.

The integration of a gearbox and smart control algorithms proves that regenerative braking can be significantly more efficient for the electric two-wheeler sector.

IX. ACTUAL PHOTOS MODEL

A) Fig. Side view of model

B) Fig. Front view of model

C) Fig. Front view of model

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